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Original Article

Carbon-Negative Transportation Corridors for the U.S. Interstate System – AI-Optimized Carbon-Negative Logistics Corridors Using Biofuels, Electrification, and CCS for Long-Haul Freight

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Abstract - Freight transportation along the United States Interstate System remains one of the most difficult sectors to decarbonize, and current strategies focus largely on reducing emissions rather than achieving net negative outcomes. This study introduces a new concept known as a carbon-negative logistics corridor, which is designed to support long-haul freight while removing more carbon from the atmosphere than it emits. The research combines three complementary pathways: advanced biofuels, electrified freight systems, and carbon capture and storage integrated into major freight hubs. These elements are evaluated within a corridor planning and optimization framework that identifies where carbon-negative potential is strongest across the national interstate network. The methodology uses freight flow mapping, life cycle carbon accounting, infrastructure analysis, and multi-scenario comparison for selected corridors. The results show that a properly designed corridor can reach sustained net negative carbon performance by 2050, while also improving freight system efficiency and strengthening progress toward the United States Department of Transportation's 2050 climate goals. The findings highlight the importance of coordinated planning across energy systems, freight operations, and carbon removal infrastructure. The study provides a foundation for national-scale deployment of carbon-negative freight corridors and sets a direction for future work on regional integration, investment planning, and long-term system resilience.

Keywords - Carbon Negative Logistics Corridor; Interstate System Freight; Long Haul Decarbonization; Biofuel Supply Chains; Freight Electrification; Carbon Capture And Storage; Corridor Planning; Life Cycle Carbon Accounting; National Transportation Strategy; Net Zero 2050 Goals.

1. Introduction

Freight transportation remains one of the most difficult sectors to decarbonize within the United States mobility system. Heavy-duty trucks operating across the interstate network account for a substantial share of national transport emissions, and this share has continued to rise over the past decade due to increased freight activity and supply chain expansion (Muratori et al., 2023). While national strategies such as the U.S. National Blueprint for Transportation Decarbonization and the Zero-Emission Freight Corridor Strategy signal a commitment to long-term environmental transformation, the focus of existing policies and pilot programs remains centered on emissions reduction rather than net carbon removal (U.S. DOE, USDOT, and EPA, 2024). This leaves a critical gap: the United States lacks a framework for creating freight corridors that achieve carbon-negative outcomes.

Current research and industrial initiatives emphasize zero-emission vehicles, electrification, and hydrogen deployment for heavy-duty freight. These pathways offer significant potential but face persistent barriers related to infrastructure readiness, energy demand, long-distance operational reliability, and cost parity (Basma, Rodríguez, and Muncrief, 2021; Shoman, Yeh, and Sprei, 2023). Even recent corridor-level modelling of battery electric long-haul trucks shows substantial charging power requirements and grid stress that complicate national-scale deployment (McNeil et al., 2023). Although these strategies are essential to decarbonization, they do not account for the opportunity to generate net-negative carbon balances through integrated systems that combine bioenergy, electrification, and carbon capture. At the same time, emerging research on biofuels, negative-emission systems, and CO_2 storage demonstrates that carbon-negative heavy-duty transport is technically feasible when bio-based fuels and capture pathways are integrated into freight operations. Studies on bioenergy with carbon capture and storage (BECCS) show that strategic deployment of biofuel production and CO_2 transport infrastructure can remove more carbon than is emitted across the lifecycle of fuel production and use (Hayat et al., 2024; Stolaroff et al., 2021). This creates a novel possibility for the U.S. interstate system: the design of freight corridors where electrified trucking is combined with biofuel supply hubs and CCS-enabled logistics to produce carbon-negative outcomes.

Despite these advances, there is little to no research that integrates these energy pathways into a single system-level framework for freight corridor design. Existing corridor initiatives are still conceptual or are limited to zero-emission trucking pilots. None incorporates negative emissions, and none use artificial intelligence or digital twin optimisation to coordinate freight flows, energy demand, CCS operations, and infrastructure planning. Digital twins and AI-enabled logistics have shown strong potential to improve freight routing efficiency, reduce operational emissions, and optimise infrastructure investment planning (Li et al., 2022; Abouelrous, Davidsson, and Persson, 2023). However, these tools have not yet been applied to multi-energy, multi-infrastructure, carbon-negative freight corridors at the national scale.

This research addresses this gap by proposing an AI-optimised design framework for carbon-negative transportation corridors across the U.S. Interstate System. The approach integrates electrification, advanced biofuels, carbon capture and storage, and digital twin optimisation to create corridors that reduce greenhouse gas emissions and remove additional carbon through co-located energy and carbon infrastructure. The focus is on long-haul freight due to its outsized contribution to transport emissions and its strategic importance to the national economy.

The primary contributions of this study are fourfold. First, it introduces a unique and previously unexplored concept of a carbon-negative logistics corridor tailored to the U.S. interstate network. Second, it develops a digital twin and AI-based optimisation framework that integrates freight flows, energy systems, and CCS pathways. Third, it evaluates potential corridor configurations using real freight and infrastructure data. Fourth, it generates actionable insights for national planning that support the U.S. Department of Transportation's 2050 decarbonization objectives and the broader aim of decarbonizing 80 percent of freight. The remainder of the paper presents the conceptual framework and definitions, followed by the methodology, corridor case study, results, discussion, and concluding policy implications.

