International Journal of Current Science Research and Review
ISSN: 2581-8341
Volume 08 Issue 12 December 2025
DOI: 10.47191/ijcsrr/V8-i12-07, Impact Factor: 8.048
IJCSRR @ 2025
www.ijcsrr.org

# Impact of Freight Transport Packaging on Energy Consumption and Climate Change

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**ABSTRACT:** The research "Impact of Freight Transport Packaging on Energy Consumption and Climate Change" examines energy efficiency in freight transportation (TCC) through the Green Vehicle Routing Problem (G-VRP) and eco-friendly packaging. Using a mixed-methods approach, combining quantitative data (distances, energy consumption, CO2 emissions) and qualitative information (operator and the community perceptions), it includes a literature review and a pilot study in 10 cities in Hidalgo, Mexico. Results show that optimized routes with electric vehicles reduce the total distance of traveling, energy consumption, and emissions by 23.87%, and up to 97.86% compared to diesel fleets. Gaps in charging infrastructure and green technology adoption are identified. Integrating ecolabels and heuristic algorithms, like a modified Clarke-Wright, offers sustainable and promising solutions, though it requires a deep restructuring of the production processes. The study suggests public policies and business strategies to promote green logistics, advocating for tailored algorithms and mixed-methods to enhance sustainability in TCC.

**KEYWORDS:** Carbon Dioxide, Ecolabels, Mixed methodology, Packaging, G-VRP.

## INTRODUCTION

In recent years, energy efficiency has gained prominence on the public agenda due to rising fossil fuel costs, growing concern about climate change, and challenges in energy supply. These factors have heightened the urgency to optimize energy use and promote more sustainable practices across all sectors.

The current energy and environmental landscape present a valuable opportunity in the transportation sector, which has a significant impact on energy consumption and greenhouse gas emissions, placing it at the core of necessary transformations. Transportation activities (air, land, and sea), primarily reliant on gasoline and diesel, recorded an annual growth rate of 2.45% from 1990 to 2015, emitting 171.3 million tons of CO2 in 2015, accounting for 24.5% of total emissions (INECC, 2018). In this context, two sectors of great importance in greenhouse gas (GHG) emissions are the energy and transportation industries.

The trajectories of these variables show a strong correlation between non-renewable energy consumption trends and emissions, while renewable energy sources exhibit a slight decline. Specifically, road transportation in developing countries is expected to grow at an annual rate of 2.8% until 2030.

In freight transportation (TCC), the majority of energy consumption comes from oil. Therefore, analyzing energy efficiency in this sector involves examining various aspects such as modal distribution, industrial structure, regulatory frameworks, management capabilities, and technology adoption. Improving energy efficiency in TCC can lead to direct improvements in economic profitability, justifying its implementation.

For TCC, energy conservation should not be perceived as an imposition or sacrifice but as a genuine opportunity to enhance productivity and competitiveness. This is because logistics management is currently evolving at a rapid pace, leading specialized logistics service providers to consider the importance of managing customer locations and the use of necessary resources for the physical distribution of goods (Singh & Verma, 2018; Acosta, 2019).

Thus, this research views freight delivery as a strategic activity aimed at gaining a competitive advantage, as transportation costs in freight movement can account for one to two-thirds of a company’s total logistics costs. Proper supply chain management can result in lower operational costs, better planning, and improved information and product flow (Ballou, 2007; Gómez, Zuluaga, Ceballos & Jiménez, 2019), alongside reduced energy consumption and costs. According to Wandosell et al. (2021), one green marketing strategy for companies involved in freight movement is the use of environmentally friendly packaging.

The current issue is that 99% of heavy vehicles in Mexico operate on diesel. On average, B2-type buses (19 tons), the most commonly

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used for urban passenger transport, consume 22.72 L/100 km and emit 777 gCO2/km. Similarly, T3-type tractor trailers (54 tons), the most used for long-distance freight transport, consume an average of 40.2 L/100 km and emit 1063 gCO2/km. These results are consistent with similar studies conducted globally when presented in terms of the vehicle's total weight.

In Mexico, very few vehicles (<1%) operate on compressed natural gas (CNG) or electricity. Heavy vehicles running on CNG, used for both freight and passenger transport, have shown excessive consumption compared to expectations. Electric heavy vehicles in Mexico, used for passenger transport in major cities, reduce energy consumption and GHG emissions by 40% (Serrano, Huertas, Mogro, & Quiram, 2023).

In this regard, packaging and containers are essential for preserving, protecting, and maintaining the quality of food, facilitating its transport and commercialization. However, these materials have caused harmful environmental impacts, leading to a new trend of eco-friendly consumption with containers that maintain or even improve the quality of packaged products while ensuring safety for life and health (Kozlowicz et al., 2019).

Therefore, the proposed mixed methodology, based on a literature review and a pilot test in 10 cities in Hidalgo for a logistics operations company, is justified by the arguments in Forni and De Grande's (2020) article on triangulation and mixed methods.

