POWERING BRAZIL'S TRANSITION TO ZERO-EMISSION TRUCKING

Improving air Quality, Public Health and the Economy with Coordinated Sector Efforts

Instituto Ar

SUMMARY

The electrification of Brazil's heavy-duty trucking sector represents a critical opportunity to reduce greenhouse gas (GHG) emissions, improve air quality, and enhance public health. While Brazil's longstanding reliance on biofuels has leveraged domestic resources and infrastructure, this strategy is best viewed as a transitional measure that may not fully meet the country's long-term climate and economic objectives.

Electrification offers a strategic pathway to decarbonize road freight, drawing on international experience from jurisdictions such as the European Union and the United States. It aligns with Brazil's national sustainability commitments and can deliver substantial co-benefits for the environment, public health, and economic resilience.

Realizing this transition will require coordinated action across government, industry, and civil society. Public sector leadership—through robust regulatory frameworks, targeted incentives, and investment in infrastructure—will be essential. Energy providers, logistics operators, municipalities, and vehicle manufacturers all have complementary roles in developing a supportive ecosystem for zero-emission freight.

Manufacturers remain key stakeholders by contributing to innovation and adapting vehicle offerings to the Brazilian context. However, the success of the transition hinges on whole-of-sector collaboration, guided by coherent policies and supported by public and private investment.

This report presents international case studies, quantifies environmental and economic impacts, and outlines actionable recommendations to inform decision-making. It aims to support policymakers, industry leaders, and other stakeholders in accelerating the electrification of Brazil's heavy-duty vehicle fleet, in line with national goals to reduce emissions and improve public health.

CASE STUDY: EMISSIONS SCENARIOS IN SÃO PAULO

The study modeled different scenarios for replacing the diesel truck fleet with cleaner technologies in São Paulo, estimating pollutant emission reductions by 2030 and 2050.

The scenarios considered were: battery electric (BEV), hydrogen fuel cell (FCEV), diesel hybrid, liquefied natural gas (LNG), compressed natural gas (CNG), and pure biodiesel (B100).

RESEARCH RESULTS IN NUMBERS

BATTERY ELECTRIC TRUCKS

- **46%** reduction in GHG emissions by 2050.
- **R$ 5 billion** in avoided environmental and health costs.

HYDROGEN FUEL CELL TRUCKS

- **27%** reduction in emissions by 2050.
- **R$ 2.9 billion** in avoided costs.

DIESEL HYBRID TRUCKS

- **8%** reduction in emissions by 2050.
- **R$ 298 million** in avoided costs.

NATURAL GAS AND BIODIESEL

Increase net emissions and economic costs over time.

GENERAL ANALYSIS AND CONCLUSIONS

Between 2013 and 2023, R$ 24.5 billion were spent on hospitalizations caused by diseases related to air pollution.

Biodiesel: Brazil currently adopts up to 14% mandatory blending (B14), with most of it derived from soybeans. Full biodiesel use (B100) by 2050 would require about 215 million hectares of agricultural land — equivalent to approximately 25% of the national territory.

Electrification: Battery electric trucks offer the largest long-term emission reductions and the greatest economic benefits.

Hydrogen: Promising, but faces high costs and infrastructure barriers.

Natural Gas (LNG/CNG): Limited short-term benefits and risk of increased emissions and costs in the long term.

The data from the São Paulo study reveal that electrifying the truck fleet is the strategy that delivers the most robust and sustained reductions in pollutant and greenhouse gas emissions.

This strategy not only benefits the environment but also generates economic and public health returns by avoiding the social damages associated with pollution.

In contrast, options such as soybean biodiesel and compressed natural gas—though promoted as "cleaner" alternatives—show considerable environmental and health side effects and represent an economic setback in terms of avoidable costs.

FINAL RECOMMENDATIONS

- Accelerate the implementation of fuel economy regulations for trucks.
- Support fleet renewal with effective policies.
- Gradually eliminate diesel subsidies, implement carbon pricing, and align policies with climate justice.
- Establish mandatory zero-emission vehicle manufacturing targets by 2040.
- Build electric and hydrogen charging infrastructure.
- Implement concrete financial mechanisms, such as credits, subsidies, and taxes.

SUMÁRIO

A eletrificação do setor de transporte rodoviário de carga pesada no Brasil representa uma oportunidade importante para reduzir as emissões de gases de efeito estufa (GEE), melhorar a qualidade do ar e fortalecer a saúde pública. Embora a longa dependência do país em biocombustíveis tenha aproveitado recursos e infraestrutura domésticos, essa estratégia deve ser entendida como uma medida transitória, que pode não atender plenamente aos objetivos climáticos e econômicos de longo prazo do Brasil.

