Highway Infrastructure and Freight Environmental Efficiency: Analysis of Colombia's 4G Program

Abstract

This study examines the volume-efficiency trade-off in transportation infrastructure environmental impacts through analysis of Colombia's $25+ billion Fourth Generation highway program using comprehensive administrative freight data spanning 2015-2024. We exploit 18 million shipment records from Colombia's mandatory National Freight Registry to assess environmental implications of large-scale infrastructure investment in developing country contexts. Our empirical strategy employs Synthetic Difference-in-Differences estimation to address parallel trends violations endemic to infrastructure evaluation research, integrating engineering-based fuel consumption models with staggered completion timing across 30 highway corridors. This methodology constructs synthetic control units achieving superior pre-treatment fit relative to conventional difference-in-differences approaches while enabling systematic examination of both per-unit efficiency improvements and total freight volume changes.

Highway completion demonstrates systematic associations with meaningful per-unit efficiency improvements, including 1.5 percent fuel efficiency gains per kilogram-kilometer and 27.4 percent reductions in fuel consumption per kilogram, translating to estimated carbon emission reductions of 151,300 tons CO_2 annually by 2024. However, infrastructure completion correlates with substantial freight volume increases of 46.8 percent in ton-kilometers, potentially overwhelming efficiency gains through rebound effects characteristic of induced demand mechanisms. Economic valuation suggests potential annual environmental benefits of $49-55 million based on per-unit improvements, with implied carbon abatement costs of $61-165 per ton CO_2. The documented volume-efficiency trade-off indicates infrastructure investment alone may be insufficient for achieving absolute emission reductions, necessitating integration with complementary environmental policies. External validity depends critically on institutional quality, vehicle fleet characteristics, and baseline infrastructure conditions across developing country contexts.

Keywords: Transportation infrastructure, environmental impacts, synthetic difference-in-differences, freight transportation, Colombia, volume-efficiency trade-off

JEL Classification: Q54, R40, O18, H54, O13

1 Introduction

Developing countries invest over $1 trillion in road networks annually, yet the environmental implications of such programs remain underexplored (World Bank, 2020). This knowledge gap presents challenges for nations balancing economic growth with climate commitments. While research demonstrates positive economic returns from infrastructure development through enhanced connectivity (Donaldson, 2018; Faber, 2014), environmental consequences lack rigorous analysis.

Colombia's Fourth Generation (4G) highway program offers a unique opportunity to examine the volume-efficiency trade-off in infrastructure environmental impacts. This $25+ billion initiative spans 30 corridors with staggered completion between 2020 and 2024, implemented following centralized technical criteria rather than political targeting. Combined with comprehensive administrative freight data, this design enables detailed assessment of both per-unit efficiency improvements and total volume changes.

Our central research question addresses how large-scale highway infrastructure affects freight environmental outcomes through two competing mechanisms: efficiency improvements that reduce environmental impact per unit of economic activity, and volume increases that expand total economic activity. This volume-efficiency trade-off represents a fundamental tension in infrastructure environmental evaluation that has received limited empirical attention.

Our empirical strategy exploits staggered completion timing using Synthetic Difference-in-Differences (SDID) estimation. This approach addresses parallel trends violations common in infrastructure evaluation by constructing synthetic control units that achieve superior pre-treatment fit. We integrate data from Colombia's mandatory National Freight Registry, encompassing over 18 million shipment records from 2015-2024, with detailed infrastructure completion data.

Our SDID estimates indicate that highway completion is associated with meaningful per-unit environmental improvements. We document fuel efficiency gains of 1.5 percent per kilogram-kilometer, fuel consumption reductions of 27.4 percent per kilogram, and estimated carbon emission reductions reaching 151,300 tons CO_2 annually by 2024. These environmental benefits concentrate among heavy vehicles and medium-distance routes, consistent with transportation engineering theory regarding rolling resistance mechanisms.

However, our analysis reveals substantial increases in total freight volumes following infrastructure completion, with freight ton-kilometers rising by 46.8 percent. While per-unit efficiency improves, volume increases exceed efficiency gains, potentially leading to net increases in total fuel consumption and emissions. This finding demonstrates rebound effects where infrastructure improvements induce additional economic activity.

These volume effects have important policy implications. Infrastructure reduces the environmental cost per unit of economic activity while enabling additional activity that may increase total environmental impacts. This tension suggests infrastructure alone may be insufficient for achieving absolute emission reductions in growing economies and requires integration with complementary environmental policies.

Economic valuation based on per-unit efficiency improvements suggests potential annual environmental benefits of $49-55 million by 2024. When compared to Colombia's carbon tax ($5.50 per ton CO_2) and regional carbon market prices ($10-25 per ton), implied abatement

costs of $61-165 per ton CO_2 position infrastructure investment as moderately cost-effective for climate policy, though more expensive than direct carbon pricing mechanisms.

Our findings contribute to several literatures. First, we provide rigorous assessment of freight transportation's environmental implications from highway infrastructure completion in a developing country context. Second, our methodological approach integrates engineering-based environmental modeling with comprehensive administrative data, addressing measurement challenges in infrastructure evaluation. Third, we document how centralized technical implementation may contribute to environmental co-benefits through institutional design.

External validity depends on institutional quality, vehicle fleet characteristics, and baseline infrastructure conditions that vary across developing countries. Our Colombia-specific findings may inform policy under specific conditions including centralized planning systems, moderate institutional capacity, significant infrastructure gaps, and diesel-dominant freight fleets. However, contexts with weak governance, decentralized decision-making, or different technological characteristics require careful adaptation.

We acknowledge important limitations constraining causal interpretation. While SDID mitigates parallel trends concerns, spatial spillovers, network effects, and general equilibrium responses in large-scale infrastructure projects mean our analysis identifies strong associations rather than isolated causal effects. Our findings provide valuable insights into infrastructure environmental outcomes while recognizing inherent complexities in establishing definitive causality.

The remainder of this paper proceeds as follows. Section 2 reviews relevant literature and establishes our conceptual framework emphasizing the volume-efficiency trade-off. Section 3 details data sources and environmental variable construction. Section 4 presents our empirical strategy and identification considerations. Section 5 presents main results on per-unit efficiency improvements. Section 6 examines freight volume effects and net environmental impacts. Section 7 presents aggregate valuation with policy context. Section 8 discusses external validity and institutional preconditions. Section 9 concludes.

2 Literature and Conceptual Framework

2.1 Theoretical Perspectives on Infrastructure Environmental Impacts

Early economic theory emphasized infrastructure as productivity-enhancing public goods (Aschauer, 1989; Barro, 1990), overlooking environmental consequences. Environmental economics introduced complexity through induced demand concepts, suggesting expanded road capacity reduces travel costs, potentially increasing vehicle travel and offsetting efficiency gains (Noland and Lem, 2002; Cervero, 2003).

However, empirical evidence challenges universal induced demand effects. Cervero and Hansen (2003) demonstrated more modest elasticities than theoretical models predicted, while Mokhtarian and Tal (2005) found limited evidence for significant induced demand when controlling for confounding factors. Freight transportation faces different constraints than passenger transport due to limited modal alternatives and economic necessity driving

demand patterns.

Contemporary frameworks recognize infrastructure's potential for environmental co-benefits. Porter and van der Linde (1995) provide theoretical foundations for policies enhancing both productivity and environmental performance through technological complementarities. Bowen and Fankhauser (2011) develop frameworks suggesting well-designed infrastructure investment can contribute to environmental outcomes when combined with institutional quality improvements.

The volume-efficiency trade-off emerges as a central theoretical consideration. Infrastructure improvements may simultaneously reduce environmental impact per unit of economic activity while enabling additional activity that increases total environmental impact. This tension requires empirical examination to inform policy design in developing countries pursuing both economic growth and environmental objectives.

2.2 Empirical Evidence on Infrastructure Environmental Impacts

Recent empirical research reveals significant geographic and institutional heterogeneity in infrastructure environmental outcomes. Ye et al. (2024) demonstrated that road infrastructure construction reduces local air pollution in China with positive spillover effects, but revealed substantial regional variation. Wang et al. (2024) reinforced these findings using spatial models, revealing systematic underestimation of infrastructure's decarbonization contributions while demonstrating carbon efficiency enhancement through spillover mechanisms.

Cross-country evidence emphasizes institutional context importance. Lu et al. (2022) examined China, Japan, and South Korea, demonstrating heterogeneous environmental effects between road and railway investments, with institutional quality and economic development moderating impact magnitude. This heterogeneity suggests policy recommendations require attention to local conditions and implementation capacity.

The freight transportation literature offers insights into infrastructure environmental benefits through mechanisms distinct from passenger transportation. Unlike passenger transport, freight movements face limited modal alternatives and exhibit different demand elasticities, potentially making freight more responsive to infrastructure quality improvements. Hennessy et al. (2024) quantified substantial health and climate benefits from freight electrification, demonstrating annual savings of $6.2-8.5 billion. However, realizing these benefits requires coordinated infrastructure development and vehicle deployment strategies.

2.3 Methodological Advances in Infrastructure Evaluation

Infrastructure evaluation faces challenges including endogenous placement, confounding development, and measurement difficulties. Recent methodological advances employ quasi-experimental approaches to address these concerns with important implications for environmental impact assessment.

Faber (2014) pioneered rigorous identification in highway infrastructure evaluation, exploiting least-cost path instruments to examine trade integration effects from China's National Trunk Highway System. Donaldson (2018) advanced this methodology through colonial railway placement instruments in India. These studies established methodological foundations for transportation infrastructure research.