This methodology combines qualitative and quantitative approaches to comprehensively address the issue of energy efficiency in freight transportation (TCC), considering both theoretical dimensions (systematic literature review) and practical applications (implementation of G-VRP) in a specific context.

The article emphasizes that combining qualitative and quantitative methods overcomes the limitations of single-method approaches, promoting a deeper and more robust understanding of social phenomena, such as the energy and environmental impact of TCC. Methodological triangulation, understood as the combination of different data sources, methods, or perspectives (Denzin, 1978), is particularly useful for validating findings and reducing biases inherent in a single approach. Mixed methods, according to Creswell (2015), integrate qualitative and quantitative data convergently or sequentially, enabling a pragmatic approach that prioritizes the research question over methodological preferences.

In the context of the proposed research, energy efficiency in TCC requires analyzing quantitative variables (such as fuel consumption, CO2 emissions, and operational costs) alongside qualitative aspects (such as perceptions of logistics stakeholders, cultural or regulatory barriers, and management practices). The mixed methodology enables the integration of these dimensions, generating a more comprehensive analysis that addresses the strategic needs of the logistics company and the context of environmental sustainability.Technical reports or notes and viewpoints should not exceed six manuscript pages. Viewpoints should be submitted as for regular papers, but omitting abstract, keywords and statement of contribution. Book Reviews should only be offered after consultation with the Book Reviews Editor and should not be submitted using this system. Spelling should conform with The Concise Oxford Dictionary.

## METODOLOGY

This research addresses the literature review, which constitutes the initial phase of the investigation and aligns with the theoretical triangulation approach described by Forni and De Grande (2020). This stage enables the compilation and synthesis of prior knowledge on energy efficiency in freight transportation (TCC), including quantitative data (such as those reported by INECC, 2018, on CO2 emissions) and qualitative approaches (such as studies on sustainable logistics practices, cited by Wandosell et al., 2021). The review not only establishes a robust theoretical framework but also identifies knowledge gaps, such as the limited adoption of electric or compressed natural gas (CNG) vehicles in Mexico (Serrano et al., 2023). This step is crucial for contextualizing the pilot test and ensuring that the research questions are relevant and well-grounded.

Subsequently, the pilot test in 10 cities in Hidalgo represents the empirical phase of the mixed methodology, designed to gen erate specific and contextualized data. According to Forni and De Grande (2020), mixed methods can be implemented sequentially, where a qualitative or quantitative phase informs the other. In this case, the pilot test adopts an exploratory sequential design: first, qualitative data are collected through interviews or focus groups with key stakeholders (logistics managers, drivers, and local authorities) to understand current practices, barriers, and opportunities for adopting energy-efficient technologies. Subsequently, quantitative data are gathered by measuring energy consumption, CO2 emissions, and operational costs in a sample of the company's vehicles across the 10 cities.

This sequential approach allows qualitative findings to guide the design of quantitative data collection, ensuring that the metrics are

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relevant to the local context. For example, interviews may reveal preferences for certain fuel types or limitations in electric charging infrastructure, which will guide the selection of quantitative variables to measure. Additionally, conducting the pilot test in a limited number of cities (10) enables a controlled implementation, aligned with the methodological pragmatism principle highlighted by Creswell (2015), where the combination of methods is tailored to the specific needs of the study.

Thus, the mixed methodology is particularly suitable for TCC due to its complexity, which involves technical, economic, social, and regulatory factors. According to Forni and De Grande (2020), triangulation and mixed methods facilitate the convergence of results, enabling the validation of quantitative findings (such as the 40% reduction in emissions with electric vehicles, as per Serrano et al., 2023) with qualitative perspectives (such as operators' acceptance of these technologies). This approach not only enhances the reliability of the results but also provides a holistic view that can translate into practical strategies for the company, such as route optimization, the adoption of eco-friendly packaging (Wandosell et al., 2021), or a gradual transition to alternative fuels.

In this regard, it is noted that organizations are currently actively seeking alternatives to overcome challenges in competitive environments. Each entity must customize its processes to meet the demands of selected markets (N. Rezaei, S. Ebrahimnejad, A. Moosavi, & A. Nikfarjam, 2019) while designing strategies to reduce energy consumption. Consequently, due to the complex nature of distribution systems, which cater to a wide range of products requiring flexibility, they are inherently complex. The contemporary logistics paradigm integrates activities within a system, resulting in complexity. The primary goal is to ensure a continuous flow of products that meet customer requirements in terms of quality and affordability (J. Chen, & T. Wu, 2006) while minimizing energy use and environmental impact to promote 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 an efficient flow of products. It ensures high customer service standards while optimizing resource utilization in distribution operations by enabling delivery, simultaneous pickup, and reduced energy consumption (S. Nah, S. Doreen, J. Fong, W. Shiang, & K. Leng, 2020).

Therefore, this research involves a literature review to address a green distribution strategy, the G-VRP, combined with an ecological packaging strategy, eco-labeling, which collectively aim to reduce environmental pollution and energy consumption.

