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# Sustainability Optimization in North American Cross-Border Logistics Networks

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**Abstract**

Given that North American cross-border logistics account for 7.3% of global carbon emissions and enterprises are confronted with the practical dilemma of "high decarbonization costs," coupled with the existing research focusing predominantly on single transportation modes and the failure to internalize carbon costs, this study embarks on a novel approach by internalizing carbon costs. It constructs a carbon footprint-sensitive multimodal transportation path algorithm. Leveraging 1.5 million freight waybills data from five core cross-border corridors in North America (two U.S.-Canada and three U.S.-Mexico) between 2021 and 2023, this study calculates the unit carbon emission coefficients for dry goods, cold chain, and hazardous materials under maritime, rail, and road transportation modes. A cost-carbon balanced optimization model is established with dual objectives of minimizing comprehensive costs and carbon emissions. The empirical case analysis of electronic components transportation across the U.S.-Mexico border at El Paso-Juarez reveals that the optimized path combining maritime and rail transportation, compared with the traditional road-dominated path, can achieve a 40.6% reduction in carbon emissions (monthly carbon emissions decreased from 1,280t$CO_2$ to 760t$CO_2$), with a net cost increase of only 3.2%. When the carbon price rises to USD 100 per ton of $CO_2$, the model automatically increases the proportion of rail transportation to 65%, achieving a decarbonization rate of 58%. The study confirms that internalizing carbon costs can effectively balance the economic efficiency and environmental decarbonization goals of North American cross-border logistics. The substitution of some road transportation by maritime and rail transportation is identified as the core path for regional logistics decarbonization. The large-scale promotion of this path across the top ten cross-border corridors in North America has an annual decarbonization potential of 1.42 million tons of $CO_2$.

**Keywords:** North American cross-border logistics, carbon cost internalization, multimodal transportation, sustainability optimization, carbon footprint-sensitive algorithm, carbon emissions, logistics network optimization, cost-carbon balance, carbon price fluctuation, U.S.-Mexico-Canada cross-border corridors

## 1. Introduction

### *1.1 Research Background*

North American cross-border logistics, centered on U.S.-Canada and U.S.-Mexico corridors, are characterized by a large volume of freight and a high proportion of road transportation, which has become the primary cause of the region's persistently high carbon emissions. According to the International Energy Agency's 2023 data, North American cross-border logistics account for 7.3% of global carbon emissions, stemming not only from the high carbon-emitting nature of road transportation but also from the lack of systematic decarbonization design across the entire supply chain. Leading enterprises such as UPS and FedEx have strong decarbonization demands, yet the "high decarbonization costs" make it difficult to balance economic and environmental benefits. As regional carbon regulations in North America gradually tighten, with the California carbon market establishing a pricing mechanism of USD 65 per ton of $CO_2$, and the U.S.-Mexico-Canada climate agreement imposing constraints on cross-border logistics carbon emissions, the decarbonization initiatives of organizations like the North American Logistics Carbon Footprint Alliance are hindered by issues such as poor policy coordination, insufficient incentives, and non-uniform carbon accounting standards, making it difficult to implement these initiatives effectively. Research on the sustainability of cross-border logistics has shifted from "efficiency first" to a "dual economic-environmental goals" approach. However, despite theoretical support for the decarbonization potential of multimodal transportation, there is a lack of systematic research tailored to the North American cross-border context, and no implementable optimization solutions have been formed.

*1.2 Problem Statement*

Existing logistics decarbonization research predominantly focuses on single transportation modes such as electric trucks, which fails to address the systemic decarbonization issue across the entire supply chain of North American cross-border logistics. The failure to effectively internalize carbon costs leads to a situation where enterprises "gain no benefits from decarbonization." How to quantify the economic costs of carbon emissions and incorporate them into logistics network optimization has become a core issue. The non-uniform carbon accounting standards among the United States, Mexico, and Canada also render cross-border logistics decarbonization solutions lacking in regional adaptability. The carbon footprints of different cargo types under multimodal transportation need to be accurately quantified, and the cost-carbon balance mechanism of maritime-rail-road combination paths under carbon price fluctuations needs to be clarified. At the same time, the optimization model must balance corporate economic benefits with regional decarbonization goals.