Arkhangelsky et al. (2021) developed Synthetic Difference-in-Differences (SDID) methodology designed to address parallel trends violations inherent in infrastructure evaluation. This innovation offers solutions for assessing environmental impacts when treated and control units follow divergent pre-treatment trajectories, representing significant methodological advance for empirical infrastructure evaluation.

Recent research integrates administrative data sources to enable precision in impact measurement. Innovations integrate engineering-based performance models with comprehensive administrative transportation data, demonstrating that credible infrastructure environmental evaluation requires both robust identification strategies and precise measurement.

2.4 Institutional Preconditions for Environmental Co-Benefits

The literature identifies specific institutional characteristics that may determine whether infrastructure investment generates environmental co-benefits. Centralized technical implementation reduces political targeting and ensures project selection follows engineering criteria rather than political considerations. This institutional design contributes to environmental benefit realization by prioritizing optimal projects and maintaining quality standards.

Predetermined completion sequences based on engineering complexity rather than political factors support conditional exogeneity while ensuring systematic implementation that may enhance environmental outcomes through learning effects. Strong administrative capacity for program coordination enables comprehensive monitoring and quality control mechanisms necessary for realizing environmental benefits.

Comprehensive regulatory frameworks governing freight transportation provide institutional foundations for environmental benefit realization through vehicle standards, fuel quality requirements, and operational regulations that interact with infrastructure improvements. These institutional characteristics suggest environmental co-benefits depend on governance quality and implementation capacity rather than simply infrastructure quantity.

2.5 Research Gaps and Contributions

Despite methodological and empirical advances, critical gaps remain. First, causal identification of infrastructure environmental impacts remains limited, particularly for freight transportation, where studies employ cross-sectional approaches without addressing endogenous placement. Second, evidence from developing countries is scarce despite substantial ongoing infrastructure investments. Third, administrative freight data for environmental assessment remains underutilized.

Our research addresses these gaps through methodological and empirical innovations. We exploit staggered 4G highway completion timing across Colombian corridors between 2020-2024, providing variation for environmental outcome assessment. Administrative freight registry data covering over 18 million shipment records enables measurement precision. Our SDID methodology addresses identification concerns while comprehensive volume analysis examines rebound dynamics absent from existing research.

This study provides assessment of freight transportation environmental implications from highway infrastructure completion in a developing country context, establishing estimates of efficiency gains, emissions reductions, and volume effects while providing a methodological

framework adaptable to alternative contexts. We emphasize that our findings reflect strong associations rather than definitive causal claims due to spatial spillovers, network effects, and general equilibrium responses inherent in large-scale infrastructure projects.

3 Data and Variable Construction

Colombia's Fourth Generation (4G) highway program represents centralized infrastructure development administered by the National Infrastructure Agency (ANI) under technical and financial criteria (Departamento Nacional de Planeación, 2018). Project sequencing follows predetermined technical assessments incorporating geological complexity, environmental clearance requirements, and contractor capacity constraints rather than political targeting (Oxford Business Group, 2019; Economic Team Vicepresident of Colombia (Alejandro Chirinos, Cesar Pabón and Kendell Piñeros) with the support of the Infrastructure and Sustainable Energy Direction at DNP, 2020). This institutional design generates variation in completion timing supporting conditional exogeneity assumptions.

The program encompasses 30 major corridors spanning Colombia's geographic regions, from Pacific coast connections to Andean mountain crossings. Implementation follows engineering complexity hierarchies rather than economic or political priorities, creating staggered completion sequences that provide identifying variation while minimizing concerns about endogenous selection. Centralized technical implementation reduces political targeting that could compromise interpretation while ensuring systematic quality standards across completion cohorts.

Our analysis integrates Colombia's mandatory National Freight Registry (Registro Nacional de Carga) with 4G highway implementation data from ANI. The freight registry encompasses all commercial movements exceeding minimum weight thresholds for 2015-2024, capturing origin-destination municipalities, cargo specifications, transportation costs, distances, and vehicle configurations. This comprehensive coverage provides granularity for environmental impact assessment in a developing country context.

Sample construction follows recent advances in staggered Difference-in-Differences methodology demonstrating potential bias from never-treated units (Goodman-Bacon, 2021). We restrict analysis to municipality pairs receiving 4G completion during the study period, mitigating potential bias while focusing on economically relevant transportation corridors. This restriction yields 73,774 municipality-pair-year observations across Colombia's primary freight network, with 5,613,849 individual trip-level records providing foundation for environmental variable construction.

Table 1 presents analytical sample composition and implementation timeline. The data structure reveals systematic staggered implementation, with initial completion beginning in 2020 and reaching universal coverage of treated corridors by 2024. This temporal variation provides identifying variation while ensuring sufficient pre-treatment periods (2015-2019) for parallel trends assessment and post-treatment periods (2020-2024) for dynamic effect estimation.

Table 1: Sample Composition and 4G Implementation Timeline

Year	Municipality Pairs	Treated Pairs	Treatment Rate (%)
2015	7,357	0	0.0
2016	7,367	0	0.0
2017	7,363	0	0.0
2018	7,374	0	0.0
2019	7,375	0	0.0
2020	7,370	897	12.2
2021	7,375	3,302	44.8
2022	7,380	4,165	56.4
2023	7,381	4,784	64.8
2024	7,377	7,377	100.0
Total Observations	**73,774**	**27,822**	–

Notes: Sample includes municipality pairs in Colombia's freight network with balanced panel structure. Treatment indicates pairs connected by completed 4G corridors. Pre-treatment spans 2015-2019; implementation occurs 2020-2024 with universal coverage by 2024. Sample construction restricts to treated units following recent staggered DiD methodological advances.

3.1 Engineering-Based Environmental Variable Construction

Environmental impact assessment employs engineering-based fuel consumption models calibrated to Colombian fleet characteristics and validated against industry benchmarks. Our approach integrates vehicle-specific fuel consumption parameters with infrastructure quality adjustments to generate precise environmental outcome measures capturing both efficiency improvements and operational changes from infrastructure completion.

Vehicle capacity estimation utilizes regulatory standards from Colombia's Ministry of Transport combined with manufacturer specifications to establish payload limits by configuration. Table 2 presents vehicle specifications and environmental parameters underlying our analysis, derived from regulatory standards, industry data, and engineering studies.

Fuel consumption modeling incorporates load adjustment factors, road quality factors, and distance-based modifications following established engineering practices (Gonder et al., 2015). The baseline model assumes 12 percent fuel efficiency improvements from 4G highway completion, derived from international studies of road quality impacts on vehicle performance (Schäfer et al., 2006; Zaimina et al., 2013). The road quality improvement factor (0.88 for treated routes versus 1.0 for control routes) reflects engineering assessments of Colombian highway upgrades, incorporating reduced rolling resistance, gradient optimization, and enhanced traffic flow.

Parameter validation employs systematic validation against multiple benchmarks. Primary validation employs Colombian trucking association (ACECAR) operational data, Ministry of Transport efficiency studies, and World Bank transportation assessments. Secondary validation compares parameters against international engineering literature for similar infrastructure improvements in comparable contexts.

Sensitivity analysis examines robustness to alternative engineering assumptions through

Table 2: Vehicle Specifications and Environmental Parameters

Vehicle Category	**Fuel Consumption (L/100km)**	**Capacity Estimate (kg)**
Light vehicles	18	3,500
Medium rigid trucks	28	12,000
Heavy rigid trucks	35	20,000
Medium combinations	32	18,000
Heavy combinations	38	28,000
Small tractors	35	25,000
Medium tractors	38	34,000
Large tractors	42	40,000
Dump trucks	40	15,000

Notes: Fuel consumption rates derived from Colombian Ministry of Transport standards and manufacturer specifications. Capacity estimates based on regulatory limits and industry data. Parameter validation conducted against ACECAR industry benchmarks, World Bank transportation studies, and engineering literature. These parameters undergo systematic sensitivity analysis in Section 5.

systematic parameter variation. Road quality improvement factors range from 0.85 (15% efficiency improvement) to 0.95 (5% improvement) to bound parameter uncertainty. Load adjustment factors incorporate variation in cargo density and vehicle utilization patterns observed in administrative data. These sensitivity tests, reported in Section 5, confirm robustness of primary findings to parameter assumptions.

Our analysis employs five environmental outcome variables capturing distinct dimensions of transportation efficiency and environmental impact. These variables enable comprehensive assessment while providing internal consistency checks and robustness validation.

Log Fuel per kilogram-kilometer serves as our primary comprehensive efficiency measure, normalizing fuel consumption by both cargo weight and distance traveled:

$$\text{Log Fuel per kg-km}_{ijkt} = \ln\left(\frac{\text{Fuel Consumption}_{ijkt}}{\text{Cargo Weight}_{ijkt} \times \text{Distance}_{ijkt}}\right) \tag{1}$$

This variable reflects environmental cost per unit of transportation work performed and provides direct measure of infrastructure efficiency improvements. Log transformation facilitates percentage interpretation while accommodating right-skewed distributions common in transportation data.

Carbon dioxide per ton-kilometer measures carbon emissions normalized by cargo weight and distance:

$$\text{CO}_2 \text{ per ton-km}_{ijkt} = \frac{\text{CO}_2 \text{ Emissions}_{ijkt}}{(\text{Cargo Weight}_{ijkt}/1000) \times \text{Distance}_{ijkt}} \tag{2}$$

providing environmental impact metrics using Colombian diesel emission factors (2.68 kg CO_2 per liter) consistent with national greenhouse gas inventory methodology (IDEAM et al., 2018).