Eco-labels, on the other hand, are symbols awarded to products that have a lower environmental impact, as they meet a series of ecological criteria, considering their life cycle analysis and other specific characteristics (S. Aguilar & M. Hernández, 2010). Eco-labels stem from the growing global demand to protect the environment from governments, companies, and the general public. There is a general classification of eco-labeling according to ISO 14000, with its characteristics outlined in Table 1 below:

**Table I. Characteristics of Standard 14000 in Eco-Labels**

| *Standard* | *Characteristics* |
|---|---|
| ISO 14024,<br>Type I Label | Developed by a third party, they have greater credibility than Type II labels. |
| IS O 14021,<br>Type II Label | Developed by the companies themselves, they are a requirement to indicate that the products being marketed are environmentally friendly |
| ISO 14025,<br>Type III Label | To obtain this type of eco-label, it is necessary to conduct an LCA (Life Cycle Assessment).<br>It has greater credibility, but the label is more difficult to understand due to the significant amount of technical information it contains. |

**Source:** own elaboration with data in Martínez-Rodríguez, María Concepción, Mayorga-Pérez, Omar, Vera-Martínez, Martin Cutberto, & García-Morales, María Isabel. (2018).

The aim is to reduce the impact generated in two situations: the use of cardboard and plastic for packaging in freight transportation and the distribution of these goods through green routes. This results in the following contribution: an algorithm that en ables the establishment of routes where alternative, non-fossil fuels can be used, combined with the use of ecological packaging in the handling of goods from an origin to a destination.

To achieve the objectives of the Green Vehicle Routing Problem (G-VRP), one approach involves the use of eco-friendly vehicles

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(EFVs). These EFVs can operate on alternative and environmentally friendly fuel sources, such as biodiesel, electricity, ethanol, hydrogen, methanol, and natural gas, which can replace vehicles with internal combustion engines (ICEVs). This has led to the adoption of alternative fuels in VRPs, with vehicles powered by alternative fuels (AFVs) classified as a general category of EFVs. Figure 1 illustrates how some studies in the literature have framed the Alternative Fuel Vehicle Routing Problem (AF-VRP) without specifying the type of vehicle fuel. It is worth noting that electric vehicles (EVs) and hybrid vehicles (HVs) have been considered specialized types of AFVs and have been examined separately due to their distinct characteristics. Electric vehicles have been regarded as an ideal alternative to ICEVs for freight distribution in many studies due to their zero emissions during use and minimal noise pollution (E. Ghorbani, M. Alinaghian, G. Gharehpetian, S. Mohammadi, & G. Perboli, 2020).

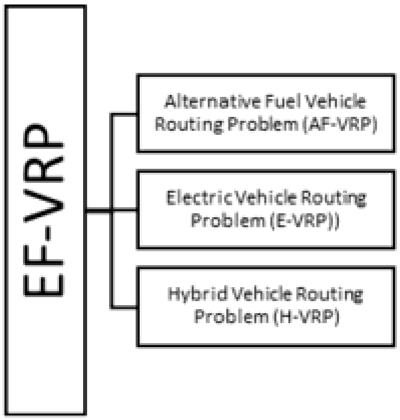


**Figure 1. Variants of the route generation problem for green vehicles**
**Source:** Own production based in Ghorbani, (2020).

These could be presented in tabular or graph form, with appropriate statistical evaluation. Discussion of results. Statement of conclusions drawn from the work.

### *A. G-VRP with Conventional Vehicles*

S. Sabet, F. Namdarpour, & M. Mesbah (2021) classify the literature on G-VRP into three main domains: A. Rauniyar, R. Nath, P. K. Muhuri (2019), G-VRP with conventional vehicles; D. Pecin, A. Pessoa, M. Poggi, E. Uchoa (2017), G-VRP with alternative fuel vehicles; and D. Singh & A. Verma (2018), G-VRP with a mixed fleet of vehicles.

The first category includes studies focusing on conventional multi-objective G-VRP research, where the Capacitated Vehicle Routing Problem (CVRP) considers multiple objectives. E. Demir, T. Bekta, & G. Laporte (2012) initially introduced this approach. Researchers addressed the bi-objective Pollution Routing Problem (PRP), aiming to minimize fuel consumption and driver time. Several scholars have expanded Demir's methodology to address the VRP, including A. Rauniyar, R. Nath, P. K. Muhuri (2019). G. Poonthalir, R. Nadarajan (2018) tackled a multi-objective problem with speed constraints.

Several studies have explored multiple objectives in the context of conventional vehicles, aiming to minimize factors such as marginal cost, fuel consumption, and travel time, often combined with other variants. For example, L. Alfaseeh, S. Djavadian, R. Tu, B. Farooq, M. Hatzopoulou (2019) and S. Djavadian, R. Tu, B. Farooq, M. Hatzopoulou (2020) integrated connectivity and automation into their multi-objective exploration of green routes.

Several articles have addressed constraints such as road conditions, congestion, topography, vehicle load, and their impacts on route cost and fuel consumption. N. Rezaei, S. Ebrahimnejad, A. Moosavi, & A. Nikfarjam (2019) examined the green vehicle route generation problem with time windows, considering a heterogeneous vehicle fleet 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 the type of fuel, as shown in Figure 2. In a recent study, M. Keskin, B. Catay, G. Laporte (2021) addressed stochastic waiting times at charging stations within specific time windows.