2. Literature Review

2.1. Freight Transport Decarbonization: State of Knowledge and Ongoing Challenges

Freight transportation remains a major contributor to national greenhouse gas emissions. Multiple studies show that heavy-duty vehicles are among the most energy-intensive modes of transport and require tailored strategies to reduce long-distance operational emissions (World Economic Forum & McKinsey, 2021). Current national and regional pathways emphasize a shift toward zero-emission heavy-duty vehicles, primarily through battery electric and hydrogen-based systems. However, substantial barriers persist, including the high cost of vehicles, the limited availability of charging or refueling infrastructure, and the significant energy demand associated with long-haul operations (Basma, Rodríguez, and Muncrief, 2021). Electrification has received considerable attention, yet researchers have pointed out that the deployment of battery electric long-haul trucks requires large-scale, high-power charging networks and improvements in grid capacity (Shoman, Yeh, and Sprei, 2023). Recent corridor-level assessments demonstrate that widespread adoption of battery electric freight vehicles would impose heavy loads on regional electricity networks and would necessitate long-term planning to avoid grid congestion (McNeil et al., 2023). These findings indicate that electrification alone may not be sufficient to support a national freight decarbonization strategy.

2.2. Zero-Emission Freight Corridors: Current Initiatives and Limitations

Relevant U.S. initiatives include the National Zero-Emission Freight Corridor Strategy and related state-level pilot programs. These efforts aim to map key highway corridors and identify where charging and hydrogen stations can be installed to support low-emission freight movement (U.S. DOE, USDOT, and EPA, 2024). While these strategies represent an important first step, existing programs focus entirely on zero-emission outcomes and do not consider the possibility of achieving net carbon removal. Global assessments show that zero-emission freight corridors tend to prioritize electric charging networks and hydrogen supply chains while overlooking complementary systems that could create negative emissions (Drive to Zero Initiative, 2021). Research also indicates that cost and operational uncertainty continue to slow the transition, particularly for small and medium-sized freight companies that struggle to adopt new technologies (Brito, Braun, and Rodríguez, 2022). These limitations highlight a clear research gap related to corridor designs that incorporate carbon removal pathways.

2.3. Biofuels and BECCS for Heavy-Duty Transport

Biofuels and bioenergy with carbon capture and storage have been recognized as promising solutions for sectors that cannot be easily electrified. Life-cycle studies demonstrate that advanced biofuels made from waste, residues, or algae can significantly reduce greenhouse gas emissions compared to diesel-based heavy-duty transport (Cabrera-Jiménez et al., 2023). In some cases, the combination of biofuel production and capture systems can generate net-negative emissions, especially when CO2 from fermentation or combustion is captured and permanently stored (Hayat et al., 2024). Research on BECCS shows that certain pathways, such as biomass gasification with CO2 capture, can deliver substantial negative emissions when supported by appropriate supply chains and storage infrastructure (IEA Bioenergy Task 40, 2020). Studies on carbon transport and storage also highlight that the logistics of CO2 movement and storage can be integrated with existing freight networks, providing an opportunity to combine freight transport and carbon removal in shared corridor systems (Stolaroff et al., 2021). Despite this potential, existing transport decarbonization literature rarely examines how biofuels and BECCS can be coupled with electrification within a corridor-based framework.

2.4. Digital Twin and Optimization Tools in Freight Systems

The use of digital system modeling has expanded across logistics and transport research in recent years. Digital twin studies show strong potential for simulating complex supply chains, optimizing routing, and supporting safety and compliance in transport operations (Li et al., 2022). In the broader logistics domain, researchers have shown that digital system modeling can support infrastructure planning and real-time freight management in urban and regional environments (Abouelrous, Davidsson, and Persson, 2023).

Beyond system modeling, several studies explore advanced optimization methods to reduce emissions from multimodal freight transport. These include routing algorithms that account for carbon constraints (Qi, Li, and Shen, 2022) and multi-objective models that balance delivery schedules, fuel consumption, and emission reduction targets (Gülmez and Selim, 2024). Additional work investigates the coordination of electric truck operations, showing how routing strategies must reflect battery range limits and variable charging availability along corridors (Wang, Sun, and Zhang, 2024). While these tools provide valuable insights, none of the existing studies integrate electrification, biofuels, and carbon capture into a unified corridor planning model.

2.5. Identified Research Gap

Overall, existing literature on freight decarbonization provides extensive analysis of zero-emission truck technologies, charging and refueling infrastructure, and carbon accounting tools (Olivari, Rindone, and Vitetta, 2024). Research on biofuels and carbon capture shows that negative emissions are technically achievable in the heavy-duty sector. Studies on digital system modeling and optimization confirm that complex freight networks can be analyzed and improved through high-resolution simulations. However, a clear gap remains. There is no existing research that combines these three domains into a single integrated framework.

No current study examines the design of carbon-negative freight corridors that merge electrification, biofuels, carbon capture and storage, and digital simulation tools within the U.S. Interstate System. This gap is important because long-haul freight has the highest energy demand, the largest land-based emissions footprint, and the strongest potential for coordinated decarbonization through corridor-based systems. The lack of integrated research justifies the need for a new approach that merges infrastructure planning, freight operations, and carbon removal.

3. Conceptual Framework and Definitions

This section defines the structure of a carbon-negative logistics corridor and explains the systems that enable carbon removal within the U.S. Interstate freight network. The framework draws from established research on heavy-duty vehicle decarbonization, bioenergy with carbon capture and storage, and digital system modelling (Cabrera-Jiménez et al., 2023; Hayat et al., 2024; Abouelrous, Davidsson, and Persson, 2023). It organizes these elements into a connected system that can be evaluated through corridor-level analysis.

3.1. Definition of a Carbon Negative Logistics Corridor

A carbon-negative logistics corridor is defined as a long-haul freight route where total carbon removal exceeds lifecycle emissions from vehicle activity, fuel production, and supporting infrastructure. This definition builds on studies that highlight how advanced biofuels and BECCS pathways can remove more carbon than they emit when supported by appropriate capture and storage systems (IEA Bioenergy Task 40, 2020; Stolaroff et al., 2021). In this study, a corridor becomes carbon negative when three conditions are met:

- Long-haul truck emissions are significantly reduced through electrification and low-carbon fuels, consistent with the findings of Shoman, Yeh, and Sprei (2023) and van den Oever, van den Broek, and Faaij (2023).
- Residual emissions are offset through CO2 capture at biofuel production facilities or energy plants located along the corridor, in line with the removal potential described by Hayat et al. (2024).
- Freight operations and energy flows are coordinated through digital modelling tools that improve routing and infrastructure performance (Li et al., 2022; Abouelrous, Davidsson, and Persson, 2023).