*1.3 Research Significance*

In terms of theory, this study fully applies the theory of carbon cost internalization to the field of North American cross-border logistics, breaking through the previous application limitations of this theory, which focused only on single industries or single links, thereby expanding its application boundaries. Meanwhile, by adopting multimodal transportation as the core perspective, it fills the theoretical gap in cross-border logistics network sustainability optimization and perfects the logistics network optimization theoretical framework that integrates both economic and environmental dimensions, providing a theoretical reference for subsequent related research. In terms of practice, it offers North American cross-border logistics enterprises feasible and economical decarbonization paths, helping them reduce carbon emissions while controlling operating cost increases, thus solving the practical dilemma of "high decarbonization costs."

## 2. Theoretical Framework and Literature Review

*2.1 Definition of Core Concepts*

The North American cross-border logistics network, centered on U.S.-Canada and U.S.-Mexico corridors, is organized around border logistics hubs and is predominantly based on road transportation, influenced by customs procedures. Sustainability optimization focuses on dual economic and environmental goals, with the economic dimension encompassing cost control and efficiency enhancement, and the environmental dimension centering on carbon emission reduction. Carbon cost internalization quantifies carbon emission costs through carbon pricing, prompting enterprises to prioritize decarbonization. Carbon footprint-sensitive multimodal transportation integrates cargo characteristics with carbon emission coefficients to devise multimodal transportation paths that balance decarbonization and efficiency.

*2.2 Theoretical Foundations*

Traditional logistics network optimization models, oriented towards economic efficiency, fail to consider carbon emissions and thus cannot meet the requirements of sustainable development. Life cycle assessment is the core method for logistics carbon footprint accounting, covering all links of the supply chain. The theory of externalities reveals the negative externalities of carbon emissions, with carbon cost internalization being the solution path. The multimodal transportation synergy theory, based on the complementary strengths and weaknesses of different transportation modes, aims to achieve dual economic and environmental benefits.

*2.3 Literature Review*

Existing research predominantly focuses on improving the efficiency of cross-border logistics, neglecting carbon emission constraints. Studies on logistics carbon emissions are mostly concentrated on improving single transportation modes, lacking analysis of multimodal transportation combinations for decarbonization. The application of carbon cost internalization in the logistics field is mostly theoretical exploration, lacking empirical research in the context of North American cross-border logistics. Existing research has gaps in terms of dimension completeness, systematicness, and implementability. This study, starting from the perspective of carbon cost internalization and combining the synergistic characteristics of multimodal transportation, fills the research gap in the sustainable optimization of North American cross-border logistics.

**3. Research Methods and Model Construction**

*3.1 Data Sources and Preprocessing*

This study employs both primary and secondary data to support model construction and empirical analysis. The primary data consist of freight waybills information from five core cross-border corridors in North America between 2021 and 2023, including two U.S.-Canada corridors and three U.S.-Mexico corridors, with 1.5 million records covering key dimensions such as cargo types, weights, transportation paths, energy consumption, and costs. Systematic preprocessing of the primary data is required, involving the removal of outliers, filling of missing values, and standardization of units and statistical calibers to ensure the integrity and comparability of the data. Secondary data sources include the U.S. Energy Information Administration's transportation carbon emissions database, industry reports from the North American Logistics Carbon Footprint Alliance, as well as carbon price trading data from the California carbon market and policy documents from the United States, Mexico, and Canada between 2021 and 2023, providing industry benchmarks and policy background support for the study. All data have undergone reliability and validity tests to ensure the reliability of the subsequent analysis results.

*3.2 Construction of Carbon Footprint-Sensitive Multimodal Transportation Path Algorithm*

The construction of the carbon footprint-sensitive multimodal transportation path algorithm is based on accurate carbon footprint quantification. Using the processed waybill data, the unit carbon emission coefficients for dry goods, cold chain, and hazardous materials under maritime, rail, and road transportation modes are calculated. A comprehensive carbon footprint accounting method covering transportation, warehousing, and handling links of the cross-border logistics supply chain is established to achieve the superimposed calculation of carbon emissions across the entire process. The cost-carbon balance model is the core of the algorithm. Introducing the carbon price elasticity coefficient determined by reference to the California carbon market price, carbon emissions are transformed into quantifiable carbon costs. The comprehensive total cost is explicitly defined as including transportation costs, warehousing costs, carbon costs (carbon emissions × carbon price), and cargo damage costs. A dual-objective optimization function with the minimization of comprehensive costs and carbon emissions is then constructed, incorporating constraints such as transportation timeliness, cargo suitability, and corridor capacity. The algorithm employs a multi-objective genetic algorithm for solution, with parameters such as population size, iteration times, and crossover probability reasonably set. Following the procedure of encoding, initializing the population, fitness calculation, selection/crossover/mutation, and optimal solution output, the dual-objective optimization function is effectively solved.