A eletrificação oferece um caminho estratégico para descarbonizar o transporte rodoviário de carga, com base na experiência internacional de jurisdições como a União Europeia e os Estados Unidos. Esta transição está alinhada com os compromissos nacionais de sustentabilidade do Brasil e pode gerar benefícios significativos para o meio ambiente, a saúde pública e a resiliência econômica.

Concretizar essa transição exigirá ação coordenada entre governo, setor produtivo e sociedade civil. A liderança do setor público — por meio de marcos regulatórios robustos, incentivos direcionados e investimentos em infraestrutura — será essencial. Fornecedores de energia, operadores logísticos, municípios e fabricantes de veículos desempenham papéis complementares no desenvolvimento de um ecossistema favorável ao transporte de carga com emissão zero.

Os fabricantes continuam sendo atores-chave, ao contribuírem com inovação e adaptação da oferta de veículos ao contexto brasileiro. No entanto, o sucesso desta transição depende de uma colaboração setorial abrangente, guiada por políticas coerentes e sustentada por investimentos públicos e privados.

Este relatório apresenta estudos de caso internacionais, quantifica impactos ambientais e econômicos, e propõe recomendações acionáveis para embasar a tomada de decisão. Seu objetivo é apoiar formuladores de políticas, lideranças do setor e demais partes interessadas na aceleração da eletrificação da frota brasileira de veículos pesados, em consonância com as metas nacionais de redução de emissões e melhoria da saúde pública.

ESTUDO DE CASO: CENÁRIOS DE EMISSÕES EM SÃO PAULO

O estudo modelou diferentes cenários de substituição da frota de caminhões a diesel por tecnologias mais limpas em São Paulo, estimando reduções de emissões de poluentes até 2030 e 2050.
Os cenários considerados foram: elétrico a bateria (BEV), célula de combustível hidrogênio (FCEV), híbrido diesel, gás natural liquefeito (LNG), gás natural comprimido (CNG) e biodiesel puro (B100).
Biodiesel apresentou pior desempenho ambiental do que o diesel.
Veículos elétricos oferecem maior redução de GEE e poluentes até 2050.

RESULTADOS DA PESQUISA EM NÚMEROS

ELÉTRICOS A BATERIA

- **46%** de redução nas emissões de GEE até 2050.
- **R$ 5 bilhões** em custos evitados com meio ambiente e saúde.

CÉLULA DE COMBUSTÍVEL (HIDROGÊNIO)

- **27%** de redução nas emissões até 2050.
- **R$ 2.9 bilhões** em custos evitados.

HÍBRIDOS A DIESEL

- **8%** de redução nas emissões até 2050.
- **R$ 298 milhões** em custos evitados.

GÁS NATURAL E BIODIESEL

Aumentam as emissões líquidas e os custos econômicos ao longo do tempo.

ANÁLISE GERAL E CONCLUSÕES

Entre 2013 e 2023 foram gastos R$ 24,5 bilhões em hospitalizações causadas por doenças relacionadas à poluição do ar.
Biodiesel: O Brasil adota atualmente até 14% de mistura obrigatória (B14), sendo a maior parte proveniente da soja. A utilização integral de biodiesel (B100) até 2050 demandaria cerca de 215 milhões de hectares de terras agrícolas — o equivalente a aproximadamente 25% do território nacional.
Eletrificação: Caminhões elétricos a bateria oferecem as maiores reduções de emissões no longo prazo e os melhores benefícios econômicos.
Hidrogênio: Promissor, mas enfrenta altos custos e barreiras de infraestrutura.
Gás Natural (GNL/GNC): Benefícios limitados no curto prazo e risco de aumento das emissões e custos no longo prazo.

Os dados do estudo de São Paulo revelam que a eletrificação da frota de caminhões é a estratégia que oferece reduções mais robustas e sustentadas das emissões de gases poluentes e de efeito estufa.
Esta estratégia não apenas beneficia o meio ambiente, mas gera retornos econômicos e à saúde pública ao evitar os danos sociais associados à poluição.
Em contraste, opções como biodiesel de soja e gás natural comprimido — embora promovidas como alternativas "mais limpas" — demonstram efeitos colaterais ambientais e sanitários consideráveis, além de representar um retrocesso econômico do ponto de vista dos custos evitáveis.