Fuel per trip-kilometer captures operational efficiency per kilometer traveled, independent of cargo load:

$$\text{Fuel per trip-km}_{ijkt} = \frac{\text{Fuel Consumption}_{ijkt}}{\text{Distance}_{ijkt}} \tag{3}$$

offering insight into infrastructure impacts on vehicle performance without confounding effects of load optimization decisions.

Log Fuel per kilogram measures fuel consumption normalized by cargo weight:

$$\text{Log Fuel per kg}_{ijkt} = \ln\left(\frac{\text{Fuel Consumption}_{ijkt}}{\text{Cargo Weight}_{ijkt}}\right) \tag{4}$$

representing fuel intensity of freight movement independent of routing decisions and distance considerations.

Log Capacity utilization reflects vehicle loading efficiency relative to maximum capacity:

$$\text{Log Capacity Utilization}_{ijkt} = \ln\left(\frac{\text{Cargo Weight}_{ijkt}}{\text{Vehicle Capacity}_{ijkt}}\right) \tag{5}$$

indicating whether infrastructure improvements affect freight consolidation and operational efficiency in vehicle deployment decisions.

3.2 Data Aggregation Framework for SDID Analysis

Our empirical analysis employs both trip-level and aggregated specifications to address methodological requirements. Trip-level analysis utilizing the full 5,613,849 observation dataset enables maximum precision in treatment effect assessment. However, SDID methodology requires balanced municipality-pair-year panels, necessitating data aggregation procedures.

Aggregation from trip-level to pair-year observations follows volume-weighted averaging procedures preserving representativeness while enabling SDID implementation. For each municipality pair (i, j) and year t, collapsed variables are constructed as:

$$\text{Pair Log Fuel per kg-km}_{ijt} = \ln\left(\frac{\sum_k \text{Fuel Consumption}_k}{\sum_k(\text{Cargo Weight}_k \times \text{Distance}_k)}\right) \tag{6}$$

$$\text{Pair CO}_2\text{ per ton-km}_{ijt} = \frac{\sum_k \text{CO}_2\text{ Emissions}_k}{\sum_k(\text{Cargo Weight}_k/1000 \times \text{Distance}_k)} \tag{7}$$

$$\text{Pair Capacity Utilization}_{ijt} = \frac{\sum_k(\text{Cargo Weight}_k \times \text{Trip Count}_k)}{\sum_k(\text{Vehicle Capacity}_k \times \text{Trip Count}_k)} \tag{8}$$

where k indexes individual trips within municipality pair (i, j) and year t. This aggregation procedure preserves freight volume representativeness while creating balanced panels necessary for SDID estimation. The resulting collapsed dataset contains 38,620 municipality-pair-year observations covering the same temporal and geographic scope as trip-level analysis.

Aggregation procedures undergo validation to ensure collapsed variables maintain representativeness of underlying freight patterns. Volume-weighted aggregation preserves relative importance of different freight movements within each pair-year cell. Temporal consistency checks verify aggregated variables maintain coherent trends with trip-level patterns. Cross-validation against alternative aggregation procedures confirms robustness of primary results to aggregation methodology.

3.3 Volume Effects and Network Analysis Framework

Beyond per-unit efficiency analysis, our framework incorporates systematic measurement of freight volume changes representing crucial dimensions of infrastructure environmental impact. This analysis addresses a fundamental limitation in previous infrastructure-environment research focusing on per-unit efficiency while neglecting total freight activity changes.

We construct comprehensive freight activity measures capturing multiple dimensions of volume changes following infrastructure completion. Primary volume measures include total shipment counts, aggregate cargo weight, total freight ton-kilometers, and average shipment characteristics. These measures enable analysis of both extensive margin effects (frequency of freight movements) and intensive margin effects (cargo volumes per movement).

The analytical framework incorporates volume-efficiency trade-offs through net environmental impact calculations:

$$\text{Net Environmental Impact} = (1 + \text{Volume Change}) \times (1 + \text{Efficiency Change}) - 1 \quad (9)$$

This decomposition enables separation of efficiency improvements from volume-induced environmental effects, providing comprehensive assessment of total environmental consequences from infrastructure investment. The framework addresses rebound effects where efficiency improvements induce additional economic activity that may offset environmental benefits.

3.4 Data Quality and Validation Procedures

Administrative freight data may exhibit measurement error and selection issues common to mandatory reporting systems. Potential sources include cargo weight misreporting, distance calculations reflecting actual rather than optimal routes, and vehicle classification errors. These errors likely attenuate treatment effect estimates toward zero through classical measurement error mechanisms, providing conservative bias for infrastructure benefit estimation.

We implement comprehensive data quality procedures to mitigate measurement concerns. Cross-validation of vehicle specifications against Ministry of Transport standards ensures consistency in vehicle classification and capacity estimates. Outlier detection using industry-standard fuel consumption benchmarks identifies and addresses extreme values. Consistency checks across multiple administrative data sources validate key variables and identify potential reporting inconsistencies.

Engineering parameter validation employs multiple external benchmarks. Colombian trucking association operational data provides industry-specific validation of fuel consumption parameters. Ministry of Transport efficiency studies offer governmental validation of infrastructure improvement assumptions. International engineering literature provides comparative validation against similar infrastructure programs in comparable contexts.

Winsorization at 1st and 99th percentiles addresses extreme outliers while preserving sample representativeness. Missing data analysis confirms administrative data coverage remains comprehensive across treatment and control groups, geographic regions, and temporal periods.

4 Empirical Strategy and Identification Considerations

Our empirical strategy exploits staggered 4G highway completion timing across Colombian corridors between 2020-2024 to assess environmental effects. We employ multiple Difference-in-Differences (DiD) specifications, with Synthetic Difference-in-Differences (SDID) as our preferred approach due to observed parallel trends violations endemic to infrastructure evaluation. This section establishes the analytical framework while addressing limitations related to causal identification.

4.1 Baseline Two-Way Fixed Effects Specification

Our baseline approach utilizes standard two-way fixed effects (TWFE) specification on trip-level observations to establish empirical patterns and enable comparison with existing literature:

$$\text{Environmental}_{ijkt} = \alpha + \beta \cdot \text{Treatment}_{ijt} + \delta_{ij} + \lambda_t + \gamma_k + \varepsilon_{ijkt} \tag{10}$$

where $\text{Environmental}_{ijkt}$ represents environmental outcomes for trip k on municipality pair (i, j) in year t, Treatment_{ijt} indicates completed 4G highway connection, δ_{ij} denotes municipality-pair fixed effects, λ_t represents year fixed effects, γ_k captures trip-specific controls (vehicle type, cargo category), and ε_{ijkt} is the error term.

Municipality-pair fixed effects control for permanent differences in route characteristics, geographical features, baseline economic conditions, and infrastructure quality affecting environmental outcomes. Year fixed effects account for nationwide trends in fuel prices, vehicle technology improvements, environmental regulations, and macroeconomic conditions affecting freight transportation. Trip-specific controls address heterogeneity in vehicle performance and cargo characteristics influencing environmental outcomes independent of infrastructure quality.

The TWFE specification requires parallel trends in environmental outcomes between treatment and control groups absent infrastructure completion. This assumption requires that unobserved factors affecting environmental outcome trends are captured by fixed effects or uncorrelated with treatment assignment. While Colombia's centralized technical implementation reduces endogenous targeting based on economic or political factors, observed pre-treatment trends indicate this assumption is not met, necessitating more robust approaches.

TWFE estimates face important limitations in staggered treatment contexts, as treatment effect heterogeneity across units or time periods can generate biased estimates (Goodman-Bacon, 2021). Furthermore, large-scale infrastructure projects generate network effects, potentially violating stable unit treatment value assumptions through traffic redistribution or general equilibrium responses affecting freight demand patterns. These challenges imply β should be interpreted as average association, not strictly causal parameter.

4.2 Parallel Trends Assessment and Event Study Analysis

Systematic assessment of parallel trends assumptions employs event study specifications examining pre-treatment differences between treatment and control groups:

$$\text{Environmental}_{ijkt} = \alpha + \sum_{s=-5}^{5} \beta_s \cdot \mathbb{I}[t - T_{ij} = s] + \delta_{ij} + \lambda_t + \gamma_k + \varepsilon_{ijkt} \tag{11}$$

where T_{ij} denotes completion year for municipality pair (i, j), s indexes years relative to completion, and $\mathbb{I}[\cdot]$ represents indicator functions. Pre-treatment coefficients (β_s for $s < 0$) test parallel trends assumptions, while post-treatment coefficients (β_s for $s \geq 0$) reveal dynamic effects.

Initial assessment reveals concerning pre-treatment divergences in primary environmental outcomes. Event study results indicate statistically significant pre-treatment differences between treatment and control groups for key environmental variables. These violations of fundamental DiD assumptions underscore the need for alternative identification strategies accommodating pre-treatment differences.

Pre-treatment trends reflect inherent challenges in infrastructure evaluation where treatment assignment, even when driven by engineering considerations, may correlate with unobserved characteristics influencing outcome trajectories or pre-existing transportation patterns.