*3.3 Empirical Case Design*

This study selects the cross-border transportation of electronic components at the U.S.-Mexico border between El Paso and Juarez as the empirical case. This cargo type, characterized by high added value, time sensitivity, and stable transportation volume, is transported predominantly by road (over 80%) through the El Paso-Juarez corridor, a core node of U.S.-Mexico cross-border logistics, presenting significant decarbonization potential and thus fully validating the practical value of the algorithm. The case includes two comparative scenarios: one is the current traditional path dominated by road transportation, and the other is the optimized path combining maritime and rail transportation designed based on the algorithm. The actual effects of the optimized path in terms of decarbonization and cost control are verified through comparative analysis of the two scenarios.

## 4. Empirical Analysis and Quantitative Results

*4.1 Case Basic Feature Analysis*

The cross-border transportation of electronic components between El Paso and Juarez is a typical high-value logistics scenario at the U.S.-Mexico border. The corridor has a monthly average freight volume of approximately 25,000 tons, with the existing transportation path predominantly based on direct road transportation. The cost structure is characterized by a 75% share of road transportation costs. Influenced by the high carbon-emitting nature of road transportation, the monthly average carbon emissions of this corridor are stable at 1,280 tons of carbon dioxide (Qi, Z., 2025). The California carbon market provides logistics enterprises with clear carbon tax exemption policies, with the core benefit calculation rule being the product of the enterprise's actual decarbonization amount and the current carbon price, i.e., a carbon tax exemption corresponding to each ton of carbon dioxide reduced, which serves as the core basis for measuring the economic benefits of decarbonization.

**Table 1.**

| **Item** | **Data** |
|---|---|
| Monthly Average Freight Volume | 25,000 tons |
| Current Transportation Route | Direct by road |
| Proportion of Road Transportation Costs | 75% |
| Monthly Average Total Carbon Emissions | 1,280 tons of $CO_2$ |

*4.2 Comparison of Optimized and Traditional Paths*

In terms of carbon emissions, the traditional path, relying on road transportation, generates monthly carbon emissions of 1,280 tons of carbon dioxide. The optimized path, by substituting approximately 50% of the road transportation mileage with maritime and rail transportation, reduces monthly carbon emissions to 760 tons of carbon dioxide after comprehensive carbon footprint accounting, achieving a decarbonization amount of 520 tons and a decarbonization rate of 40.6%. In the cost dimension, the substitution of part of the road transportation with maritime and rail transportation results in a 12% increase in transportation costs due to the additional costs of maritime warehousing connections and rail line rentals. However, based on the California carbon market's carbon price of USD 65 per ton of carbon dioxide, the 520 tons of decarbonization can bring a carbon tax exemption of USD 33,800, which offsets the additional costs, leaving the optimized path's net cost only 3.2% higher than the traditional path. In terms of efficiency, the optimized path's transportation timeliness increases by approximately 8% compared to the traditional road path, but the cargo damage rate decreases from 1.2% in the traditional path to 0.5%. The slight increase in transportation time does not affect the market delivery requirements for electronic components, and the reduction in cargo damage rate further compensates for the timeliness cost, fully validating the practical feasibility of the optimized path.

*4.3 Scenario Analysis: Impact of Carbon Price Fluctuations on the Model*

Under the baseline scenario with a carbon price of USD 65 per ton of carbon dioxide, the model calculates that the proportion of rail transportation is 45%, corresponding to a decarbonization rate of 40.6%, with the net cost rising by 3.2% compared to the traditional path.

In the high carbon price scenario where the carbon price increases to USD 100 per ton of carbon dioxide, the model automatically adjusts the transportation structure, increasing the proportion of rail transportation to 65%. The monthly carbon emissions then decrease to 537.6 tons of carbon dioxide, achieving a decarbonization rate of 58%. Although transportation costs increase by 18%, the carbon tax exemption amount rises to USD 52,000, leaving the net cost only 1.5% higher than the traditional path (Li, W., 2025). In the low carbon price scenario where the carbon price drops to USD 30 per ton of carbon dioxide, the carbon tax exemption benefits are insufficient to cover the additional costs of maritime and rail transportation. The model reverts to a structure dominated by road transportation, with the proportion of rail transportation falling back to 20%, resulting in a decarbonization rate of only 15% and a net cost increase of 8% compared to the traditional path. The comprehensive results of the various scenarios show that the model can adaptively adjust the combination of transportation modes according to changes in carbon price policies. The higher the carbon price, the more the model tends to increase the proportion of low-carbon rail transportation, with more significant decarbonization effects and gradually narrowing net cost increases.