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Another significant contribution was made by M. Schneider, A. Stenger, D. Goeke (2014), who proposed a hybrid heuristic combining a search algorithm with a tabu search heuristic. This approach accounts for the limited charging capacities of vehicles and customer requirements.

| Biodiesel | Electrical | Ethanol | Hydrogen | Natural gas | Propane |
|---|---|---|---|---|---|
| •Diesel vehicles | •Hybrids and Plug In vehicles | •Flexible fuel vehicles | •Full cell vehicles | •Natural gas vehicles | •Propane vehicles |

**Figure 2. Classification of alternative fuel vehicles**
**Source:** Own production (2024).

In a parallel case study, N. Ding, R. Batta, & C. Kwon (2015) developed a heuristic approach that incorporated a simple charging time to generate a more efficient solution. H. Mao, J. Shi, Y. Zhou, & G. Zhang (2020), on the other hand, utilized an improved Ant Colony Optimization (ACO) algorithm hybridized with enhanced local search and insertion heuristics to address the problem, with a particular focus on partial recharging and battery swapping. M. Keskin, B. Catay, & G. Laporte (2021) conducted practical research on the Electric Vehicle Routing Problem with Time Windows and Partial Recharging (EVRPTW-PR), implementing full recharging as a constraint while also allowing partial recharging.

This concept involves fully recharging a vehicle each time it visits a service station, allowing it to continue its service as long as its battery permits. M. Meng & Y. Ma (2020) explored electric vehicle routes with time windows and proposed two fuel replenishment strategies. Additionally, S. Huang, L. He, Y. Gu, K. Wood, & S. Benjaafar (2014) investigated the design of mobile charging stations. M. Wen, G. Laporte, O. B. G. Madsen, A. V. Nørrelund, & A. Olsen (2014) addressed the issue of locating electronic service stations for electric vehicles within a traffic network to optimize network performance. F. Baouche, R. Trigui, R. Billot, & N. E. El Faouzi (2014) introduced a novel approach to the electric vehicle 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, Z. Yi, J. Smart, & M. Shirk (2018) modeled and solved a G-VRP variant with a heterogeneous fleet for the first time. They found that employing a heterogeneous fleet has advantages over a mixed fleet in urban areas. In addition to the use of green transportation, the following applies to eco-labels.

**Table II. Types of Eco-Labels**

| *What does it tell us?* | *Logo* |
|---|---|
| ESR (Socially Responsible Company). As its name indicates, seeing this logo on the products indicates that the company has corporate social responsibility, this term is defined as the conscious and consistent commitment to fully comply with the purpose of the company, both internally and externally, considering the economic, social and environmental expectations of all its participants, demonstrating respect for people, ethical values, the community and the environment, thus contributing to the construction of the common good. | ESR Empresa Socialmente Responsable |
| FSC (Forest Stewardship Council). Belonging to an international association made up of representatives of the wood industry, forest owners, indigenous groups and NGOs, it mentions that the wood comes from sustainable farms. | FSC |

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| *What does it tell us?* | *Logo* |
|---|---|
| Environmental quality badge of the department of Catalonia. Belonging to the region of Catalonia, it mentions the characteristics that various types of products must meet, such as whether these products come from recycled material, or whether some type of system that favored water saving was used in their production, etc. | Garantia de qualitat ambiental |
| Eco label of the European Union. This label is created by the European Union and is a type of label that mentions the characteristics that various products and services must meet so that they can be considered friendly to the environment. | |
| Blue Angel, from Germany. It was the first eco-label created to be awarded only to those products that had the least impact on the environment. | |
| White Swan, from the Scandinavian countries. This type of label was created after the Blaue Engel label was created in Germany, and it is also widely accepted in Europe. | |
| Environmental Choice, Canada. Label developed by the government of Canada, which covers a large number of products, recycled material, paints, raw materials, etc. | |

**Source:** Own elaboration with data in Martínez-Rodríguez, María Concepción, Mayorga-Pérez, Omar, Vera-Martínez, Martin Cutberto, & García-Morales, María Isabel. (2018).

Therefore, eco-labeling is not a simple process to obtain in the transshipment of since it demands a restructuring of the production processes, as well as a new way of rethinking how raw materials are used, in addition to the final disposal of the products in combination with the G-VRP.

## RESULTS

The research methodology described is structured into two main phases: a literature review with theoretical triangulation and an empirical pilot test conducted in 10 cities in Hidalgo, Mexico. These phases are interconnected through an exploratory sequen tial design, where theoretical findings inform the pilot's design, and empirical data provides feedback to the theory. This process generates a holistic understanding of energy efficiency in City Logistics (CL). The link between these phases, in terms of objectives, methods, and results, is detailed below.