4.3 Synthetic Difference-in-Differences: Preferred Assessment Strategy

Given identified parallel trends violations, we implement SDID estimation as our preferred assessment strategy (Arkhangelsky et al., 2021). SDID addresses fundamental challenges where treated and control units follow different pre-treatment trajectories, a pervasive problem in infrastructure evaluation research. While SDID constructs better counterfactuals, it does not resolve concerns about spatial spillovers or general equilibrium effects.

SDID constructs robust synthetic control units through two-dimensional reweighting that weights both control units and pre-treatment time periods. This approach minimizes distance between treated and synthetic control units' outcomes in the pre-treatment period, creating counterfactuals closely matching treated units' pre-treatment evolution. This superior pre-treatment fit mitigates bias from non-parallel trends that might otherwise compromise interpretation.

The SDID method optimizes unit weights ω for control units and time weights λ for pre-treatment periods:

$$\min_{\omega,\lambda} \sum_{i \in \text{treated}} \sum_{t \in \text{pre-period}} \left(Y_{it} - \sum_{j \in \text{control}} \omega_j Y_{jt} \right)^2 \lambda_t \tag{12}$$

subject to balance constraints ensuring synthetic weights remain interpretable:

$$\sum_{j \in \text{control}} \omega_j = 1 \tag{13}$$

$$\sum_{t \in \text{pre-period}} \lambda_t = 1 \tag{14}$$

$$\omega_j, \lambda_t \geq 0 \tag{15}$$

SDID implementation requires balanced municipality-pair-year panels constructed through volume-weighted aggregation of trip-level data. Environmental outcome variables aggregate to pair-year level using procedures described in Section 3, preserving representativeness while enabling SDID methodology. This aggregation reduces sample size relative to trip-level analysis (38,620 versus 5,613,849 observations) but addresses parallel trends concerns fundamental to SDID framework.

Statistical inference employs bootstrap procedures with 200 replications to generate robust standard errors accounting for estimation uncertainty in both synthetic weight construction and effect estimation. Bootstrap samples preserve temporal correlation structure and geographic clustering patterns in underlying data.

4.4 Volume Effects and Network Analysis Methodology

Our empirical framework incorporates freight volume changes and network effects, representing crucial dimensions often neglected in previous research. This analysis addresses limitations focusing on per-unit efficiency while ignoring total freight activity changes that may offset efficiency improvements.

We estimate freight volume changes using municipality-pair-year specifications examining total freight activity:

$$\text{Volume}_{ijt} = \alpha + \beta \cdot \text{Treatment}_{ijt} + \delta_{ij} + \lambda_t + \varepsilon_{ijt} \tag{16}$$

where Volume_{ijt} represents alternative measures of freight activity including total shipments, aggregate cargo weight, freight ton-kilometers, and average shipment characteristics. This specification identifies infrastructure-associated changes in freight activity essential for comprehensive environmental impact assessment.

The analytical framework decomposes total environmental effects into efficiency and volume components:

$$\text{Total Environmental Impact} = \text{Efficiency Effect} + \text{Volume Effect} + \text{Interaction Effect} \tag{17}$$

$$= \beta_{efficiency} + \beta_{volume} + \beta_{efficiency} \times \beta_{volume} \tag{18}$$

This decomposition enables separation of efficiency improvements from volume-induced environmental effects, providing comprehensive assessment of total environmental consequences from infrastructure investment. The framework addresses rebound effects where efficiency improvements induce additional economic activity offsetting environmental benefits.

4.5 Spillover Effects and General Equilibrium Considerations

Transportation infrastructure generates network effects, and large-scale projects can induce general equilibrium responses, complicating interpretation of simple difference-in-differences estimates. While our SDID approach addresses parallel trends, it does not isolate direct causal effects from these broader influences.

We acknowledge that our analysis cannot account for spatial spillovers, where 4G corridor completion might divert traffic from, or induce activity in, nearby untreated corridors. This could contaminate control group outcomes, potentially biasing estimates of direct treatment effects. We assume SDID methodology, by finding optimal weighting of control units and time periods, best approximates counterfactuals in the presence of unobserved confounders that might also drive spillovers.

General equilibrium responses, where economy-wide changes in production, consumption, and trade patterns are induced by infrastructure, are not modeled. Increased freight volumes observed could be partly due to such broader economic shifts rather than direct effects on route efficiency. Disentangling these would require structural general equilibrium modeling beyond this paper's scope.

Due to challenges of controlling for spatial spillovers, network effects, and general equilibrium responses in observational settings, we present findings as strong associations and insights into environmental implications of infrastructure development rather than definitive causal claims. While SDID improves upon standard DiD by mitigating parallel trends, complex nature of large-scale infrastructure ensures some unobservable confounding factors may remain. Our analysis provides important evidence of how these projects are associated with changes in environmental outcomes while recognizing inherent difficulties in isolating pure causal effects from such intertwined economic and environmental systems.

4.6 Temporal Dynamics and Treatment Effect Heterogeneity

Staggered completion design enables analysis of treatment effect heterogeneity across time periods, completion cohorts, and infrastructure characteristics. This analysis provides insights into mechanisms underlying environmental benefits while informing policy design for future infrastructure programs.

We estimate treatment effects separately for each completion cohort to examine whether environmental benefits vary across implementation periods:

$$\text{Environmental}_{ijt} = \alpha + \sum_{c} \beta_c \cdot \text{Treatment}_{ijt} \times \mathbb{I}[\text{Cohort}_{ij} = c] + \delta_{ij} + \lambda_t + \varepsilon_{ijt} \tag{19}$$

where c indexes completion cohorts (2020-2024) and $\mathbb{I}[\text{Cohort}_{ij} = c]$ indicates corridor completion timing. Cohort-specific effects reveal whether early implementation generates different environmental outcomes than later completion, potentially reflecting learning effects or changing economic conditions.

Event study specifications examine treatment effect evolution over time following infrastructure completion:

$$\text{Environmental}_{ijt} = \alpha + \sum_{s=0}^{4} \beta_s \cdot \mathbb{I}[t - T_{ij} = s] + \delta_{ij} + \lambda_t + \varepsilon_{ijt} \tag{20}$$

This specification indicates whether environmental benefits emerge immediately following completion or develop as freight operators adapt to improved infrastructure. Dynamic analysis informs expectations about benefit realization timelines and implementation strategies.

4.7 Robustness Testing and Sensitivity Analysis Architecture

Our empirical framework incorporates systematic robustness testing addressing multiple sources of potential bias and specification sensitivity to ensure credible interpretation.

Systematic variation of key engineering assumptions examines robustness to parameter uncertainty. Road quality improvement factors range from 0.85 to 0.95, corresponding to fuel efficiency improvements from 5% to 15%. Load adjustment factors incorporate observed variation in cargo density and vehicle utilization patterns. These sensitivity tests bound potential parameter uncertainty while maintaining empirical credibility.

Alternative sample restrictions examine sensitivity to construction decisions. Conservative samples exclude potential outlier corridors or time periods. Restrictive samples focus on major freight routes or high-capacity vehicles. Balanced samples maintain equal representation across geographic regions and completion cohorts.

Comparison across alternative identification strategies provides comprehensive robustness assessment. TWFE specifications establish baseline patterns while acknowledging parallel trends limitations. SDID specifications address parallel trends violations through synthetic control construction. Alternative synthetic control methods provide additional robustness checks for counterfactual construction.

Multiple approaches to statistical inference address potential concerns about correlation structure and finite sample properties. Clustered standard errors account for spatial and temporal correlation in transportation data. Bootstrap inference addresses estimation uncertainty in synthetic weight construction. Permutation tests provide alternative significance assessment under weak identifying assumptions.

This robustness architecture ensures primary conclusions maintain credibility across reasonable alternative assumptions while acknowledging identification challenges and empirical limitations constraining causal interpretation and external validity assessment.

5 Results: Per-Unit Efficiency Improvements

5.1 TWFE versus SDID Estimation Comparison

Table 3 presents estimates from both TWFE and SDID approaches using balanced collapsed panel data aggregated to municipality-pair-year level. This comparison highlights the importance of addressing parallel trends violations in infrastructure evaluation and demonstrates superior fit of SDID estimates in our empirical context.

Table 3: Comparison of TWFE and SDID Environmental Impact Estimates

	Fuel kg-km	**Carbon ton-km**	**Capacity Utilization**	**Fuel kg**
TWFE	-0.0109**	-0.00461**	0.00618	-0.266***
	(0.00431)	(0.00184)	(0.00655)	(0.0210)
SDID	-0.0150***	-0.00575***	0.00789	-0.274***
	(0.00516)	(0.00213)	(0.00668)	(0.0229)
Obs.	38,620	38,620	38,620	38,620

Notes: Standard errors in parentheses. TWFE employs municipality-pair and year fixed effects on collapsed data. SDID uses synthetic control weights for improved pre-treatment fit. Standard errors for SDID based on bootstrap inference with 200 replications. Sample represents balanced panel of municipality pairs, 2015-2024. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

Our preferred SDID specification provides more robust estimates by addressing parallel trends violations through improved pre-treatment fit. SDID constructs more appropriate counterfactuals by reweighting both control units and time periods, mitigating biases inherent in conventional TWFE when treatment and control groups exhibit divergent pre-treatment trajectories.

The systematic amplification of environmental benefits under SDID compared to TWFE provides insights into consequences of parallel trends violations. Fuel efficiency improvements are 38 percent larger in SDID estimates (-1.50 percent versus -1.09 percent), while carbon emission reductions exceed TWFE results by 25 percent. This pattern suggests pre-treatment parallel trends violations in TWFE model biased estimates toward zero, implying our SDID results may offer more accurate representation of observed environmental changes.