RECOMENDAÇÕES FINAIS

- Acelerar a implementação de regulamentações de economia de combustível para caminhões.
- Apoiar renovação da frota com políticas eficazes.
- Eliminar gradualmente os subsídios ao diesel, implementar precificação de carbono e alinhar políticas com justiça climática. Estabelecer metas obrigatórias de fabricação de Veículos com Emissão Zero até 2040.
- Criar infraestrutura de recarga elétrica e hidrogênio.
- Implementar mecanismos financeiros concretos, tais como créditos, subsídios, taxações.

1. BRAZIL'S FREIGHT TRANSPORT SECTOR – A HEAVY BURDEN ON THE ROAD

Every day, millions of tons of goods crisscross the Brazilian vast territory, keeping the economy running. Yet, beneath this essential flow of commerce lies a fragile system, overwhelmingly dependent on roads. With over 65% of total freight tonnage transported by trucks, Brazil stands as one of the most road-reliant freight economies in the world (ICCT, 2021). This dependence is not merely a result of geography but a legacy of policies that have shaped a transport network where roads dominate, often at the expense of efficiency, sustainability, and resilience.

Historically, Brazil's road dominance emerged from mid-20th-century industrial strategies designed to foster domestic automobile production. Throughout the 1950s and 1960s, the government introduced tax incentives, import restrictions, and subsidies to attract global vehicle manufacturers, embedding trucking into the country's economic fabric (IEA-EPE, 2021). As part of this auto-centric industrialization, massive public investments prioritized national highways such as BR-101 and BR-116, transforming them into the backbone of freight logistics. While these policies fueled economic expansion, they also sidelined rail and waterway development, leaving Brazil with an imbalanced and inefficient freight system.

Over the years, demand for freight transport has surged, propelled by economic growth and rising trade volumes. Between 2005 and 2018, Brazil's truck fleet expanded at an average annual rate of 3.5%, leading to an increase in diesel consumption from 20 to 30 million tonnes of oil equivalent (toe) over the same period (IEA-EPE, 2021). By 2019, the total freight truck fleet was estimated at 2 million vehicles, accounting for 76% of all fossil diesel consumed in Brazil and 40% of all greenhouse gas emissions from the transport sector. By 2020, heavy-duty trucks accounted for 60% of total freight energy use, far surpassing medium and light trucks (ICCT, 2021).

The challenges of Brazil's freight sector extend beyond fuel consumption. Poor road conditions further exacerbate costs and emissions. Ranked 103rd out of 137 countries in road quality, Brazil faces persistent infrastructure deficiencies that increase fuel use, vehicle maintenance costs, and travel time (World Economic Forum (WEF), 2017). Studies show that a significant annual diesel savings, reaching 4.52 billion liters, or 16% of fuel efficiency could be achieved with better road conditions in the country, with positive return of investment by the year of 2037 (Santos et al., 2024).

Structural challenges within the trucking sector further constrain efficiency. Brazil permits some of the heaviest trucks in the world, with legal gross combination weights of up to 74 tonnes and special authorizations reaching 91 tonnes, compared to 40 tonnes in the U.S. and 49 tonnes in China. Heavier trucks consume more fuel per kilometer and cause faster road deterioration, exacerbating infrastructure degradation. Meanwhile, Brazil's truck fleet is significantly older than in other major economies, with 6.1% of trucks exceeding 30 years of age, operating under outdated efficiency standards. Over the past two decades, fuel efficiency improvements in heavy-duty trucks have averaged just 0.6% per year, significantly lagging behind economies such as the EU and Japan, where efficiency gains surpass 1% annually due to stricter fuel economy regulations (IEA-EPE, 2021).

Despite these challenges, Brazil is taking initial steps toward efficiency improvements. The government is currently collecting fuel consumption data to establish formal efficiency targets for heavy-duty trucks by 2032, expected to be introduced in 2027 (Brazil, 2018). Until then, progress will depend on voluntary technology adoption and fleet modernization. Without a shift toward fuel economy regulations, investments in modern infrastructure and fleet renovation, and a more balanced multimodal freight system, Brazil's dependence on road transport will continue to drive rising costs, inefficiency, and mounting environmental concerns.

Fuel Efficiency and Regulatory Gaps in Brazil's Freight Transport

Although Brazil's freight sector has expanded significantly over the past decades, improvements in fuel efficiency for heavy-duty vehicles have not kept pace. This lag is largely due to the absence of mandatory fuel economy regulations specifically targeting heavy-duty trucks. Various programs have attempted to address different aspects of transport efficiency—such as vehicle technology, infrastructure modernization, and emissions control—but none have imposed direct fuel efficiency mandates for heavy trucks. Consequently, the sector remains reliant on voluntary industry efforts and fragmented policy interventions.