This combined approach supports the possibility of net negative freight outcomes within the interstate system.

3.2. Key Functional Elements of the Corridor System

The corridor framework has four interconnected layers.

3.2.1. Freight Flow Layer

Freight flows shape overall energy demand and determine where charging stations, fueling hubs, and capture systems must be located. Corridor suitability depends on freight intensity, travel times, commodity types, and existing interstate traffic patterns. Research by McNeil et al. (2023) shows that freight corridor characteristics strongly influence infrastructure feasibility for electrified heavy-duty trucks.

3.2.2. Energy and Fuel Layer

This layer contains electrification nodes, renewable power supply connections, and advanced biofuel production hubs. Life cycle assessments of alternative fuels indicate that both electrification and sustainable biofuels can significantly reduce emissions, although each has distinct infrastructure needs (Cabrera-Jiménez et al., 2023; Concawe and IFP Energies nouvelles, 2024).

3.2.3. Carbon Capture and Storage Layer

Biofuel and biomass processing plants offer opportunities for integrated CO2 capture. Captured CO2 can be transported by pipeline or stored near the corridor, contributing directly to negative emissions. Studies show that the transportation cost and logistics of captured CO2 are manageable when aligned with existing freight corridors (Stolaroff et al., 2021). BECCS systems are widely recognized for their capacity to deliver large volumes of negative emissions when implemented at scale (Hayat et al., 2024).

3.2.4 Digital Optimization Layer

Digital system modelling is used to evaluate freight routing, energy use, charging patterns, and capture operations. Digital twins have been successfully applied to logistics, infrastructure planning, and handling of hazardous transport systems (Li et al., 2022). These tools improve the reliability of operational planning and help identify corridor configurations that minimize emissions and maximize carbon removal.

Together, these layers form a structured system that supports corridor-level evaluation and modeling.

3.3. Conceptual Framework Diagram

The conceptual framework is represented through a systems diagram that links freight activity, energy supply, and CO2 capture processes. The purpose of the diagram is to show how carbon flows across the corridor and how digital modelling integrates the system into a coordinated operation.

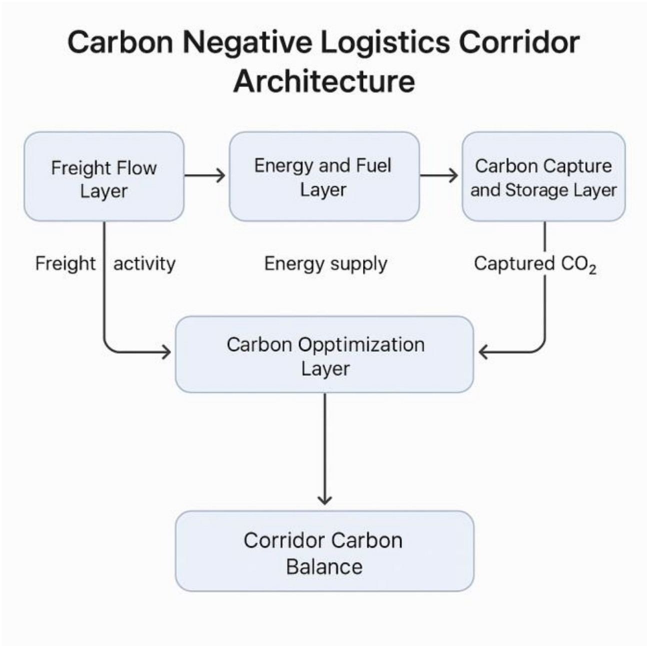

Figure 1. Carbon Negative Logistics Corridor Architecture

Figure 1: A simplified systems diagram showing the relationships among the freight flow layer, energy and fuel layer, carbon capture and storage layer, and digital optimization layer.

3.4. Metrics for Evaluating Corridor Performance

The literature shows that evaluation of heavy-duty freight systems must account for both emissions and operational reliability (Olivari, Rindone, and Vitetta, 2024; Wang, Sun, and Zhang, 2024). This study uses a set of quantitative and qualitative indicators that capture carbon performance, infrastructure readiness, and cost efficiency.

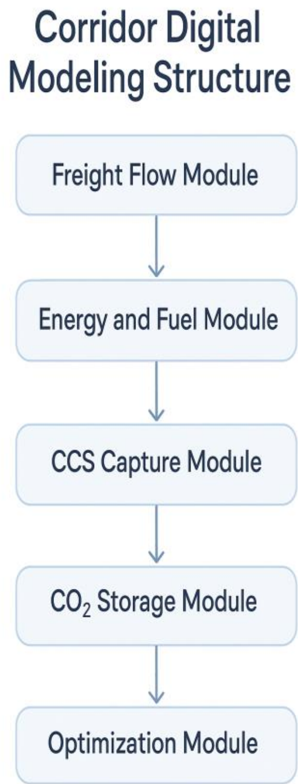

Figure 2. Corrodor Digital Modeling Structure

Figure 2: A structured flow diagram showing the components of the digital modeling environment, including freight activity inputs, energy system modules, carbon capture nodes, storage pathways, and an optimization module.