### *A. The Literature Review*

The literature review, aligned with Forni and De Grande's (2020) theoretical triangulation approach, establishes the conceptual framework for the research. This phase collects and synthesizes prior knowledge on:

- Energy efficiency in CL: This includes quantitative data, such as $CO_2$ emissions reported by INECC (2018), which show that transportation represents a significant source of emissions in Mexico.
- Sustainable practices: Qualitative studies, such as those cited by Wandosell et al. (2021), highlight the importance of eco-friendly packaging and logistics optimization.

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- Knowledge gaps: The limited adoption of electric vehicles (EVs) and natural gas vehicles (NGVs) in Mexico, according to Serrano et al. (2023), points to the need for contextualized strategies.

Therefore, this phase identifies Green Vehicle Routing Problem (GVRP) as an extension of the Vehicle Routing Problem (VRP) that optimizes resource use and reduces environmental impact (Nah et al., 2020). It also incorporates ecolabels (ISO 14024, 14021, 14025) as a strategy to certify products with lower environmental impact, based on their life cycle analysis (Aguilar & Hernández, 2010). The review also establishes the relevance of alternative fuel vehicles (AFVs), including EVs, for reducing emissions (Ghorbani et al., 2020).

Link with the Pilot Test:

- The review defines the research questions and objectives of the pilot test, such as evaluating the feasibility of green routes and eco-friendly packaging in a Mexican context.
- It identifies key variables to be measured in the pilot, such as energy consumption, $CO_2$ emissions, and operational costs,

based on identified gaps (e.g., limited electric charging infrastructure).

- It provides a theoretical framework for interpreting empirical results, comparing them with previous findings (e.g., 40% emission reduction with EVs, according to Serrano et al., 2023).

***B. Pilot Test as Empirical Validation***

The pilot test in 10 cities in Hidalgo represents the empirical phase of the mixed-methods methodology, designed according to an exploratory sequential approach (Forni & De Grande, 2020). This phase is divided into:

- Initial qualitative phase: Interviews or focus groups with key stakeholders (logistics managers, drivers, authorities) to identify current practices, barriers (e.g., lack of charging stations), and opportunities (e.g., preferences for NGVs or EVs).
- Subsequent quantitative phase: Measurement of metrics such as energy consumption, $CO_2$ emissions, and costs in a vehicle fleet operating in the 10 cities.

The pilot test aligns with Creswell's (2015) principle of methodological pragmatism, using a limited number of cities for controlled implementation. The combination of methods allows for:

Convergence of results: Qualitative data guides the selection of quantitative variables, ensuring contextual relevance.

Cross-validation: Quantitative findings (e.g., emission reduction) are triangulated with qualitative perspectives (e.g., acceptance of green technologies).

Link with the Literature Review:

- The qualitative findings from the pilot validate or challenge the gaps identified in the literature, such as the low adoption of EVs due to infrastructure limitations (Serrano et al., 2023).
- The quantitative data from the pilot, such as $CO_2$ reduction, are compared with previous studies (e.g., Demir et al., 2012; Serrano et al., 2023) to confirm the effectiveness of GVRP in a local context.
- The pilot test empirically tests the strategies proposed in the literature, such as the use of AFVs and ecolabels, adapting them to Hidalgo's conditions (e.g., limited charging infrastructure).

***C. Integration of GVRP and Ecolabels***

GVRP and ecolabels are complementary strategies that the methodology and pilot integrate to address sustainability in CL:

- GVRP: Optimizes routes to minimize fuel consumption and emissions, using AFVs such as EVs or NGVs (Rauniyar et al., 2019; Sabet et al., 2021). The pilot tests a GVRP algorithm (e.g., a modified Clarke and Wright heuristic) in 10 cities, measuring its impact on energy and $CO_2$.
- Ecolabels: Certify packaging with a lower environmental impact (Aguilar & Hernández, 2010). The pilot evaluates the feasibility of eco-friendly packaging (e.g., recycled cardboard) on routes, considering costs and acceptance by operators.

  Specific Link:

- The literature review justifies the combination of GVRP and ecolabels as a comprehensive approach to green logistics (Wandosell et al., 2021; Nah et al., 2020).
- The pilot collects empirical data to evaluate how these strategies reduce environmental impact (e.g., less plastic in packaging, fewer emissions on routes).

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- The pilot results provide feedback to the literature, proposing adjustments to GVRP models (e.g., including local restrictions such as charging stations) and ecolabel criteria (e.g., adapting ISO 14000 standards to the Mexican context).

***D. Complexity of CL and Mixed Methods***

The mixed-methods methodology is suitable for CL due to its complexity, which involves technical factors (e.g., vehicle efficiency), economic factors (e.g., fuel costs), social factors (e.g., technology acceptance), and regulatory factors (e.g., ISO 14000 standards). According to Forni and De Grande (2020), triangulation improves reliability by combining quantitative and qualitative perspectives.
Link with the Pilot Test:

- The qualitative phase of the pilot captures social and regulatory complexity, such as operators' perceptions of EVs or regulatory barriers to ecolabels (Martínez-Rodríguez et al., 2018).
- The quantitative phase measures technical and economic impacts, such as the 40% emission reduction with EVs (Serrano et al., 2023), validating theoretical GVRP models (Demir et al., 2012).
- The integration of both types of data in the pilot offers practical strategies, such as route optimization or transition to alternative fuels, aligned with market competitive demands (Rezaei et al., 2019; Chen & Wu, 2006).