For instance, the Rota 2030 program has incentivized technological advancements and improvements in fuel efficiency by encouraging automakers to invest in research and development (Brazil Ministry of Development, Industry, Commerce and Services, 2020). However, unlike the progressive fuel economy targets imposed in the United States and the European Union, Brazil's efforts under Rota 2030 have primarily focused on passenger vehicles. Although the data collected through Rota 2030 is expected to support the formulation of the country's first heavy-duty vehicle efficiency standards, these regulations are not anticipated to be implemented before 2032, delaying critical improvements in fuel consumption and emissions reduction.

Similarly, Inov@BR (Brazil Minister of Infrasctructure, 2021) was introduced with the goal of improving road maintenance, logistics coordination, and freight tracking. Yet, it lacks enforceable fuel economy requirements for the trucking sector, leaving the country's freight system heavily dependent on road transport and contributing to persistently high fuel consumption levels.

On the emissions front, Brazil has made more measurable progress. The implementation of Proconve P8—which will align Brazilian emission standards with Euro VI regulations—is projected to significantly reduce nitrogen oxides (NO_x) and particulate matter (PM) emissions from diesel trucks (Brazil Ministry of Environment, 2018). However, because Proconve P8 does not address fuel efficiency, overall fuel consumption and greenhouse gas emissions may remain high unless further measures are adopted. In contrast, many leading economies in Europe and North America have integrated emissions control with mandatory fuel economy improvements. These regions not only achieve lower pollutant emissions but also reduce fuel consumption per kilometer traveled (International Council of Clean Transportation, 2019).

The lack of binding fuel efficiency standards for heavy-duty vehicles places Brazil at a distinct disadvantage compared to global best practices. In key markets such as the United States, China, Canada, Japan, and the European Union, regulatory frameworks drive continuous improvements in truck efficiency, which in turn lower operational costs and minimize environmental impacts (IEA-EPE, 2021). For instance, the U.S. Phase 2 Heavy-Duty Vehicle Efficiency Standards require a 16% reduction in fuel consumption for large trucks and a 24% reduction for vocational vehicles between 2017 and 2027 (International Council of Clean Transportation (ICCT), 2016b). Similarly, the European Union mandates a 45% reduction in truck CO_2 emissions by 2030 (European Comission, 2021). These policies create a clear trajectory for efficiency gains, catalyzing technological innovation and promoting cost-effective fuel use in the freight sector.

In Brazil, fuel efficiency targets for trucks are still in the preliminary phase. Current regulations are expected to be formulated by 2027 and implemented by 2032 (Brazil Ministry of Development, Industry, Commerce and Services, 2020). Without immediate and decisive measures to accelerate fleet modernization and enhance fuel efficiency, Brazil risks falling further behind its global counterparts. This delay may lead to increased fuel dependency, higher operational costs, and mounting environmental pressures. In the absence of mandatory efficiency targets, progress will continue to rely on voluntary industry initiatives and piecemeal infrastructure investments, leaving significant gaps in Brazil's path toward a more efficient freight transport system.

Benchmarking Brazil's Heavy-Duty Sector: Efficiency Gaps and Global Comparisons

Brazil's heavy-duty freight sector operates under unique regulatory and infrastructure conditions that set it apart from other major economies. While the country benefits from high truck capacity limits that enhance transport efficiency, these allowances also pose significant challenges, including accelerated road wear, higher fuel consumption, and safety concerns. A comparative analysis of

Brazil's truck regulations and enforcement mechanisms against global standards provides valuable insights into the sector's efficiency gaps and areas for improvement.

Brazil's regulations permit gross combination vehicle weights (GCVWs) of 74 tonnes for standard road trains and up to 91 tonnes with special authorizations, making the country one of the nations with the highest truck weight limits globally. In comparison, Argentina allows trucks to operate at a maximum of 75 tonnes, while Australia has the highest limit at 122.5 tonnes, but only on specific routes under controlled permit systems. Other countries impose more restrictive limits: Canada caps truck weights at 62.5 tonnes, China at 49 tonnes, India at 55 tonnes, Mexico at 47.5 tonnes, Russia at 44 tonnes, and the United States limits vehicles to 40 tonnes for interstate highways. These variations reflect differing regulatory approaches to balancing transport efficiency, road infrastructure durability, and safety concerns. Brazil's high weight allowances enable greater freight transport capacity per trip but also contribute to accelerated road deterioration, higher maintenance costs, and increased fuel consumption. Unlike in North America and Europe, where strict axle weight enforcement and braking system regulations mitigate these risks, Brazil's enforcement mechanisms remain relatively weak, allowing overloading and excessive road wear (IEA-EPE, 2021)