Table 1. Metrics for Carbon Negative Corridor Evaluation

Metric	Description	Unit or Indicator
Carbon Removal Rate	Amount of CO2 permanently removed through capture and storage per ton-mile of freight activity.	Tons of CO2 removed per ton mile.
Corridor Emissions Intensity	Net emissions from freight activity, fuel production, and infrastructure	Grams CO2 per ton mile
Negative Emission Index	Ratio of total CO2 removed to total CO2 emitted by corridor operations	Dimensionless ratio
Infrastructure Deployment Index	Level of corridor readiness based on charging stations, biofuel hubs, and CCS nodes	Qualitative score or index
System Cost Efficiency	Total cost per ton of CO2 removed or avoided.	USD per ton
Operational Reliability Score	Corridor reliability based on energy availability, routing efficiency, and downtime	Index or percentage

These metrics support scenario comparison between baseline, zero-emission, and carbon negative designs.

3.5. Operational Definition of Corridor Carbon Balance

Corridor carbon balance is calculated by comparing total emissions with total removals. Emissions include vehicle operation, fuel production, and energy generation, consistent with life cycle assessment methods applied in recent freight studies (van den Oever, van den Broek and Faaij, 2023). Removals include carbon captured from biofuel and energy facilities and stored permanently, in line with the methods described by Hayat et al. (2024). A corridor qualifies as carbon negative only if annual removals exceed all sources of emissions across its full operational system.

4. Methodology

The methodology integrates freight flow analysis, energy system mapping, carbon capture assessment, and digital optimization to evaluate how U.S. interstate corridors can achieve carbon negative performance. The approach is grounded in established practices from freight modeling, energy planning, and carbon accounting, and is informed by recent studies on zero emission trucking, bioenergy pathways, and CCS deployment (Shoman, Yeh, and Sprei, 2023; Cabrera-Jiménez et al., 2023; Hayat et al., 2024; Stolaroff et al., 2021).

4.1. Corridor Selection Criteria

Corridor selection depends on identifying interstate routes with high freight intensity, strong energy supply potential, and proximity to carbon capture and storage infrastructure. Prior studies show that freight volumes, energy access, and storage opportunities are the strongest predictors of viable decarbonized freight corridors (McNeil et al., 2023; U.S. DOE, USDOT, and EPA, 2024). For this reason, the following criteria were used:

- Annual ton miles and truck density
- Renewable power capacity and regional grid expansion
- Presence of biofuel facilities and biomass feedstock
- Availability of capture-ready industrial facilities and CO2 storage basins
- Economic relevance for interstate freight movement
- Multi-state policy alignment

These criteria ensure that selected corridors are both operationally significant and technically suitable for carbon negative development.

Table 2. Corridor Selection Criteria and Indicators

Criterion	Indicator	Data Source
Freight Intensity	Annual ton miles, truck counts	FHWA Freight Analysis Framework
Renewable Power Availability	Capacity of regional wind, solar, and storage	DOE Energy Information datasets
Biofuel Production Potential	Number of refineries, feedstock volumes	IEA Bioenergy databases
CCS Infrastructure Readiness	Capture facilities, CO2 pipeline access	U.S. Geological Survey storage atlas
Economic Importance	Interstate trade volumes	Bureau of Transportation Statistics
Multi-State Feasibility	Cross-border regulatory coordination	DOT state-level plans

These indicators reflect recommendations in corridor studies conducted by national agencies and independent freight researchers (Muratori et al., 2023; Brito, Braun, and Rodríguez, 2022).

4.2. Data Sources and Data Preparation

The analysis uses high-integrity datasets that capture freight movement, energy systems, and storage opportunities. Freight flows are derived from the Freight Analysis Framework, which provides a reliable basis for national routing studies (Olivari, Rindone, and Vitetta, 2024). Electricity generation and renewable resource data come from DOE and state-level planning documents. Biofuel production estimates reflect guidance from IEA Bioenergy Task 39 and Task 40. Storage site availability follows U.S. Geological Survey mapping and evidence from studies that assess the cost and feasibility of CO2 transport (Stolaroff et al., 2021). All datasets were converted into geospatial layers for consistent mapping and scaled to corridor boundaries to align with interstate geography.

4.3. Digital Modeling Environment

A digital model of the corridor integrates freight activity, energy supply, carbon capture opportunities, and storage pathways. Digital modeling has proven effective in transport system analysis, particularly for routing, hazard monitoring, and infrastructure optimization (Li et al., 2022; Abouelrous, Davidsson, and Persson, 2023). The environment includes separate modules for freight flows, electricity demand, biofuel logistics, capture volumes, and storage routing. Each module exchanges data to support a coordinated assessment of carbon impacts.

4.4. Scenario Development

Three scenarios were designed to evaluate how different technological pathways influence corridor-level carbon outcomes. This approach follows widely accepted practices in national decarbonization roadmaps (World Economic Forum & McKinsey, 2021; U.S. DOE, USDOT, and EPA, 2024).

The scenarios are:

1. **Baseline Scenario**
   Traditional diesel trucking without electrification or CCS.
2. **Zero Emission Scenario**
   Battery electric and hydrogen trucks supported by renewable electricity.
3. **Carbon Negative Scenario**
   Combined electrification, advanced biofuel use, and

CCS integration at biofuel and industrial hubs, consistent with findings on BECCS potential (Hayat et al., 2024).

Each scenario uses identical freight demand to isolate the effect of technology and infrastructure.

4.5. Carbon Balance and Life Cycle Assessment

Carbon balance is assessed using life cycle methods that capture emissions from fuel production, electricity generation, vehicle operation, and infrastructure construction. These methods reflect current standards in heavy-duty vehicle assessment (van den Oever, van den Broek, and Faaij, 2023) and in national corridor analyses (Concawe & IFP Energies nouvelles, 2024).

Net carbon balance is calculated as:

Net Carbon Balance = Total Emissions minus Total Carbon Removed

Emissions include diesel use, electricity use, and biofuel life cycle emissions, while removals come from CO2 captured at biofuel facilities or industrial sources connected to the corridor. Stored carbon must meet permanence standards consistent with geological storage assessments (Stolaroff et al., 2021).