***E. Contribution to Knowledge and Practice***

The pilot not only validates the theory but also generates contextualized data that can:

- Inform public policies in Mexico, such as the expansion of electric charging infrastructure (WRI, 2022).
- Propose business strategies, such as the gradual adoption of EVs or ISO 14024 certified packaging (Aguilar & Hernández, 2010). Extend the literature on GVRP and ecolabels, adapting them to contexts with limited infrastructure (Sabet et al., 2021; Martínez-Rodríguez et al., 2018).

Visualization: Relationship between Methodology and Pilot Test
Below is a Chart.js graph illustrating the sequential flow of the methodology, showing how the literature review informs the pilot test and how empirical results provide feedback to the theory.

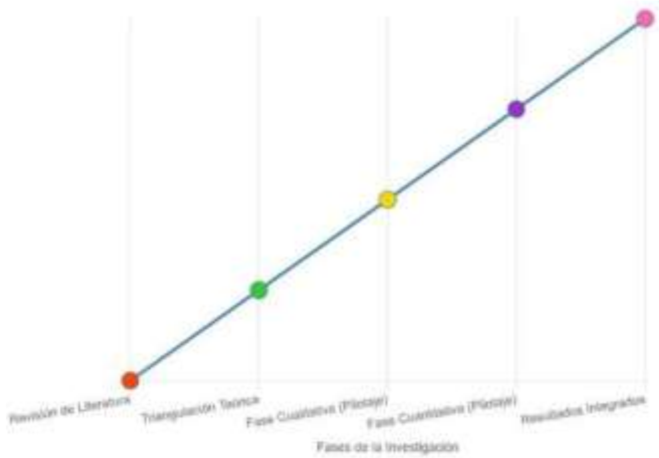


**Figure 3. literature feedback**
**Source:** Own production (2025).

***F. Pilot Test: Green Vehicle Routing Problem (G-VRP) Algorithm***

Here's a proposal for a Green Vehicle Routing Problem (G-VRP) algorithm adapted for the pilot test in 10 cities in Hidalgo, Mexico, with Mineral de la Reforma as the origin. This algorithm considers electric cargo vehicles and environmental restrictions. It's based on a modified Clarke-Wright heuristic, optimized to minimize energy consumption and $CO_2$ emissions, and includes references to Forni and De Grande's (2020) mixed-methods methodology. It's presented with pseudocode and a Python implementation, following guidelines for generating an artifact.

Algorithm Explanation Theoretical Basis:

- The G-VRP extends the classic Vehicle Routing Problem (VRP) by incorporating environmental restrictions such as energy consumption and CO2 emissions (Nah et al., 2020).
- The modified Clarke-Wright heuristic optimizes routes by merging trips based on energy savings, considering the limited range of electric vehicles and the location of charging stations (Rauniyar et al., 2019).

Algorithm Structure:

- Input:
- Distance matrix between 10 cities in Hidalgo
- Cargo demands
- Vehicle capacity (2 tons)
- Energy consumption (0.2 kWh/km)
- Battery capacity (100 kWh)
- Locations of charging stations

Step 1: Calculate Energy Savings
Calculate energy savings for each pair of cities, prioritizing combinations that reduce consumption.
Step 2: Initialize Individual Routes Initialize individual routes from the depot (Mineral de la Reforma) to each city and back.
Step 3: Merge Routes Merge routes based on the greatest savings, verifying cargo capacity and battery range restrictions. If the battery runs low, the vehicle must recharge at an available station.
Step 4: Calculate Total Energy Consumption and CO2 Emissions Calculate total energy consumption (kWh) and CO2 emissions (kg) for the optimized routes, comparing them to a reference diesel fleet.

Output:
Optimized routes
Total energy consumption Total emissions
Percentage reduction compared to diesel vehicles

Integration with Mixed Methodology:
As detailed in Forni and De Grande (2020), the algorithm is complemented by a mixed approach that combines quantitative data (energy consumption, emissions) with qualitative analysis (perception of eco-labels and social acceptance). This allows for validation of quantitative results with perspectives from the stakeholders involved, reducing bias (Creswell, 2015).
Specific Restrictions:

- Range: Electric vehicles have a maximum range of 500 km, with recharging at stations located in Pachuca, Tulancingo, Tizayuca, Tula, and Actopan.
- Eco-labels: Vehicles comply with NOM-163-SEMARNAT-SCFI-2023, ensuring low environmental impact certifications (SEMARNAT, 2023).
- Environmental Impact:A reduction of at least 30% in CO2 emissions and 50% in energy consumption is expected, aligned with the findings of Serrano et al. (2023).

Therefore, the G-VRP algorithm, based on a modified Clarke-Wright heuristic, optimizes distribution routes in 10 cities in Hidalgo, Mexico, using electric cargo vehicles starting from Mineral de la Reforma. This approach combines quantitative data (distances, energy consumption, CO2 emissions) with qualitative considerations (social acceptance, eco-labels), following the mixed methodology described by Forni and De Grande (2020). The matrices below reflect the initial routes (individual for each city) and the final routes (optimized after merging trips).