In addition to truck weight policies, road infrastructure remains a critical challenge for the country's freight sector, contributing to high fuel consumption, increased vehicle wear, and logistical inefficiencies. According to the World Economic Forum's Global Competitiveness Report 2017–2018, Brazil ranked 80th out of 137 countries in terms of overall infrastructure quality, reflecting the deteriorated condition of many highways that are essential for freight transport (World Economic Forum (WEF), 2017). Poorly maintained roads lead to higher rolling resistance and inefficient fuel usage, increasing operational costs for logistics companies. Research from the Massachusetts Institute of Technology (MIT) suggests that improving road stiffness could lead to significant reductions in fuel consumption for heavy vehicles, as less energy is lost to road deformation. While the exact decline in fuel efficiency on degraded roads varies, studies indicate that smoother, more rigid pavements contribute to lower fuel costs and reduced emissions from freight transport (MIT, 2020). These findings highlight the urgent need for infrastructure investment in Brazil to improve road conditions, enhance trucking efficiency, and reduce environmental impacts.

Compounding this issue, Brazil's geographical landscape necessitates extensive long-haul transportation routes for its key exports, particularly soybeans and iron ore. For instance, soybeans produced in Mato Grosso, the country's leading soybean-producing state, often travel approximately 2,200 kilometers to reach the Port of Paranaguá in Paraná, significantly increasing transportation costs and logistical inefficiencies (Fliehr, 2013). Similarly, iron ore extracted from Carajás, a major mining region in Pará, must travel approximately 800 kilometers via railway to reach the Port of São Luís, highlighting the reliance on long-haul freight transport for bulk commodities (Rodrigues, 2024). These vast distances not only contribute to high operational costs but also increase fuel consumption and greenhouse gas emissions, exacerbating environmental concerns.

In contrast, countries like the United States, China, and Russia have developed more diversified freight transportation networks. The United States moves approximately 39.9% of its freight ton-miles via rail, benefiting from an extensive railway infrastructure that reduces dependency on long-distance trucking. China and Russia similarly rely heavily on railways and inland waterways for bulk freight movement, leveraging these modes to enhance efficiency, reduce transportation costs, and mitigate emissions (Rodrigues, 2024).

The aging truck fleet in Brazil remains a significant barrier to improving efficiency and reducing emissions. Data shows that 6.1% of Brazil's heavy-duty trucks are over 30 years old, meaning a substantial portion of the fleet lacks modern fuel-saving technologies and continues to operate at low efficiency (IEA-EPE, 2021). In comparison, fleet turnover in North America and Europe is much faster, with commercial trucks generally retired before reaching 15 to 20 years of age (International Council of Clean Transportation (ICCT), 2015). This faster replacement cycle ensures that trucking fleets in these regions benefit from the latest advancements in fuel efficiency and emissions reduction technologies.

Brazil's efforts to modernize its vehicle fleet have encountered challenges, particularly in implementing effective scrappage programs. Unlike countries such as Chile, Mexico, and China, where strict monitoring and financial incentives ensure the permanent removal of outdated vehicles, past programs in Brazil have struggled to achieve similar success. In Chile, the government offered incentives to replace trucks over 25 years old, contingent upon proof of vehicle destruction. This approach ensured that older, less efficient vehicles are permanently removed from operation. Mexico's truck renewal program, active between 2004 and 2010, successfully replaced approximately 21,000 trucks over 10 years old. Incentives provided either as cash upon scrapping the vehicle or as a reduction in the purchase price of a new vehicle equipped with advanced emission control technology. China has implemented several "cash-for-clunkers" programs to encourage the scrapping of older vehicles (International Council of Clean Transportation (ICCT), 2016a).

In contrast, Brazil's previous attempts at vehicle renewal, such as the Procaminhoneiro program (Brazil National Development Bank, 2007), have been less effective. These programs often failed to enforce the permanent removal of old vehicles, resulting in minimal impact on fleet modernization. Without stronger enforcement mechanisms and financial incentives, older vehicles continue to contribute to high fuel consumption, emissions, and rising operational costs. To address these challenges, Brazil has recently initiated new efforts to correct distortions in its incentive program for trucks. In June 2023, the government released tax incentives for the sale of trucks and buses with discounts. However, uptake has been low, with only 14% of the allocated funds utilized so far. A new ordinance aims to correct these distortions by allowing owners of scrapped vehicles to receive benefits without the obligation to purchase a new one, acknowledging that many autonomous truckers may not have the financial capacity to make such a transition (Valor Economico, 2023).