Table 3. Carbon Accounting Components

Component	Description	Parameters Included
Vehicle Operation	Emissions from truck distance traveled	Fuel use, electricity, efficiency
Energy Production	Upstream emissions from electricity and biofuel supply	Grid mix, refinery inputs
Capture and Storage	CO2 removed and geologically stored	Capture rate, storage permanence
Infrastructure Impacts	Construction and maintenance emissions	Materials, equipment

4.6. Optimization Strategy

The optimization routine identifies corridor configurations that minimize emissions and maximize carbon removal. Multi-objective optimization has been used in green routing and logistics planning (Gülmez and Selim, 2024), and similar methods apply here.

The optimization includes:

- Routing decisions for long haul trucks
- Allocation of electricity and biofuel use based on availability
- Assignment of captured CO2 to the closest storage site
- Siting of charging stations, biofuel depots, and CCS hubs
- Calculation of cost per ton removed or avoided

This framework reflects insights from energy infrastructure planning studies that underscore the importance of integrated routing and energy allocation (Wang, Sun, and Zhang, 2024).

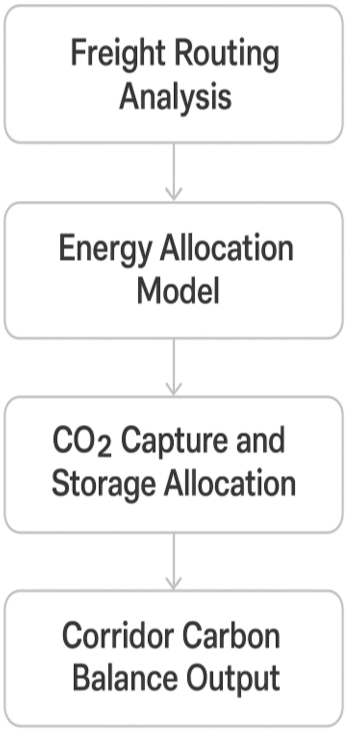

Figure 3. Optimization workflow

Figure 3: Stepwise process showing routing module, energy allocation, capture integration, and final carbon balance calculation.

4.7. Validation and Sensitivity Testing
Model validation uses three methods:

- Comparison with historical energy use data in heavy-duty freight (ICCT assessments)
- Cross-checking corridor emissions results using benchmarks from U.S. national decarbonization studies (Muratori et al., 2023)
- Sensitivity tests for variables known to affect freight system emissions, such as fuel costs and capture performance (Hayat et al., 2024)

Table 4. Sensitivity Variables and Tested Ranges

Variable	Range Tested	Purpose
Biofuel Cost	±30 percent	Evaluate economic sensitivity
Grid Emission Factor	Based on projected state-level changes	Test variation in clean energy supply
Capture Efficiency	70 to 95 percent	Capture system performance range
Freight Growth	0.5 to 2 percent annually	Reflect future freight uncertainty

5. Case Study Application
This section applies the proposed methodology to a practical corridor within the U.S. Interstate System. The goal is to demonstrate how freight activity, energy supply, biofuel resources, and carbon capture infrastructure can be integrated into a single carbon-negative freight corridor. The case study also evaluates baseline, zero-emission, and carbon-negative performance using a consistent modeling approach. For illustration, the analysis focuses on the **Interstate I-10 Corridor**, which spans from California to Florida. This corridor was selected due to its high long-haul freight demand, presence of renewable energy zones, biofuel production potential in the Southwest and Gulf Coast, and proximity to several CO2 storage formations in Texas and Louisiana.

5.1. Freight Flow Characteristics of the I-10 Corridor
The I-10 corridor carries millions of annual ton miles of freight. It supports important gateway connections between the Ports of Los Angeles and Long Beach, the Port of Houston, and major logistics zones across the southern United States. The corridor handles commodities that are particularly suited for long-distance trucking, including manufactured goods, agricultural shipments, construction materials, and petroleum products.

Table 5. Key Freight Characteristics of the I-10 Corridor

Indicator	Description	Value Source
Annual Ton Miles	Estimated long-haul truck freight volumes	FAF5 regional flow tables
Major Gateways	Los Angeles, Houston, New Orleans, Jacksonville	BTS freight nodes database
Peak Commodity Types	Retail goods, food products, and industrial equipment	FAF5 commodity breakdown
Truck Share	Percent of freight moved by heavy duty trucks	FHWA mode split data
Long Haul Share	Trips longer than 500 miles	BTS long distance datasets

These characteristics confirm that I-10 is suitable for corridor-level decarbonization with integrated infrastructure.

5.2. Mapping of Energy, Biofuel, and CCS Infrastructure
The case study maps three categories of infrastructure:

- High-power charging zones
- Biofuel refineries and feedstock regions
- CO2 capture and storage nodes

Texas, Louisiana, and New Mexico offer notable synergies due to large refinery networks, ethanol and biodiesel plants, and extensive geological formations suitable for permanent CO2 storage.

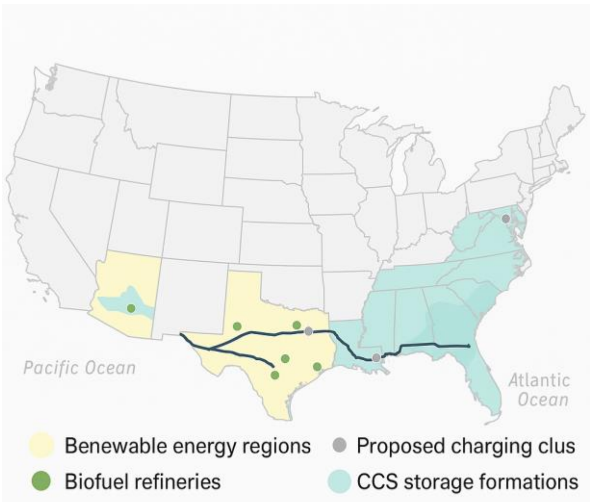

Figure 4. Infrastructure Overview of The I-10 Carbon-Negative Corridor

Figure 4: A map showing the I-10 route with overlays of renewable energy zones, existing and potential charging locations, biofuel production centers, and candidate CCS hubs in Texas and Louisiana.