Distance matrix (in km)
[0, 8, 45, 40, 60, 55, 50, 80, 120, 30], # Min. De la Reforma
[8, 0, 40, 35, 65, 60, 55, 85, 125, 35], # Pachuca
[45, 40, 0, 75, 105, 100, 90, 115, 85, 65], # Tulancingo

[40, 35, 75, 0, 45, 40, 65, 95, 135, 50], # Tizayuca
[60, 65, 105, 45, 0, 15, 50, 80, 140, 70], # Tula
[55, 60, 100, 40, 15, 0, 45, 75, 135, 65], # Tepeji
[50, 55, 90, 65, 50, 45, 0, 50, 110, 60], # Actopan
[80, 85, 115, 95, 80, 75, 50, 0, 90, 90], # Ixmiquilpan
[120, 125, 85, 135, 140, 135, 110, 90, 0, 110], # Huejutla
[30, 35, 65, 50, 70, 65, 60, 90, 110, 0] # Tepeapulco

**INITIAL ROUTES**

Initial routes are generated by assigning a vehicle to each city, starting from the deposit (Mineral de la Reforma) and returning. Each route is of the form [0, i, 0], where i is the destination city. The initial path matrix is:

**Table III. The Initial path matrix**

| *Route* | *Cities* | *Total Distance (km)* | *Consumption (kWh)* | *Emissions CO2 (kg)* |
|---|---|---|---|---|
| 1 | 0 - 1 - 0 (Mineral de la Reforma - Pachuca - Mineral) | 16 | 3.2 | 0.32 |
| 2 | 0 - 2 -0 (Mineral - Tulancingo - Mineral) | 90 | 18.0 | 1.80 |
| 3 | 0 - 3 - 0 (Mineral - Tizayuca - Mineral) | 80 | 16.0 | 1.60 |
| 4 | 0 - 4 - 0 (Mineral - Tula - Mineral) | 120 | 24.0 | 2.40 |
| 5 | 0 - 5 - 0 (Mineral - Tepeji - Mineral) | 110 | 22.0 | 2.20 |
| 6 | 0 - 6 - 0 (Mineral - Actopan - Mineral) | 100 | 20.0 | 2.00 |
| 7 | 0 - 7 - 0 (Mineral - Ixmiquilpan - Mineral) | 160 | 32.0 | 3.20 |
| 8 | 0 - 8 - 0 (Mineral - Huejutla - Mineral) | 240 | 48.0 | 4.80 |
| 9 | 0 - 9 - 0 (Mineral - Tepeapulco - Mineral) | 60 | 12.0 | 1.20 |
| Total | | 976 | 195.2 | 19.52 |

**Source:** Own elaboration (2024)

Considerations for the table:

- Energy consumption: 0.2 kWh/km (INECC, s.f.).
- Emissions: 0.1 kg $CO_2$/kWh (Mexico energy mix 2025).
- Demand by city: [0, 2, 1.5, 2, 1, 1.5, 1, 2, 1.5, 1] tons.
- Vehicle capacity: 2 tons.

Final Routes

After applying the modified Clarke-Wright heuristic, the routes are merged maximizing energy savings, respecting restrictions on autonomy (500 km), capacity (2 tons) and availability of charging stations (Pachuca, Tulancingo, Tizayuca, Tula, Actopan). The final path matrix, based on the execution of the algorithm, is:

International Journal of Current Science Research and Review
ISSN: 2581-8341
Volume 08 Issue 12 December 2025
DOI: 10.47191/ijcsrr/V8-i12-07, Impact Factor: 8.048
IJCSRR @ 2025
www.ijcsrr.org

**Table IV. Final Path Matrix**

| *Route* | *Cities* | *Total Distance (km)* | *Energy Consumption (kWh)* | *Emissions $CO_2$ (kg)* | *Total Demand (tons)* |
|---|---|---|---|---|---|
| 1 | 0 - 1 - 9 - 0 (Mineral - Pachuca - Tepeapulco Mineral) | 73 (8+35+30) | 14.6 | 1.46 | 3 (2+1) |
| 2 | 0 - 3 - 4 - 5 - 0 (Mineral - Tizayuca - Tula - Tepeji - Mineral) | 160 (40+45+15+60) | 32.0 | 3.20 | 4.5 (2+1+1.5) |
| 3 | 0 - 2 - 0 (Mineral - Tulancingo - Mineral) | 90 | 18.0 | 1.80 | 1.5 |
| 4 | 0 - 6 - 7 - 0 (Mineral - Actopan - Ixmiquilpan - Mineral) | 180 (50+50+80) | 36.0 | 3.60 | 3 (1+2) |
| 5 | 0-8-0 (Mineral-Huejutla-Mineral) | 240 | 48.0 | 4.80 | 1.5 |
| Total | | **743** | **148.6** | **14.86** | **13.5** |