Addressing these issues requires a multifaceted approach, including stricter axle weight enforcement, investments in road and rail infrastructure, and policies that accelerate fleet modernization. Learning from international best practices—such as efficient scrappage programs, fuel economy standards, and improved intermodal transport integration—could help Brazil reduce costs, improve logistics efficiency, and lower emissions. By aligning its heavy-duty transport policies with global leaders in freight sustainability, Brazil can enhance competitiveness while mitigating the environmental and economic burdens of its current system.

2. THE CURRENT LANDSCAPE OF TRUCK EMISSIONS IN BRAZIL AND THEIR HEALTH IMPACTS

Heavy-duty trucks are a significant source of greenhouse gas (GHG) emissions in Brazil's transport sector. In 2020, these vehicles consumed approximately 45.1 billion liters of diesel, resulting in the emission of 185.3 million tons of CO_2, accounting for 49.9% of the transportation sector's CO_2 emissions (De Castro et al., 2023). This underscores the urgent need for improved vehicle efficiency, alternative technologies, and sustainable transport policies.

Diesel engines, the predominant power source for heavy-duty trucks, are also major emitters of nitrogen oxides (NO_x), which contribute to ground-level ozone formation (smog) and acid rain. Despite comprising a small percentage of the vehicle fleet, heavy-duty trucks and buses are responsible for a disproportionate share of NO_x emissions. In São Paulo, such vehicles account for less than 4% of the fleet but produce over 80% of NO_x emissions (Andrade et al., 2012). Similarly, in the Metropolitan Region of Salvador, heavy vehicles make up about 7% of the fleet yet contribute approximately 84% of NO_x emissions (Da Silva Marques et al., 2021). High concentrations of NO_x in urban environments exacerbate respiratory diseases, impacting public health and increasing healthcare costs.

Another significant environmental and health concern associated with heavy-duty trucks is the emission of fine particulate matter ($PM_{2.5}$). Diesel exhaust produces these microscopic particles, which can penetrate deep into the lungs and enter the bloodstream, leading to cardiovascular and respiratory diseases. The impact of PM emissions is particularly severe in densely populated cities, where freight corridors often intersect with residential and commercial zones (De Miranda et al., 2012).

Emissions from heavy-duty trucks have well-documented health impacts, particularly in urban areas and along major freight corridors. Exposure to fine particulate matter ($PM_{2.5}$) and nitrogen oxides (NO_x) from diesel-powered trucks is strongly linked to chronic respiratory conditions such as asthma, bronchitis, and impaired lung function. Children and the elderly are particularly vulnerable to these effects due to their higher susceptibility to air pollution. A study conducted across six Brazilian cities identified vehicle emissions as a major contributor to urban $PM_{2.5}$ concentrations, correlating with increased respiratory

24.5 billion reais

were spent on hospitalizations related to these diseases between 2013 and 2023, according to our analysis

illnesses. In addition to respiratory diseases, prolonged exposure to diesel exhaust has been associated with a higher risk of cardiovascular conditions, including hypertension, stroke, and heart attacks. $PM_{2.5}$ plays a key role in triggering systemic inflammation and vascular dysfunction, exacerbating cardiovascular health risks. Research indicates that individuals living near highways, industrial zones, and logistics hubs face disproportionately higher exposure to these pollutants, increasing their likelihood of developing severe health complications (Andrade et al., 2012).

The International Council on Clean Transportation (ICCT) estimated that emissions from diesel vehicles, including heavy-duty trucks, are responsible for thousands of premature deaths annually in Brazil. A one-year delay in adopting the P-8 emission standards was projected to result in an additional 6,000 premature deaths between 2023 and 2050. Delays in implementing cleaner diesel technologies are expected to escalate health expenditures by nearly USD 11.5 billion by 2040 (International Council of Clean Transportation (ICCT), 2022).

The study by the International Council on Clean Transportation (ICCT) highlights the substantial economic burden that diesel truck emissions impose on Brazil's healthcare system. The treatment of respiratory and cardiovascular diseases costs billions of reais annually, diverting critical resources from other public health priorities.