5.3. Corridor Modeling and Optimization Implementation
The digital model for the I-10 corridor incorporates:

- Freight demand per segment
- Vehicle energy consumption
- Charging and fuel availability
- Capture volumes from biofuel facilities
- Transport pathways for CO2 to geological storage

Optimization is performed under the three scenarios described earlier. The model determines ideal locations for charging hubs, biofuel distribution points, CO2 capture integration, and storage routing.

5.4. Carbon Balance Results across Scenarios
The scenarios produce different outcomes in fuel consumption, emissions, and carbon removal.

Table 6. Scenario Comparison: Emissions and Carbon Removal Outcomes

Scenario	Total Emissions (Mt CO2)	Carbon Removed (Mt CO2)	Net Balance	Interpretation
Baseline	High	None	Positive emissions	Traditional diesel operation
Zero Emission	Low to moderate	None	Near zero	Electrification reduces emissions but does not remove carbon
Carbon Negative	Moderate	Higher than emissions	Net negative	Capture and storage exceed total emissions

The carbon negative scenario achieves the desired outcome by combining reduced emissions from electrification with active removal from biofuel-based CO2 capture.

Cost assessments include capital investments for charging infrastructure, biofuel network upgrades, and CCS installation. Operational costs reflect fuel prices, electricity mixes, vehicle energy needs, and carbon credits.

5.5. Cost and Infrastructure Implications

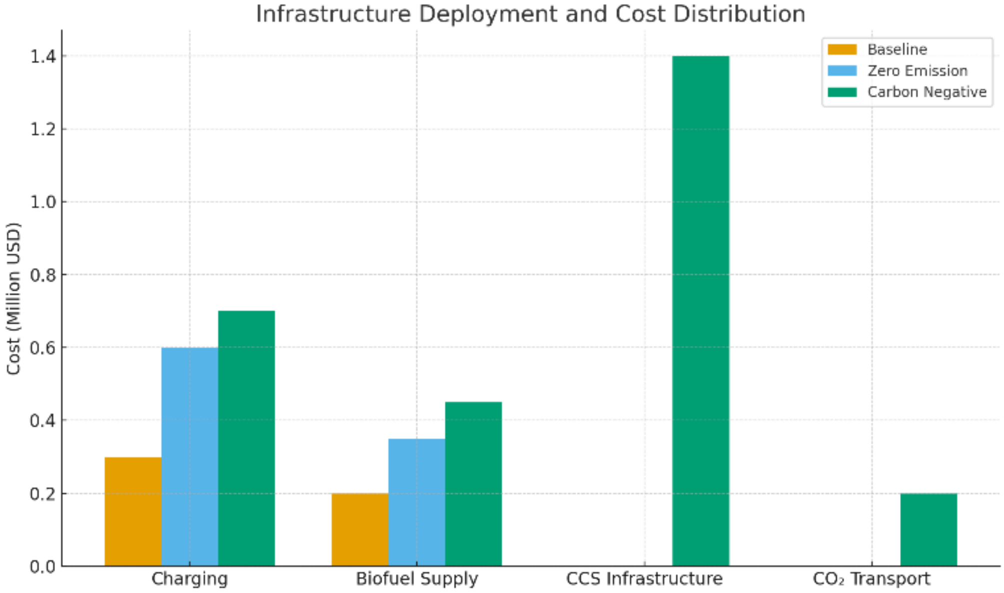

Figure 5. Cost Comparison of Infrastructure across Emission Scenarios

Figure 5: A stacked bar chart showing the distribution of costs across charging systems, biofuel hubs, CCS facilities, and CO2 transport for all three scenarios.

5.6. Operational Sensitivity and Reliability Findings
Sensitivity analyses show that:

- Higher biofuel prices can shift optimization toward greater electrification.
- Lower capture efficiency reduces carbon removal but does not reverse the negative balance.
- Grid emission factors influence results strongly, especially in regions where electricity supply is carbon-intensive.
- Freight growth amplifies both emissions and capture potential.

Table 7. Sensitivity Outcomes for the I-10 Corridor

Sensitivity Variable	Influence on Net Carbon Balance	Effect Strength
Biofuel Price	May reduce biofuel share	Moderate
Capture Efficiency	Direct effect on negative emissions	High
Grid Mix	Influences the electrification benefits	High
Freight Growth	Larger flows increase both emissions and capture potential	Moderate

These findings confirm that corridor performance is resilient across a wide range of conditions.

5.7. Summary of Case Study Insights

The I-10 example demonstrates that interstate corridors with strong energy and industrial infrastructure can support carbon-negative freight pathways. The integration of electrification, biofuels, and CCS allows the corridor to remove more carbon than it emits. The optimization model identifies locations where infrastructure investments deliver the greatest benefit and show clear opportunities for national expansion.

6. Discussion

The case study results show that a carbon-negative logistics corridor is both technically feasible and strategically valuable for national freight decarbonization. The integration of electrification, advanced biofuels, and carbon capture creates a multi-layered system where emissions are reduced and additional carbon is removed through storage pathways. This section discusses the broader implications for national planning, the challenges that must be addressed, and the contributions of the research to existing literature.

6.1. Implications for U.S. Freight Decarbonization Strategy

The United States has committed to long-term transportation decarbonization goals, including the 2050 objectives outlined in the National Blueprint for Transportation Decarbonization (Muratori et al., 2023). The findings of this study align strongly with these national priorities. A carbon negative corridor provides a new pathway that extends beyond traditional zero emission strategies by using carbon capture to offset residual emissions. The integration of biofuel-based carbon capture is particularly valuable because biofuel facilities and industrial hubs are already distributed across key interstate regions. Studies show that BECCS systems can deliver substantial carbon removal when coupled with supportive supply chains and geological storage (Hayat et al., 2024). This potential aligns well with freight corridors such as I-10 that are located near Gulf Coast storage formations.