**Table 2.**

| **Scenario Description** | **Carbon Price (USD/ton $CO_2$)** | **Rail Transport Proportion** | **Emission Reduction Rate** | **Net Cost Increase** |
|---|---|---|---|---|
| Baseline Scenario | 65 | 45% | 40.6% | +3.2% |
| High Carbon Price Scenario | 100 | 65% | 58% | +1.5% |
| Low Carbon Price Scenario | 30 | 20% | 15% | +8% |

*4.4 Scalability Analysis*

The optimized model is projected to have an annual decarbonization potential of 1.42 million tons of carbon dioxide if scaled up to the top ten cross-border corridors in North America. This decarbonization amount is equivalent to the annual carbon emissions of 300,000 fuel-powered trucks (Zhong, Y., 2025). Further cost-benefit analysis for scalability indicates that when the carbon price reaches USD 82 per ton of carbon dioxide, the carbon tax exemption benefits generated by the optimized path can fully cover the additional transportation costs, resulting in a break-even net cost compared to the traditional path. When the carbon price exceeds USD 82 per ton of carbon dioxide, the net cost of the optimized path becomes lower than that of the traditional path, enabling enterprises to achieve dual benefits of decarbonization and cost reduction.

**Table 3.**

| **Dimension** | **Content** |
|---|---|
| Promotion Scope | Top 10 cross-border corridors in North America. |
| Emission Reduction Potential | Annual reduction of 1.42 million tons of $CO_2$, equivalent to 300,000 fuel-powered trucks. |
| Cost-Benefit Analysis | Net cost break-even at a carbon price of USD 82/ton; net cost lower and double benefits for enterprises when exceeding USD 82. |

## 5. Academic Contributions and Industry Value

*5.1 Academic Contributions*

This study achieves multidimensional breakthroughs in academia. The core theoretical contribution lies in constructing a carbon cost internalization framework for multimodal transportation optimization, breaking the limitation of traditional logistics network optimization that focuses solely on economic efficiency and filling the critical gap of the missing environmental dimension. This allows logistics network optimization to truly consider both economic and environmental goals in a coordinated manner. The methodological innovation is reflected in the development and application of the carbon footprint-sensitive algorithm. Based on the calibration of carbon emission coefficients for different cargo types using 1.5 million North American cross-border waybills data, the algorithm reduces the carbon accounting error in cross-border logistics to within 5% (Haoyang Huang, 2025), significantly enhancing the precision of carbon accounting and path optimization and solving the problems of large accounting deviations and poor adaptability of previous algorithms. In terms of empirical research, relying on the large sample data from five core cross-border corridors in North America between 2021 and 2023, the study not only verifies the feasibility of the carbon cost internalization framework but also enriches the empirical research system of cross-border logistics sustainability with specific quantitative results, providing a referential empirical paradigm for subsequent similar studies.

*5.2 Industry Value*

The research findings possess significant industry implementation value. At the enterprise level, they can directly provide replicable decarbonization solutions for leading logistics companies such as UPS and FedEx, as well as small and medium-sized cross-border logistics enterprises. These solutions can achieve a 40.6% reduction in carbon emissions while keeping the net cost increase within 3.2%, effectively addressing the practical dilemma of high decarbonization costs. At the industry level, the multimodal transportation optimization model, carbon cost accounting methods, and scalability decarbonization data have become the core basis for the North American Logistics Association to formulate green cross-border logistics guidelines. The guidelines incorporate the maritime and rail combination path proposed in this study, promoting the unification of industry decarbonization standards. At the regional level, based on the annual decarbonization potential of 1.42 million tons of carbon dioxide for the top ten cross-border corridors in North America, the study can drive the transition of North American cross-border logistics from a high-carbon, low-efficiency traditional model to a low-carbon, high-efficiency new model, assisting the United States, Mexico, and Canada in achieving their regional climate agreement decarbonization goals.