To quantify these financial impacts, we conducted an updated assessment of hospitalization expenses within the Brazilian Unified Health System (SUS) for conditions with well-documented associations with air pollution. Our analysis estimates that between 2013 and 2023, approximately 24.5 billion reais were spent on hospitalizations related to these diseases. The conditions examined in this study include malignant neoplasms of the trachea, bronchi, and lungs; diabetes mellitus; acute myocardial infarction; other acute ischemic heart diseases; intracerebral hemorrhage; cerebral infarction; unspecified strokes; influenza; pneumonia; chronic obstructive pulmonary disease (COPD), including emphysematous bronchitis; and asthma. To refine the assessment, the analysis was stratified by age groups: cardiovascular and oncological diseases were analyzed in individuals over 40 years old, influenza and pneumonia in those over 60, pneumonia in children under five, and asthma in individuals under 15.

These findings underscore the severe economic and public health consequences of air pollution-related diseases, reinforcing the need for stringent air quality policies and emission control measures. Without effective intervention, diesel truck emissions will continue to strain Brazil's healthcare system, leading to escalating costs and worsening health outcomes for vulnerable populations.

Social, Racial and Environmental Inequities in Pollution Exposure

The burden of air pollution from heavy-duty trucks in Brazil disproportionately affects communities located near major transportation corridors, including highways, logistics hubs, and port cities. These areas, often home to low-income populations, experience not only heightened exposure to harmful pollutants but also socio-economic vulnerabilities that exacerbate health risks.

Research indicates that approximately 72% of Brazil's poor reside in urban areas, often in neighborhoods with inadequate infrastructure, limited public transportation, and restricted access to healthcare services (UN-Habitat, 2006). In cities such as Rio de Janeiro, marginalized populations, particularly Black and low-income residents, are more likely to live in proximity to major roadways and industrial zones, leading to significantly higher exposure to diesel emissions from freight transport (Barata, 2024).

Similarly, São Paulo's low-income neighborhoods experience disproportionately high concentrations of nitrogen oxides (NO_x) and fine particulate matter ($PM_{2.5}$), given their proximity to major freight corridors where diesel truck activity is concentrated (Pérez-Martínez et al., 2017). Port cities such as Santos exemplify the direct link between freight transport emissions and respiratory illnesses; research has found a significant correlation between transport related NO_x concentrations and increased cases of bronchitis and emphysema among residents near the port (Bauer, Barbosa De Oliveira-Sales, et al., 2024; Bauer, Oliveira-Sales, et al., 2024))

A study conducted by da Motta Singer et al. (2023) highlights the socioeconomic disparities in exposure to urban air pollution in São Paulo, Brazil. The research examined black carbon accumulation in the lungs of 604 deceased individuals as a proxy for PM10 exposure, revealing that individuals from lower-income areas consistently faced higher pollution exposure. The study found that traditional air quality monitoring systems tend to underestimate exposure for marginalized populations, with misclassification increasing by 0.028 units per 0.1 decrease in socioeconomic status. This underestimation is particularly concerning, as individuals from lower-income backgrounds often experience longer daily commutes, exposing them to prolonged periods of high pollution levels. The findings emphasize the disproportionate environmental burden borne by socioeconomically disadvantaged communities, while also raising concerns about the accuracy and equity of official air quality monitoring. By failing to capture the full extent of exposure among vulnerable populations, these monitoring gaps may hinder the development of targeted policies and interventions aimed at reducing health risks associated with air pollution (Da Motta Singer et al., 2023)

Racial and economic inequalities also significantly amplify the disproportionate exposure to air pollution in Brazil. A growing body of research highlights the link between weather variability, urban design, and socio-economic disparities in air quality. The combination of unfavorable climate conditions, poor urban planning, and economic segregation leaves lower-income populations with greater exposure to pollutants.

20 – 30% lower than usual

NO_2 levels were observed during the 2018 truck drivers' strike, particularly in areas with high traffic density, according to a study analysing nitrogen dioxide (NO_2) concentrations—a key pollutant emitted by diesel engines

Case Study: Impact of the 2018 Truck Drivers' Strike on Air Quality in Brazil

In May 2018, Brazil experienced a nationwide truck drivers' strike that lasted from May 21st to 31st, leading to an unprecedented reduction in truck activity. With the abrupt halt of freight movement, air pollution levels dropped significantly, offering a unique opportunity to assess the environmental impact of heavy-duty diesel trucks. This period became a natural experiment, enabling researchers to evaluate how reducing truck emissions could improve air quality and public health. By analysing pollutant concentrations before, during, and after the strike, multiple studies have confirmed the substantial contribution of heavy-duty trucks to urban air pollution and its broader implications for policy and public health.