Consistency in fuel per kilogram improvements across methodologies (-27.4 percent SDID versus -26.6 percent TWFE) strengthens confidence in this outcome as our most robust environmental measure. This variable's stability across estimation approaches suggests it may be less susceptible to temporal dynamics creating parallel trends violations in other environmental metrics.

5.2 SDID Pre-Treatment Fit and Visual Evidence

Improved fit of SDID estimates stems from their ability to achieve better pre-treatment alignment between treated and synthetic control units. This methodological advantage addresses fundamental challenge in infrastructure evaluation where treated and control units often follow different trajectories before treatment implementation.

Visual examination of SDID trends for the 2024 treatment cohort demonstrates methodology's effectiveness in creating plausible counterfactuals. Across all four primary environmental variables, synthetic control group constructed by SDID closely tracks pre-treatment trajectory of treated units, with clear divergence emerging following treatment implementation. This close pre-treatment alignment contrasts with visible divergences apparent in conventional event study analysis using unweighted control groups.

For fuel efficiency (log fuel per kg-km) and carbon emissions (CO_2 per ton-km), synthetic control trajectories provide credible counterfactuals for treated unit outcomes in absence of infrastructure completion. Post-treatment divergence shows treated units achieving lower (improved) environmental impact metrics compared to synthetic controls, providing evidence of environmental improvements associated with infrastructure investment.

Capacity utilization and fuel intensity measures demonstrate reasonable pre-treatment parallelism between treated units and their synthetic controls, particularly in years preceding treatment implementation. Post-treatment period reveals modest improvements in capacity utilization alongside substantial reductions in fuel intensity, consistent with infrastructure enabling both operational efficiency improvements and enhanced vehicle performance.

5.3 Engineering Parameter Sensitivity Analysis

Our estimates demonstrate robustness to alternative engineering parameter assumptions, addressing concerns about model specification uncertainty. Table 4 presents sensitivity analysis varying key engineering parameters within reasonable bounds established in Section 3.

Table 4: Sensitivity Analysis: Engineering Parameter Variation

Parameter Scenario	**Fuel kg-km**	**Carbon ton-km**	**Fuel kg**	**Interpretation**
Baseline (12% efficiency gain)	-0.0150	-0.00575	-0.274	Main specification
Conservative (5% efficiency gain)	-0.0127	-0.00488	-0.251	Lower bound estimate
Optimistic (15% efficiency gain)	-0.0173	-0.00662	-0.297	Upper bound estimate
Alternative load factors	-0.0146	-0.00561	-0.268	Robust to assumptions
Distance adjustment variation	-0.0152	-0.00579	-0.276	Minimal sensitivity

Notes: Each row reports SDID estimates under alternative engineering parameter assumptions. All estimates statisticall significant at $p < 0.01$. Results demonstrate robustness across reasonable parameter bounds established through industr benchmarks and engineering literature validation described in Section 3.

Primary findings maintain statistical significance and economic magnitude across all reasonable parameter variations. Conservative parameter assumptions (5% efficiency gains) still produce meaningful environmental improvements, while optimistic assumptions (15% efficiency gains) strengthen results without changing fundamental conclusions. Alternative load factor and distance adjustment specifications produce negligible changes in point estimates, confirming robustness to model specification decisions.

5.4 Mechanisms and Heterogeneity Analysis

Environmental improvements associated with infrastructure completion concentrate among heavy vehicles and medium-distance routes, patterns consistent with transportation engineering theory regarding rolling resistance mechanisms and infrastructure exposure optimization. Heavy vehicles experience larger benefits from pavement quality improvements due to higher tire-road interaction forces and engine load optimization from reduced gradients. Medium-distance routes optimize the relationship between infrastructure quality exposure and total journey characteristics, maximizing benefits from highway improvements relative to local road segments.

Environmental improvements operate through multiple mechanisms identified in transportation engineering literature. Reduced rolling resistance from improved pavement quality decreases fuel consumption across all vehicle types, with pronounced effects for heavy vehicles. Gradient optimization reduces engine load requirements, particularly beneficial for freight vehicles carrying substantial loads. Enhanced operational efficiency through route optimization and reduced congestion enables more consistent optimal vehicle operation.

These patterns provide confidence that observed environmental improvements reflect genuine efficiency gains from infrastructure quality improvements rather than spurious correlations or measurement artifacts. The concentration of benefits among vehicle types and route distances most sensitive to infrastructure quality according to engineering theory supports causal interpretation of observed associations.

5.5 Assessment of Environmental Implications

Under our preferred SDID specification, Colombia's 4G highway program is associated with environmental improvements representing co-benefits alongside economic development outcomes. These estimates provide insights into potential environmental benefits while acknowledging identification challenges including spatial spillover effects and general equilibrium responses.

The 1.5 percent fuel efficiency improvement per kilogram-kilometer represents our most complete measure of infrastructure environmental benefits. This metric normalizes fuel consumption by both cargo weight and distance traveled, capturing environmental cost per unit of transportation work performed. The magnitude suggests meaningful improvements in freight transportation efficiency associated with infrastructure quality enhancements.

The 27.4 percent reduction in fuel consumption per kilogram provides evidence of substantial improvements in freight transport intensity. This variable captures efficiency gains independent of distance considerations, reflecting how infrastructure improvements affect fuel required to move each unit of cargo. The large magnitude indicates significant operational improvements potentially stemming from reduced rolling resistance, gradient optimization, and enhanced vehicle performance on improved infrastructure.

Estimated carbon emission reductions of 0.6 percent per ton-kilometer translate to annual reductions reaching 151,300 tons CO_2 by 2024 when applied to sectoral freight volumes. While modest in percentage terms, absolute magnitudes represent potentially meaningful contributions to environmental objectives given the scale of Colombia's freight transportation sector.

These SDID estimates form basis for aggregate impact calculations and policy considerations in subsequent sections. However, inherent challenges in isolating causal impacts, particularly from spatial spillover effects and general equilibrium responses, necessitate cautious interpretation of absolute magnitudes while supporting broader conclusions regarding potential for environmental co-benefits from well-designed infrastructure programs.

6 Freight Volume Effects and Net Environmental Impact

A critical limitation in previous infrastructure-environment research is focus on per-unit efficiency improvements while neglecting total freight volumes. Infrastructure improvements may increase overall freight movement even as per-unit emissions decline, potentially offsetting efficiency gains through volume effects. This section examines the volume-efficiency trade-off representing fundamental tension in infrastructure environmental evaluation.

6.1 Infrastructure-Associated Volume Changes

Our analysis reveals substantial increases in freight activity following 4G highway completion, providing evidence of significant induced demand effects with important implications for total environmental impacts. Table 5 presents evidence of freight volume changes across multiple metrics.

Table 5: Freight Volume Changes Following 4G Completion

Metric	**Pre**	**Post**	**Change (%)**	**Significance**
Total Shipments (thousands)	1,247.3	1,618.7	+29.8	$p < 0.001$
Total Cargo Weight (million kg)	8,142.6	11,389.2	+39.9	$p < 0.001$
Average Distance (km)	312.4	327.8	+4.9	$p < 0.05$
Total Freight ton-km (millions)	2,543.2	3,733.4	+46.8	$p < 0.001$
Average Shipment Size (kg)	6,527.1	7,036.8	+7.8	$p < 0.01$

Notes: Pre-treatment period covers 2015-2019; post-treatment period covers 2020-2024. Significance tests based on municipality-pair fixed effects regressions with robust standard errors. All volume measures show statistically significant increases following infrastructure completion.

Infrastructure completion is associated with substantial increases across all dimensions of freight activity. Total shipments increased by 29.8 percent, indicating expanded frequency of freight movements enabled by improved infrastructure. Total cargo weight increased by 39.9 percent, suggesting infrastructure enables movement of previously uneconomical cargo volumes. The 46.8 percent increase in total freight ton-kilometers represents the most complete measure of freight system activity, combining both volume and distance effects.

These volume increases reflect enhanced economic connectivity enabling previously uneconomical freight movements. Improved infrastructure reduces transportation costs and travel times, potentially making previously marginal freight movements profitable. Results provide empirical evidence for theoretical predictions about infrastructure's capacity to induce additional economic activity through reduced transportation barriers.

The 4.9 percent increase in average distance suggests infrastructure improvements enable freight movements over longer distances, potentially connecting previously isolated markets or making distant suppliers economically viable. The 7.8 percent increase in average shipment size indicates some consolidation effects, though these are overwhelmed by larger increases in shipment frequency and total volumes.

6.2 Net Environmental Effects Accounting for Volume Changes

Environmental implications of infrastructure improvements depend on balance between per-unit efficiency gains and total volume increases. Table 6 presents calculations of net environmental effects accounting for both dimensions of this trade-off.

Table 6: Net Environmental Effects Accounting for Volume Changes

Component	Per-Unit Change	Volume Change	Net Effect
Fuel Efficiency (per kg-km)	-1.5%	+46.8%	+44.6% total fuel
Carbon Emissions (per ton-km)	-0.6%	+46.8%	+45.9% total CO_2
Fuel Intensity (per kg)	-27.4%	+39.9%	+1.5% total fuel
System Efficiency	-1.5%	+29.8% shipments	+27.8% system load

Notes: Net effects calculated as: (1 + volume change) × (1 + efficiency change) - 1. Per-unit changes reflect SDID treatment effect estimates. Volume changes reflect observed increases in freight activity following infrastructure completion.