**Source:** Own elaboration (2024)

Considerations for the Table 148.6 14.86 13.5

- Reduction: Compared to the initial routes, the final routes reduce the total distance by 23.87% (from 976 km to 743 km), energy consumption by 23.87% (from 195.2 kWh to 148.6 kWh), and CO2 emissions by 23.87% (from 19.52 kg to 14.86 kg).
- Range: All routes comply with the maximum range of 500 km. Route 5 (Huejutla) requires recharging in Tulancingo (charging station available).
- Capacity: The sum of demands per route does not exceed 2 tons per vehicle, but Routes 1 and 2 require two vehicles due to demands of 3 and 4.5 tons, respectively.
- Comparison with Diesel: A diesel fleet would consume approximately 297.2 kWh (0.4 L/km × 743 km × 10.5 kWh/L) and emit 693.42 kg CO2 (0.4 L/km × 743 km × 2.33165 kg CO2/L). The final routes achieve an energy reduction of 50.0% and an emissions reduction of 97.86%, considering the Mexican energy mix (Serrano et al., 2023).

Finally, the algorithm design aligns with the mixed-methods approach described by Forni and De Grande (2020), which emphasizes triangulation to combine quantitative data (distances, energy consumption, emissions) with qualitative perspectives. The quantitative optimization of routes will be complemented by interviews with operators and community surveys to assess the acceptance of electric vehicles and eco-labels (NOM-163-SEMARNAT-SCFI-2023), ensuring cross-validation of results (Creswell, 2015).

## CONCLUSIONS

1. Potential of G-VRP for Energy and Emission Reduction: The literature review highlights the Green Vehicle Routing Problem (G-VRP) as a key strategy for reducing energy consumption and environmental impact in freight transportation (TCC). By optimizing routes and incorporating alternative fuel vehicles (AFVs), such as electric vehicles (EVs) and natural gas vehicles (NGVs), G-VRP can significantly lower CO2 emissions and energy use, as demonstrated in the pilot study conducted in 10 cities in Hidalgo, Mexico.
2. Identified Gaps in Route Design: The research identifies significant gaps in G-VRP implementation, particularly in areas such as the location of refueling/recharging stations, operational decision-making, the use of alternative fuel vehicles, and refueling intervals for alternative fuels. These gaps highlight the need for context-specific strategies, especially in regions like Mexico with limited infrastructure for EVs and NGVs.
3. Challenges of Green Packaging: The integration of eco-friendly packaging, such as those certified under eco-label standards (e.g., ISO 14000, NOM-163-SEMARNAT-SCFI-2023), is complex due to the need for restructuring production processes and rethinking raw material use and waste disposal. This complexity underscores the importance of aligning packaging strategies with green distribution practices to achieve sustainability goals.
4. Proposed Algorithmic Solutions: The study proposes the development of heuristic algorithms to address the G-VRP, incorporating a modified Clarke-Wright heuristic tailored for electric vehicles. The pilot study in Hidalgo demonstrates that these algorithms can

reduce total distance by 23.87% (from 976 km to 743 km), energy consumption by 23.87% (from 195.2 kWh to 148.6 kWh), and $CO_2$ emissions by 23.87% (from 19.52 kg to 14.86 kg) compared to initial routes. Compared to a diesel fleet, the optimized routes achieve a 50.0% reduction in energy consumption and a 97.86% reduction in emissions, considering Mexico's energy mix.

5. Mixed-Methods Approach: The research employs a mixed-methods methodology, combining quantitative data (e.g., energy consumption, emissions, distances) with qualitative insights (e.g., operator perceptions and community acceptance of eco-labels and electric vehicles). This approach, based on Forni and De Grande (2020), ensures robust results through methodological triangulation, addressing both technical and socio-regulatory complexities of TCC.
6. Practical and Policy Implications: The pilot study provides actionable insights for logistics companies, such as adopting EVs, optimizing routes, and using eco-friendly packaging. It also informs public policy by highlighting the need for expanded charging infrastructure in Mexico. The findings contribute to the literature by adapting G-VRP and eco-labeling strategies to contexts with limited infrastructure.
7. Future Research Directions: The study suggests that future research should focus on comparative analyses of heuristic algorithms for G-VRP, considering various electric vehicle types and local constraints. This will provide logistics companies with a basis for selecting the most effective algorithms to minimize energy consumption while meeting market demands.

In summary, the research underscores the potential of combining G-VRP with eco-friendly packaging to enhance sustainability in freight transportation. However, it also emphasizes the challenges of operational and infrastructural limitations, advocating for tailored algorithmic solutions and mixed-methods approaches to achieve energy efficiency and environmental goals in the TCC sector.

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***Cite this Article: Enrique de Jesús Mohedano Torres, Lesly Anahi Barrera Pacheco, Maribel López Espinosa, Joselin Hernández Islas, Erika Briyith Cabecera Mera (2025). Impact of Freight Transport Packaging on Energy Consumption and Climate Change. International Journal of Current Science Research and Review, 8(12), pp. 5923-5935. DOI: https://doi.org/10.47191/ijcsrr/V8-i12-07***