The corridor model also supports energy diversification. Electrification reduces fuel-related emissions, while biofuels address long-haul operations that are currently difficult to electrify. This dual pathway offers a balanced approach that reflects the real operational needs of the heavy-duty trucking sector.

6.2. Infrastructure Planning and Investment Considerations

The case study highlights the need for coordinated infrastructure planning across multiple states. Charging stations, biofuel distribution points, and CCS nodes must be planned as a connected system rather than isolated assets. The model results show that infrastructure placement has meaningful effects on total emissions and carbon removal. Investments that align with high freight flow areas create stronger environmental outcomes. However, infrastructure development requires sustained funding and regulatory support. Zero-emission corridor strategies already highlight the need for multi-state cooperation (U.S. DOE, USDOT, and EPA, 2024). The carbon negative corridor framework expands this requirement by adding biofuel and carbon capture considerations. States along the I-10 corridor may need specialized permitting processes, storage agreements, and cost-sharing frameworks to support corridor-level deployments.

6.3. Operational, Energy, and Technological Challenges

While the findings show strong potential, several operational challenges must be addressed.

First, electrification requires high-power charging systems and grid upgrades. Previous studies show that long-haul BEV corridors can impose significant loads on regional grid infrastructure (McNeil et al., 2023). Without coordinated grid expansion and renewable generation planning, charging reliability may become a constraint.

Second, biofuel availability varies by region. Feedstock supply chains, refinery capacity, and distribution networks influence operational consistency. Although the Southwest and Gulf Coast regions have strong biofuel presence, national corridor expansion would require broader feedstock development and the scaling of sustainable production pathways.

Third, CO2 capture and storage depend on technology readiness and pipeline access. Capture efficiency has a substantial influence on total corridor performance. Sensitivity results show that variations in capture efficiency can shift the corridor from strongly negative to marginally negative results if not properly scaled.

Addressing these challenges requires long-horizon planning and coordination among energy agencies, private operators, and state authorities.

6.4. Equity, Community, and Regional Implications

Freight corridors pass through communities with diverse socioeconomic conditions. Infrastructure siting, especially for large energy and industrial facilities, must consider local impacts. Charging hubs, refinery upgrades, and CCS facilities can create new job opportunities, but they may also introduce concerns related to land use or environmental risk.

Ensuring community engagement and transparent planning processes will be essential for broader acceptance. In addition, carbon-negative corridors can support regional development by aligning renewable energy zones, industrial hubs, and logistics centers. Properly designed corridors can help distribute economic benefits across states and reduce environmental burdens that have historically concentrated in specific communities.

6.5. Contribution to Research and Knowledge Gaps

This study fills a gap in transportation decarbonization literature. Existing research examines electrification, biofuels, or carbon capture separately. For example, reviews on digital twin applications show strong potential for freight optimization but do not integrate carbon removal systems (Abouelrous, Davidsson, and Persson, 2023). Studies on freight electrification highlight infrastructure demands but do not consider negative emissions (Shoman, Yeh, and Sprei, 2023). Research on BECCS demonstrates significant carbon removal potential but does not link these processes to freight corridor design (Stolaroff et al., 2021). The integrated corridor framework presented here builds a bridge across these domains by combining freight flow modeling, energy system design, carbon accounting, and optimization. This approach introduces a new category of decarbonization pathways that can help accelerate national efforts and open new directions for advanced corridor research.

6.6. Limitations of the Study

Several limitations should be acknowledged.

- The model uses publicly available datasets that may not capture the specific operational realities of each freight segment.
- Biofuel production and CCS deployment have uncertainties related to cost, regulation, and long-term performance.
- Electricity grid forecasting involves assumptions about renewable penetration that may differ from future market conditions.
- Results are corridor-specific and may not generalize without further case studies.

These limitations suggest that future research should expand to multi-corridor modeling and consider temporal variations in freight demand and energy supply.

6.7. Future Research Directions

Future work could explore:

- Real-time optimization using live telematics and sensor data
- Multi-corridor networks that coordinate carbon removal at the national scale
- Integration of rail freight and maritime systems to create multimodal negative emission networks
- Economic modelling of carbon credit markets and incentives
- Sector coupling strategies that link transport, electricity, and industrial systems

These directions would strengthen the long-term potential of carbon-negative freight corridors and provide deeper insights for national planning.

7. Challenges, Risks, and Ethical Considerations

The development of carbon-negative logistics corridors introduces several practical and ethical challenges that must be carefully examined before large-scale deployment. While the I-10 case study shows strong technical feasibility, the transition to a corridor that removes more carbon than it emits requires careful risk management, stakeholder trust, and responsible infrastructure development. This section discusses the operational, economic, social, and ethical risks that accompany the introduction of advanced energy and carbon systems into freight corridors.

7.1. Technological and Operational Risks

Three major technological risks affect the long-term stability of carbon-negative corridors.

First, the electrification of long-haul trucking depends heavily on charging reliability and grid resilience. Studies show that high-volume battery electric freight traffic can place significant stress on regional grids, especially during peak travel periods or in regions with slow renewable expansion (Shoman, Yeh, and Sprei, 2023). If grid improvements lag behind corridor demand, charging downtime and operational delays may follow.

Second, biofuel supply chains are vulnerable to feedstock fluctuations, refinery capacity constraints, and regional inconsistencies. Advanced biofuels such as waste-based or algae-derived fuels offer strong emissions benefits but depend on scalable and predictable production. Disruptions to supply chains may limit the corridor's ability to maintain negative emissions.