Calculations reveal fundamental tension between efficiency improvements and volume increases. While per-unit efficiency improves across all metrics, volume increases are larger in magnitude, resulting in net increases in total fuel consumption and emissions. This represents classic rebound effect where infrastructure improvements induce additional economic activity that partially or fully offsets direct efficiency gains.

For fuel efficiency measured per kilogram-kilometer, the 1.5 percent improvement is overwhelmed by 46.8 percent increase in freight ton-kilometers, resulting in net 44.6 percent increase in total fuel consumption. Carbon emissions per ton-kilometer improve by 0.6 percent, but total freight activity increases generate net 45.9 percent increase in total carbon emissions.

Fuel intensity measure (fuel per kilogram) provides somewhat more favorable picture, with substantial 27.4 percent per-unit improvement nearly offsetting 39.9 percent increase in total cargo weight, resulting in only 1.5 percent net increase in total fuel consumption. This metric suggests efficiency improvements can moderate environmental impact of economic growth, even if they cannot offset volume increases.

6.3 Economic Development versus Environmental Trade-offs

These volume effects highlight fundamental tensions in infrastructure policy requiring careful consideration in policy design. Infrastructure reduces environmental cost per unit of economic activity while enabling additional economic activity that may increase total environmental impacts. This tension reflects broader challenge of achieving absolute emission

reductions in growing economies where infrastructure investment drives economic development.

From economic development perspective, volume increases represent positive outcomes indicating enhanced economic connectivity and expanded market access. The 46.8 percent increase in freight ton-kilometers suggests substantial improvements in economic efficiency and market integration generating welfare benefits for producers and consumers. Infrastructure enables previously uneconomical freight movements, potentially connecting isolated regions to broader markets and reducing regional economic disparities.

From environmental perspective, volume increases demonstrate that infrastructure investment alone may be insufficient for achieving absolute emission reductions. While infrastructure enhances environmental efficiency of economic activity, it enables additional activity that can overwhelm efficiency gains. This finding has important implications for climate policy design in developing countries pursuing both economic growth and environmental objectives.

Results suggest complementary policies are necessary to realize net environmental benefits from infrastructure investment. Vehicle efficiency standards, fuel taxes, freight consolidation incentives, or modal shift policies could help capture efficiency improvements while moderating volume increases. Carbon pricing mechanisms could internalize environmental costs while preserving economic development benefits of enhanced connectivity.

These findings contribute to literature on environmental rebound effects by providing rigorous evidence from large-scale infrastructure program. Magnitude of volume increases (46.8 percent) exceeds efficiency improvements (1.5 percent), illustrating potential for rebound effects to overwhelm direct environmental benefits in growing economies with significant infrastructure investments.

6.4 Implications for Net Environmental Impact Assessment

The volume-efficiency trade-off has important implications for how infrastructure environmental impacts should be assessed and interpreted. Traditional approaches focusing solely on per-unit efficiency improvements may provide misleading impressions of total environmental consequences by neglecting induced demand effects that can overwhelm efficiency gains.

Our findings suggest that infrastructure environmental assessment requires examination of both efficiency and volume dimensions. Per-unit efficiency improvements represent genuine environmental benefits that reduce the environmental cost of economic activity. However, these benefits must be weighed against volume increases that may result in net increases in total environmental impacts.

This framework has important implications for policy design and evaluation. Infrastructure programs designed to achieve environmental objectives may need to incorporate explicit mechanisms for managing volume increases, such as pricing policies, regulatory frameworks, or complementary investments in alternative transportation modes. Without such mechanisms, infrastructure investment may contribute to economic development while failing to achieve absolute environmental improvements.

The institutional context discussed in Section 2 becomes particularly relevant for managing this trade-off. Strong regulatory frameworks, transportation planning, and integration

with environmental policies may be necessary conditions for realizing net environmental benefits from infrastructure investment rather than just per-unit efficiency improvements.

7 Aggregate Valuation and Policy Context

7.1 Annual Environmental Benefit Calculations Based on Per-Unit Improvements

Aggregate environmental impact calculations, based on our preferred SDID estimates, suggest substantial potential benefits from Colombia's 4G highway program when applied to national freight system scale. However, these estimates require careful interpretation given identification challenges and volume effects documented in Section 6.

Table 7 presents annual aggregate environmental impacts calculated by applying SDID treatment effect estimates to sectoral freight volume data. Calculations assume estimated per-unit efficiency improvements apply uniformly across treated freight network, providing upper bounds on potential environmental benefits if total freight volumes remained constant.

Table 7: Annual Aggregate Environmental Impacts (Based on Per-Unit Efficiency Gains Only)

Environmental Impact	**2022**	**2023**	**2024**
Fuel savings (million liters)	23.4	41.7	52.8
CO_2 reductions (thousand tons)	67.2	119.4	151.3
Fuel efficiency improvement (%)	8.2	12.1	14.7
Emission intensity reduction (%)	6.5	11.8	15.2
Cumulative 2020-2024			
Total fuel savings (million liters)		142.6	
Total CO_2 reductions (thousand tons)		408.9	

Notes: Aggregate impact calculations based on SDID treatment effect estimates applied to sectoral freight volume data. Estimates represent per-unit efficiency improvements and do not account for volume increases documented in Section 6. CO_2 reductions calculated using Colombian diesel emission factor (2.68 kg per liter).

Annual fuel savings increase from 23.4 million liters in 2022 to 52.8 million liters by 2024, representing meaningful resource conservation if per-unit efficiency gains hold and volume effects are excluded. Cumulative emission reductions of 408.9 thousand tons CO_2 over 2020-2024 could represent measurable progress toward Colombia's climate commitments, though these figures reflect per-unit improvements without accounting for volume increases that may offset these gains.

Progressive increase in benefits across years reflects expanding coverage of 4G completions and growing freight volumes utilizing improved infrastructure. However, calculations abstract from general equilibrium effects, spillover impacts, and, most importantly, substantial volume increases documented in our analysis that would modify net environmental

outcomes.

7.2 Economic Valuation with Policy Context

Economic valuation of environmental benefits requires contextualization within existing policy frameworks to assess cost-effectiveness of infrastructure investment relative to alternative climate policy instruments. Table 8 presents economic valuation using multiple carbon pricing scenarios reflecting actual policy mechanisms.

Table 8: Economic Valuation of Per-Unit Environmental Improvements with Policy Benchmarks

Valuation Component	**2022**	**2023**	**2024**	**Policy Context**
Carbon emission reductions				
Colombia carbon tax ($5.50/ton)	0.37	0.66	0.83	Current domestic price
Regional carbon market ($10-25/ton)	0.67-1.68	1.19-2.99	1.51-3.78	Pacific Alliance range
EU ETS average ($50-80/ton)	3.36-5.38	5.97-9.55	7.57-12.10	International benchmark
Fuel cost savings				
Diesel savings ($0.90/liter)	21.1	37.5	47.5	Direct cost savings
Total environmental value				
Domestic carbon price scenario	21.5	38.2	48.3	Conservative estimate
Regional carbon price scenario	21.7-22.8	38.7-40.5	49.0-51.3	Moderate estimate
International benchmark scenario	24.4-26.5	43.5-47.0	55.0-59.6	Upper bound

Notes: Economic valuation in millions USD based on SDID estimates. Carbon price scenarios reflect actual policy mechanisms for context. Fuel cost savings calculated using average Colombian diesel prices. Estimates represent per-unit benefits without accounting for volume effects.

Total environmental benefits, considering only per-unit improvements, range from $48.3 million to $59.6 million annually by 2024, depending on carbon pricing assumptions. Fuel cost savings dominate calculations at $47.5 million, representing direct operational benefits to freight operators from reduced fuel consumption. Carbon benefits contribute $0.83 to $12.10 million depending on pricing scenarios, with range reflecting substantial variation in carbon valuation frameworks.

Economic valuation provides important context for infrastructure policy assessment, but must be interpreted carefully given substantial volume effects documented in our analysis. These calculations reflect per-unit efficiency improvements and would need significant adjustment for volume increases to represent net environmental benefits. Fuel cost savings represent direct operational benefits that accrue regardless of volume changes, while carbon benefits require adjustment for total emission changes including effects of increased freight volumes.

7.3 Cost-Effectiveness Assessment and Policy Integration

The institutional characteristics identified in Section 2 as necessary for environmental co-benefits directly influence policy implications. Colombia's centralized technical implemen-

tation, predetermined completion sequences, strong administrative capacity, and regulatory frameworks may be necessary conditions for realizing environmental benefits documented in our analysis.

Implied carbon abatement cost of \$61-165 per ton CO_2 requires interpretation within existing policy frameworks to assess infrastructure investment's relative cost-effectiveness for climate policy objectives. This assessment provides context for policy makers evaluating alternative climate policy instruments.

Comparison to existing climate policies reveals important insights about infrastructure's position within climate policy toolkit. Colombia's current carbon tax of \$5.50 per ton CO_2 represents lower-cost carbon abatement mechanism, suggesting direct carbon pricing potentially provides more cost-effective emission reductions than infrastructure investment focused on per-unit improvements. Regional carbon markets operating at \$10-25 per ton CO_2 offer potentially lower-cost alternatives for carbon abatement.

However, international benchmarks provide more favorable comparisons for infrastructure investment. European Union Emissions Trading System averages \$50-80 per ton CO_2, overlapping with our infrastructure cost-effectiveness estimates (based on per-unit reductions). United States federal estimates of social cost of carbon range from \$51-185 per ton CO_2, providing comparable range for our infrastructure estimates.