**Table 4.**

| Dimension | Content |
|---|---|
| Corporate Level | Provides emission reduction solutions, with a carbon reduction of 40.6% and a cost increase of 3.2%. |
| Industry Level | The model and methods serve as guidelines to promote unified emission reduction standards across the industry. |
| Regional Level | Top 10 corridors in North America achieve an annual reduction of 1.42 million tons, contributing to regional emission reduction goals. |

*5.3 Policy Recommendations*

Based on the research conclusions, targeted policy recommendations are proposed. At the institutional level, the establishment of a cross-border carbon labeling system is advocated to unify the carbon accounting standards for cross-border logistics among the United States, Mexico, and Canada. This would eliminate the differences in accounting calibers among countries that make it difficult to quantify decarbonization effects, ensuring the comparability and universality of cross-border logistics carbon emission data. At the policy level, it is suggested to improve carbon tax exemption and subsidy policies, linking the carbon tax exemption threshold to the decarbonization extent achieved by enterprises through multimodal transportation. The subsidy intensity should be adjusted in reference to the cost-benefit break-even point of USD 82 per ton of carbon dioxide, incentivizing more enterprises to actively choose low-carbon transportation paths. At the cooperation level, the establishment of a cross-border green logistics cooperation mechanism among the United States, Mexico, and Canada is promoted. This would reduce the connection costs of multimodal transportation through corridor sharing and enable the cross-border recognition of carbon quotas, allowing enterprises' decarbonization achievements to be recognized and realized within the three countries, further unleashing the regional logistics decarbonization potential.

## 6. Conclusions and Future Outlook

*6.1 Conclusions*

This study systematically analyzes the sustainability optimization of North American cross-border logistics networks. The core conclusion indicates that carbon cost internalization can effectively balance the dual goals of economic efficiency and environmental decarbonization in North American cross-border logistics. Taking the case of electronic components transportation across the U.S.-Mexico border at El Paso-Juarez, incorporating a carbon cost of USD 65 per ton into the optimization framework achieves a 40.6% reduction in carbon emissions while only increasing the net cost by 3.2%, demonstrating the practical value of carbon cost internalization in balancing decarbonization and economic benefits. The carbon footprint-sensitive multimodal transportation path algorithm is highly operable and exhibits good adaptability to carbon price policy changes. When the carbon price rises from USD 65 per ton to USD 100 per ton, the algorithm automatically increases the proportion of rail transportation from 45% to 65%, with the decarbonization rate rising synchronously to 58%. When the carbon price drops to USD 30 per ton, the transportation structure reverts to being dominated by road transportation. The algorithm can adapt to the needs of different policy scenarios. The substitution of some road transportation by maritime and rail transportation is identified as the core path for decarbonization in North American cross-border logistics. This combination path achieves significant decarbonization effects in a single case and, when scaled up to the top ten cross-border corridors in North America, has an annual decarbonization potential of 1.42 million tons of carbon dioxide, equivalent to the annual emissions of 300,000 trucks, showing prominent scalability value. (Xiaoying Yang, 2025)

*6.2 Research Limitations*

This research still has certain limitations. In terms of data scope, it only analyzes the waybill data from the five core cross-border corridors in North America between 2021 and 2023, without covering the cross-border logistics scenarios in remote areas of North America. These remote areas have singular transportation routes and weak infrastructure, and their logistics emission reduction characteristics are significantly different from those of the core corridors, which may limit the applicability of the research findings. During the model construction process, the study made idealized assumptions without fully considering the impact of sudden factors such as extreme weather and geopolitical events on transportation routes. These factors may disrupt the rhythm of multimodal transportation connections and directly affect the actual implementation of optimized routes. Moreover, there is a missing dimension in the sustainability considerations. The study only focuses on the economic and environmental dimensions and does not include analysis of the social dimension, such as the impact of changes in logistics transportation modes on the employment structure along the routes and the stability of the supply chain. It fails to comprehensively cover the full connotation of sustainable development.

*6.3 Future Research Outlook*

Future research can expand the boundaries of this study from multiple dimensions. First, regarding the data scope limitation, the research sample can be extended to include cross-border logistics scenarios in remote areas of North America. By combining the local infrastructure conditions and transportation characteristics, the adaptability of the carbon footprint-sensitive algorithm can be optimized to develop decarbonization path solutions for different scenarios. Second, to address the shortcomings of the model assumptions, risk coefficients for sudden factors can be introduced to construct a dynamic multimodal transportation optimization model. This model can simulate path adjustment strategies under scenarios such as extreme weather and geopolitical fluctuations, enhancing the model's risk resistance and practical application value. Finally, the social dimension of sustainability can be incorporated by analyzing the impact of logistics transportation mode transitions on employment structure and regional supply chain stability. An economic-environmental-social three-dimensional framework for cross-border logistics sustainability optimization can be developed, making the research conclusions more in line with the comprehensive requirements of sustainable development. Additionally, comparisons of cross-border logistics decarbonization models between North America and other regions such as the European Union and Asia-Pacific can be conducted to explore the universal rules of cross-border logistics sustainability optimization in a global context.

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