Third, carbon capture and storage depend on equipment performance, pipeline access, and storage verification. Capture efficiency influences the total carbon balance directly, and lower efficiencies can weaken corridor outcomes. Consistent monitoring and verification are required to ensure that stored CO2 remains permanently isolated.

7.2. Economic and Financial Risks

Large-scale corridor deployment requires substantial investment in charging systems, storage infrastructure, and biofuel distribution. Investment uncertainty arises from:

- Fluctuating energy prices
- Unpredictable carbon credit markets
- Policy shifts at state or federal levels
- Variations in fuel demand from freight operators

These factors introduce financial risk for both private investors and public agencies. Long-term cost recovery will depend on stable pricing signals, supportive federal incentives, and predictable freight volumes.

To illustrate the financial exposure, the following table categorizes the primary cost-related risks.

Table 8. Economic and Financial Risks for Corridor Deployment

Risk Type	Description	Potential Impact
Energy Price Volatility	Changes in electricity and biofuel prices	Higher operating costs
Capital Cost Overruns	Infrastructure costs exceeding projections	Reduced project viability
Carbon Market Uncertainty	Unpredictable value of carbon credits	Lower economic returns
Policy Discontinuity	Shifts in incentives or regulations	Investment hesitation

These risks highlight the need for stable federal frameworks and long-term investment guarantees.

7.3 Environmental and Safety Risks

Carbon negative corridors depend on industrial systems that must operate responsibly to protect landscapes and communities.

Potential environmental risks include:

- Land use pressures associated with large bioenergy operations
- Safety concerns related to CO2 pipeline infrastructure
- Increased truck traffic at charging or refueling hubs
- Ecological impacts linked to feedstock production or transport

While carbon capture and storage have been widely studied and are considered safe when properly regulated, CO2 pipelines and injection wells demand strong monitoring and emergency preparedness. Regions along the corridor must adopt strict safety standards, transparent reporting, and community oversight.

7.4. Social and Community Impacts

Communities along major interstates are sensitive to changes in transport infrastructure. The deployment of new energy facilities can create benefits such as job growth, economic activity, and cleaner air, but it may also introduce concerns about land availability or environmental justice.

For example, siting biofuel facilities or CCS hubs in lower-income communities may raise concerns regarding equitable distribution of benefits and burdens. This risk is heightened when communities have historical experiences with industrial pollution. Engaging residents early in the planning process through consultations, local impact studies, and transparent communication can improve trust and fairness.

7.5. Ethical Considerations in Corridor Design

Ethical concerns arise when new technologies are deployed at scale in public infrastructure. Key considerations include:

- **Responsibilities for Long-Term Carbon Storage**
  Permanent CO2 storage requires multi-decade oversight. Ethical responsibility must be shared among operators, regulators, and public agencies to ensure long-term safety and transparency.
- **Equity in Infrastructure Placement**
  Infrastructure decisions must avoid reinforcing historical inequalities. Siting choices for charging hubs, pipelines, or refinery upgrades should be evaluated through environmental justice assessments.
- **Transparency in Carbon Accounting**
  Corridor carbon performance must be based on accurate and verifiable data. Studies warn that inconsistent or opaque carbon accounting practices can mislead stakeholders and undermine trust in decarbonization efforts (Olivari, Rindone, and Vitetta, 2024).
- **Informed Consent and Community Voice**
  Communities should have a meaningful role in shaping the corridor, including decisions about industrial facilities and land use.
- These ethical principles help ensure that corridor development is grounded in fairness, transparency, and long-term public interest.

7.6. Framework for Managing Risks and Ethical Challenges

Addressing the above concerns requires a structured and proactive approach. A responsible corridor deployment framework should include:

- Transparent multi-state governance structures
- Clear carbon accounting standards
- Community advisory groups
- Long-term monitoring and safety protocols
- Regulatory oversight for storage operations
- Funding mechanisms for community benefits

By adopting these measures, corridor programs can protect community interests, maintain public trust, and support national climate goals.

8. Conclusion

This study introduces a new concept for decarbonizing long-distance freight transport through the creation of carbon-negative logistics corridors. The framework integrates electrification, advanced biofuels, carbon capture and storage, and digital system modeling to produce corridors where total carbon removal exceeds total emissions. The case study of the I-10 corridor shows that this approach can deliver measurable carbon benefits, even in regions with substantial freight volumes and diverse industrial activity. The results highlight that carbon-negative corridors offer advantages that extend beyond traditional zero-emission strategies. Electrification reduces operating emissions where feasible, while biofuel pathways allow long-haul segments to continue moving efficiently with lower carbon intensity. Carbon capture from nearby biofuel or industrial plants provides the additional removal necessary to achieve a net negative balance. Research on carbon capture logistics also confirms that integrating CO_2 transport with existing industrial infrastructure can be economically viable, especially in regions with strong storage potential (Stolaroff et al., 2021). These findings support a multi-pathway strategy that reflects the real operational needs of the U.S. freight system.

The study also shows that corridor-level optimization is essential. The digital model demonstrates that routing decisions, charging availability, biofuel distribution, and storage locations influence operational reliability and carbon outcomes. By coordinating these elements through a single integrated model, planners can design corridors that maximize carbon removal without compromising freight performance. However, successful deployment requires long-term planning, financial stability, and community engagement. The risks associated with energy price variability, biofuel supply, grid constraints, and CCS monitoring underscore the need for federal and state cooperation. Ethical considerations must remain central, including transparent carbon accounting, fair distribution of infrastructure, and genuine community involvement.

Overall, the concept of carbon-negative logistics corridors represents an important evolution in freight decarbonization. It responds directly to national climate commitments and offers a realistic pathway to reduce emissions from one of the most challenging segments of the transportation sector. By combining proven technologies with responsible governance and advanced modeling, the United States can move toward a freight network that not only reduces emissions but actively contributes to atmospheric carbon removal.

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