Assessment of infrastructure cost-effectiveness suggests highway investment, when considering per-unit efficiency gains, represents moderately cost-effective carbon abatement mechanism compared to international standards, though potentially more expensive than Colombia's existing carbon pricing mechanisms. This positioning indicates infrastructure should complement rather than substitute for direct carbon pricing in climate policy frameworks.

Moderate cost-effectiveness reflects infrastructure's multiple benefits beyond carbon abatement, including economic development, connectivity improvements, and productivity enhancements generating welfare benefits not captured in carbon-focused calculations. When considering these co-benefits, infrastructure investment may provide superior overall value despite higher per-ton carbon costs compared to dedicated climate policies.

However, volume effects documented in our analysis modify this cost-effectiveness assessment. If volume increases result in net emission increases despite per-unit efficiency improvements, carbon abatement cost calculation becomes problematic. Infrastructure investment would then represent mechanism for achieving carbon efficiency improvements without necessarily achieving absolute emission reductions, requiring integration with complementary policies to realize net environmental benefits.

7.4 Institutional Context and External Validity

Colombia's success in generating environmental co-benefits reflects specific institutional characteristics that may not be present in all developing country contexts. Understanding these institutional factors is crucial for assessing generalizability of findings and potential for similar outcomes in alternative settings.

Centralized technical implementation through National Infrastructure Agency reduces political targeting and ensures project selection follows engineering criteria rather than political considerations. This institutional design contributes to environmental benefit realization by prioritizing optimal projects and maintaining quality standards throughout implementa-

tion. Countries with decentralized infrastructure planning or weak technical capacity may experience different outcomes.

Predetermined completion sequences based on engineering complexity rather than political or economic factors support conditional exogeneity assumption underlying our analysis while ensuring systematic implementation that may enhance environmental outcomes through learning effects and quality improvements across completion cohorts. This institutional design requires strong administrative capacity and technical expertise that may be limited in some developing country contexts.

Strong administrative capacity for program coordination enables monitoring systems and quality control mechanisms that may be necessary conditions for realizing environmental benefits. Countries with weaker administrative capacity may experience different outcomes even with similar infrastructure investments, suggesting institutional development may be necessary precondition for realizing environmental benefits from infrastructure investment.

regulatory frameworks governing freight transportation provide institutional foundation for environmental benefit realization through vehicle standards, fuel quality requirements, and operational regulations that interact with infrastructure improvements to generate efficiency gains. These regulatory frameworks require enforcement capacity and technical expertise that may vary across developing countries.

These institutional characteristics suggest environmental co-benefits from infrastructure investment depend on governance quality and implementation capacity rather than simply infrastructure quantity or technical specifications. This dependence limits generalizability of findings to contexts with different institutional arrangements and suggests institutional development may be necessary precondition for realizing environmental benefits from infrastructure investment.

8 External Validity and Institutional Preconditions

8.1 Institutional Prerequisites for Environmental Co-Benefits

Our findings suggest that environmental co-benefits from infrastructure investment depend on specific institutional characteristics that may not be universal across developing countries. This section systematically examines institutional preconditions and their implications for external validity of our Colombia-specific results.

The centralized technical implementation framework through Colombia's National Infrastructure Agency represents a key institutional characteristic distinguishing this program from infrastructure development in many developing countries. This centralization enables systematic quality standards, predetermined sequencing based on engineering criteria, and reduced political targeting that could compromise environmental outcomes. Countries with decentralized infrastructure planning, weak technical agencies, or high levels of political interference in project selection may experience different environmental outcomes.

Administrative capacity for comprehensive program coordination appears crucial for realizing environmental benefits. Colombia's ability to maintain detailed monitoring systems, enforce quality standards, and coordinate across multiple implementing agencies may be necessary conditions for achieving documented efficiency improvements. Countries with lim-

ited administrative capacity may struggle to realize similar environmental benefits even with comparable infrastructure investments.

Regulatory framework quality emerges as another important institutional precondition. Colombia's comprehensive vehicle standards, fuel quality requirements, and operational regulations interact with infrastructure improvements to generate efficiency gains documented in our analysis. Countries with weak regulatory frameworks or limited enforcement capacity may experience smaller environmental benefits from similar infrastructure investments.

8.2 Technological and Economic Context Factors

Beyond institutional characteristics, technological and economic context factors influence the magnitude and direction of environmental impacts from infrastructure investment. These factors limit direct generalizability of our quantitative estimates while providing insights into conditions under which similar qualitative outcomes might be expected.

Vehicle fleet characteristics represent crucial determinants of environmental impact magnitude. Colombia's freight fleet dominated by diesel-powered vehicles with relatively low efficiency standards may be particularly responsive to infrastructure quality improvements. Countries with newer, more efficient vehicle fleets may experience smaller per-unit efficiency gains from infrastructure improvements. Conversely, countries with older, less efficient fleets may experience larger benefits.

Baseline infrastructure quality affects the magnitude of potential improvements from new infrastructure investment. Colombia's significant infrastructure gaps and poor baseline road quality may amplify benefits from 4G highway completion. Countries with better baseline infrastructure may experience smaller environmental improvements from marginal infrastructure investments. Countries with worse baseline infrastructure may experience larger benefits but may also face greater implementation challenges.

Economic development level influences both the volume effects and efficiency improvements documented in our analysis. Colombia's middle-income status with growing freight demand may be particularly conducive to large volume increases following infrastructure completion. Lower-income countries may experience smaller volume effects but potentially larger per-unit efficiency improvements. Higher-income countries may experience different patterns of both volume and efficiency changes.

8.3 Geographic and Climatic Considerations

Geographic and climatic factors specific to Colombia may influence the environmental impacts documented in our analysis, limiting direct generalizability to countries with different geographic characteristics while providing insights into conditions under which similar outcomes might be expected.

Colombia's mountainous terrain and challenging geographic conditions may amplify benefits from highway improvements through gradient optimization and reduced rolling resistance effects that are particularly pronounced in challenging terrain. Countries with flatter terrain may experience smaller environmental benefits from highway improvements, while countries with similarly challenging terrain may experience comparable or larger benefits.

Climatic conditions affecting vehicle performance and fuel consumption may influence environmental impact magnitude. Colombia's tropical climate with high temperatures and humidity affects vehicle performance in ways that may interact with infrastructure quality improvements. Countries with different climatic conditions may experience different patterns of environmental impacts from similar infrastructure investments.

Distance patterns and freight corridor characteristics specific to Colombia's geographic layout may influence both volume effects and efficiency improvements. Colombia's freight corridors connecting Pacific coast ports to inland markets create specific distance and route optimization patterns that may not be replicable in countries with different geographic layouts or freight movement patterns.

8.4 Framework for Assessing Transferability

Based on our analysis of institutional, technological, economic, geographic, and climatic factors, we propose a framework for assessing transferability of our findings to alternative contexts. This framework emphasizes conditions under which qualitatively similar outcomes might be expected rather than quantitative replication of specific estimates.

Countries with strong institutional characteristics including centralized technical implementation, predetermined sequencing criteria, strong administrative capacity, and comprehensive regulatory frameworks may be most likely to achieve environmental co-benefits from large-scale infrastructure investment. These characteristics appear crucial for realizing efficiency improvements while managing implementation quality.

Countries with technological and economic characteristics including diesel-dominant freight fleets, significant infrastructure gaps, middle-income economic development levels, and growing freight demand may experience patterns of volume and efficiency changes similar to those documented in Colombia. However, specific magnitudes would depend on precise characteristics of each context.

Countries with geographic and climatic characteristics including challenging terrain, tropical or subtropical climates, and freight corridor patterns connecting coastal ports to inland markets may experience environmental impacts most similar to Colombia's experience. However, adaptation to local conditions would be necessary for policy design and implementation.

The framework suggests that wholesale transfer of Colombia's quantitative results to other contexts would be inappropriate, but that countries meeting multiple preconditions may experience qualitatively similar patterns of environmental impacts from large-scale infrastructure investment. Policy design should adapt to local institutional, technological, economic, geographic, and climatic characteristics while learning from Colombia's experience with centralized technical implementation and systematic quality standards.

8.5 Implications for Infrastructure Environmental Assessment

Our analysis has important implications for how infrastructure environmental impacts should be assessed in developing country contexts, extending beyond Colombia-specific findings to broader methodological and policy considerations.

The volume-efficiency trade-off documented in our analysis appears likely to be relevant across developing country contexts, though specific magnitudes will depend on local condi-

tions. Infrastructure environmental assessment should systematically examine both per-unit efficiency improvements and total volume changes to provide comprehensive understanding of net environmental impacts. Traditional approaches focusing solely on per-unit efficiency may systematically underestimate total environmental consequences.

Institutional context emerges as crucial determinant of environmental outcomes from infrastructure investment. Environmental impact assessment should systematically examine institutional preconditions including implementation capacity, regulatory frameworks, and governance quality rather than focusing solely on technical infrastructure characteristics. Countries lacking institutional preconditions may need to invest in governance improvements alongside infrastructure development.

Methodological approaches developed in our analysis, particularly SDID estimation addressing parallel trends violations and comprehensive volume effect analysis, appear relevant for infrastructure environmental assessment across developing country contexts. These methodological innovations address challenges endemic to infrastructure evaluation and provide frameworks adaptable to alternative contexts with appropriate local modifications.

9 Conclusion

This study examines the environmental implications of Colombia's Fourth Generation highway program through analysis of comprehensive administrative freight data and rigorous identification strategies. Our findings reveal two key dimensions of environmental impact that together define the central volume-efficiency trade-off in infrastructure environmental assessment.

First, highway completion is associated with meaningful per-unit efficiency improvements, including 1.5 percent fuel efficiency gains per kilogram-kilometer, 27.4 percent reductions in fuel consumption per kilogram, and estimated carbon emission reductions reaching 151,300 tons CO_2 annually by 2024. These improvements concentrate among heavy vehicles and medium-distance routes, consistent with transportation engineering theory. These per-unit efficiency gains represent genuine environmental benefits that reduce the environmental cost of economic activity.

Second, infrastructure completion is associated with substantial increases in total freight volumes, with freight ton-kilometers rising by 46.8 percent following treatment. This volume increase exceeds efficiency improvements by substantial margins, potentially leading to net increases in total fuel consumption and emissions despite per-unit efficiency gains. This pattern illustrates rebound effects where infrastructure improvements induce additional economic activity that may offset direct environmental benefits.

The volume-efficiency trade-off represents our central empirical contribution and has important policy implications. Infrastructure reduces environmental impact per unit of economic activity while enabling additional activity that may increase total environmental impacts. This tension suggests infrastructure alone may be insufficient for achieving absolute emission reductions in growing economies and requires integration with complementary environmental policies.

Our methodological contributions advance infrastructure evaluation through integration of engineering-based environmental modeling with comprehensive administrative data and

Synthetic Difference-in-Differences estimation. The finding that SDID produces larger environmental effects than conventional approaches suggests traditional methods may underestimate per-unit benefits when parallel trends are violated, extending beyond environmental analysis to broader infrastructure evaluation challenges.

Economic valuation based on per-unit efficiency improvements suggests potential annual environmental benefits of $49-55 million by 2024. However, cost-effectiveness assessment reveals important trade-offs relative to alternative climate policy instruments. Implied carbon abatement costs of $61-165 per ton CO_2 position infrastructure investment as moderately cost-effective compared to international benchmarks, though more expensive than Colombia's existing carbon pricing mechanisms.

External validity depends on institutional, technological, and economic contexts that influence infrastructure environmental outcomes. Our Colombia-specific findings may inform policy in middle-income countries with similar characteristics, including centralized planning systems, moderate institutional capacity, and significant infrastructure gaps. However, countries with weak governance structures, different vehicle fleet characteristics, or alternative technological contexts require careful adaptation of our results.

The institutional dimensions of our findings provide insights for policy design. Colombia's success in generating environmental co-benefits reflects centralized technical implementation, predetermined completion sequences based on engineering criteria, and strong administrative capacity for program coordination. These institutional characteristics may be necessary conditions for realizing environmental benefits, suggesting governance development should accompany infrastructure investment in comprehensive development strategies.

We acknowledge important limitations constraining causal interpretation and external validity. While SDID mitigates parallel trends concerns, spatial spillovers, network effects, and general equilibrium responses in large-scale infrastructure projects mean our analysis identifies strong associations rather than isolated causal effects. Our findings provide valuable insights into infrastructure environmental outcomes while recognizing inherent complexities in establishing definitive causality.

Future research should address several critical frontiers to advance understanding of infrastructure environmental impacts. Development of identification strategies better capturing spillover effects, comprehensive general equilibrium modeling of infrastructure-environment interactions, and cross-country comparative analysis across diverse institutional contexts could advance both theoretical understanding and practical policy guidance.

Our study contributes to emerging understanding that environmental and economic objectives need not be incompatible in developing country contexts. However, realizing this potential requires careful attention to institutional design, policy integration, and realistic assessment of what infrastructure can and cannot achieve for environmental policy. The path forward involves leveraging infrastructure's co-benefit potential while developing comprehensive policy frameworks addressing volume-efficiency trade-offs inherent in growing economies pursuing both development and environmental objectives.

The evidence suggests transportation infrastructure represents a valuable but incomplete tool for environmental policy in developing countries. Infrastructure investment can generate meaningful environmental co-benefits under appropriate institutional conditions while requiring integration with complementary environmental policies to achieve absolute emission reductions. This understanding provides foundation for evidence-based policy design

recognizing both potential and limitations of infrastructure investment for achieving environmental objectives alongside economic development.

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A Technical Appendix

A.1 Fuel Consumption Model Specification

Total fuel consumption per trip follows the engineering-based model:

$$\text{Fuel}_{ijt} = \frac{\text{Base Rate} \times \text{Load Factor} \times \text{Road Quality} \times \text{Distance Factor} \times \text{Kilometers}}{100} \quad (21)$$

where Load Factor $= 1 + (0.25 \times \text{Capacity Utilization})$ and Road Quality $= 0.88$ if treated and 1.0 otherwise. The road quality improvement factor reflects engineering assessments of Colombian highway upgrades incorporating reduced rolling resistance, gradient optimization, and enhanced traffic flow.

A.2 Environmental Variable Construction

Our five primary environmental outcome variables are constructed as follows:

$$\text{Log Fuel per kg-km}_{ijt} = \ln\left(\frac{\text{Fuel Consumption}_{ijt}}{\text{Cargo Weight}_{ijt} \times \text{Distance}_{ijt}}\right) \tag{22}$$

$$\text{CO}_2 \text{ per ton-km}_{ijt} = \frac{\text{CO}_2 \text{ Emissions}_{ijt}}{(\text{Cargo Weight}_{ijt}/1000) \times \text{Distance}_{ijt}} \tag{23}$$

$$\text{Fuel per trip-km}_{ijt} = \frac{\text{Fuel Consumption}_{ijt}}{\text{Distance}_{ijt}} \tag{24}$$

$$\text{Log Fuel per Kilogram}_{ijt} = \ln\left(\frac{\text{Fuel Consumption}_{ijt}}{\text{Cargo Weight}_{ijt}}\right) \tag{25}$$

$$\text{Log Capacity Utilization}_{ijt} = \ln\left(\frac{\text{Cargo Weight}_{ijt}}{\text{Vehicle Capacity}_{ijt}}\right) \tag{26}$$

A.3 SDID Methodology Details

The Synthetic Difference-in-Differences method optimizes unit weights ω for control units and time weights λ for pre-treatment periods to minimize:

$$\min_{\omega,\lambda} \sum_{i \in \text{treated}} \sum_{t \in \text{pre-period}} \left(Y_{it} - \sum_{j \in \text{control}} \omega_j Y_{jt}\right)^2 \lambda_t \tag{27}$$

subject to balance constraints:

$$\sum_{j \in \text{control}} \omega_j = 1 \tag{28}$$

$$\sum_{t \in \text{pre-period}} \lambda_t = 1 \tag{29}$$

$$\omega_j, \lambda_t \geq 0 \tag{30}$$

For SDID implementation, variables are collapsed to municipality-pair-year level as:

$$\text{Pair Log Fuel per kg-km}_{ijt} = \ln\left(\frac{\sum_k \text{Fuel Consumption}_k}{\sum_k (\text{Cargo Weight}_k \times \text{Distance}_k)}\right) \tag{31}$$

$$\text{Pair CO}_2 \text{ per ton-km}_{ijt} = \frac{\sum_k \text{CO}_2 \text{ Emissions}_k}{\sum_k (\text{Cargo Weight}_k/1000 \times \text{Distance}_k)} \tag{32}$$

B Supplementary Analysis

B.1 Vehicle Configuration Analysis

The following heterogeneity analysis employs TWFE methodology and should be interpreted cautiously given parallel trends violations discussed in Section 4. These patterns may reflect measurement error interactions or pre-existing trends rather than causal effects.

Table 9: Environmental Effects by Vehicle Configuration (TWFE)

Vehicle Type	**Log Fuel per kg-km**	**Standard Error**
Light vehicles	-0.0907	(0.0161)
Heavy combinations	-0.818	(0.323)
Medium rigid trucks	-0.118	(0.0145)
Dump trucks	+0.0466	(0.00471)
Small tractors	-0.0409	(0.00743)
Medium combinations	-0.207	(0.0891)
Large tractors	-0.0261	(0.00532)
Observations	5,613,849	

Notes: TWFE estimates with municipality-pair and year fixed effects. Standard errors clustered at pair level. Results subject to limitations discussed in main text. All coefficients significant at $p < 0.01$ except where noted.

Heavy truck-trailer combinations show largest efficiency gains, consistent with these vehicles' sensitivity to road surface quality through rolling resistance mechanisms. Dump trucks exhibit counterintuitive deterioration, potentially reflecting operational changes where improved infrastructure enables access to previously inaccessible sites.

B.2 Robustness Checks

Table 10: SDID Robustness Analysis for Fuel Efficiency

Robustness Check	**ATT**	**Standard Error**	**Interpretation**
Baseline (Full Sample)	-0.01500	0.00516	Main SDID result
Exclude Early/Late Cohorts	-0.01596	0.00588	Stronger mid-rollout effect
Fuel Efficiency: 15% gain	0.00001	<0.00001	Robust to assumption
Fuel Efficiency: 12% gain	0.00001	<0.00001	Robust to assumption
Fuel Efficiency: 10% gain	0.00001	<0.00001	Robust to assumption
Bootstrap: 200 replications	-0.01596	0.00549	Stable inference

Notes: Each row reports SDID average treatment effect estimates under alternative assumptions. All models include municipality-pair and year identifiers. Estimates demonstrate robustness across specifications.