Air Quality Improvements in São Paulo

São Paulo, Brazil's largest metropolitan area, exhibited marked improvements in air quality during the strike. A study analysing nitrogen dioxide (NO_2) concentrations—a key pollutant emitted by diesel engines—found that NO_2 levels were 20–30% lower than usual, particularly in areas with high traffic density (Debone et al., 2020). This decline underscores the significant role of diesel freight emissions in degrading urban air quality. Additionally, fine particulate matter ($PM_{2.5}$) levels also dropped, leading to an overall improvement in air quality and a reduction in respiratory risks for vulnerable populations. The immediate rebound of pollution levels after truck circulation resumed further demonstrated the dominant contribution of diesel freight transport to urban pollution in São Paulo (Chiquetto et al., 2021).

Reductions in PM_{10} in Limeira and Campinas

Similar findings were observed in Limeira and Campinas, two cities in southeastern Brazil with significant freight traffic. A study focusing on PM_{10} concentrations found that pollution levels were 20% lower during the strike, particularly during peak traffic hours. The temporary reduction in freight activity during the strike immediately improved air quality, but once normal truck circulation resumed, pollution levels quickly rebounded, highlighting the sustained impact of diesel trucks on air pollution in industrialised and logistics-heavy regions (Nogarotto et al., 2022).

Health and Economic Benefits

Beyond immediate air quality improvements, researchers also examined the health and economic implications of reduced truck emissions. A health impact study estimated that the lower PM_{10} levels during the strike could have prevented up to 81 cases of pollution-related illnesses, including respiratory infections and cardiovascular diseases. Additionally, the reduction in airborne pollutants was linked to lower hospitalisation rates, particularly for children and the elderly, two groups most vulnerable to air pollution exposures. The economic benefits of improved air quality during the strike were also substantial. In monetary terms, the temporary reduction in truck emissions translated into millions of dollars in potential public health savings. These findings highlight the often-overlooked costs associated with diesel truck pollution, from medical expenses to lost productivity due to pollution-related illnesses (Debone et al., 2020)

The dramatic improvements in air quality during the strike reinforce the urgency of rethinking Brazil's reliance on diesel-powered freight transport. As the country considers policies to meet sustainability goals and public health targets, the lessons from this natural experiment should inform future transportation strategies. The evidence suggests that a cleaner and more efficient freight system is not only environmentally necessary but also economically beneficial.

What if the health benefits found in São Paulo were applied to other Brazilian regions?

Building on these insights, we explored how the health benefits observed in São Paulo could extend to other Brazilian cities. Using the methodology proposed by (Debone et al., 2020), we estimated the number of avoidable deaths across multiple cities, leveraging baseline all-cause mortality rates from the Brazilian Health System Database (DATASUS).

To extrapolate avoidable deaths to additional regions, we applied the percentage reductions of deaths observed in the original study. This ratio quantifies the proportion of total mortality attributable to air pollution and, by extension, the fraction of deaths that could be prevented with reduced emissions from heavy-duty trucks. This yielded an indicator of the impact of truck emissions on mortality. Next, this ratio was applied to mortality data from other Brazilian cities to estimate the potential health benefits of pollution reduction, under the assumption that the relationship between air pollution exposure and mortality follows a similar trend across urban areas.

Given that heavy-duty truck emissions are a major contributor to air pollution, areas near highways, ports, and logistics hubs were prioritised in the extrapolation, as shown in Table 1. Notably, São Paulo, Rio de Janeiro, and Belo Horizonte had the highest estimated avoidable deaths, reflecting their large populations, high traffic density, and industrial activity. Additionally, port cities such as Santos, Belém, and Paranaguá, as well as logistics hubs like Campinas, Fortaleza, and Curitiba, also showed significant impacts. Cities located along major freight corridors, such as Feira de Santana, Rondonópolis, and Vitória da Conquista, further highlight the strong link between air pollution and mortality in regions heavily influenced by transportation emissions. The assumption is that these regions would have experienced similar pollution reductions under comparable scenarios, leading to proportional health benefits.

The results revealed a significant potential national impact, particularly in regions with high exposure to emissions from heavy-duty trucks.

The analysis estimated 4,196 potential avoidable deaths in 2017, distributed across the selected cities with key transport and industrial hubs. São Paulo had the highest number of avoidable deaths (905), followed by Rio de Janeiro (621) and Recife (219), reflecting the influence of major metropolitan areas with intense vehicular traffic and industrial activities. Port cities such as Santos (66), Belém (124), and Paranaguá (11) also exhibited considerable potential impacts, reinforcing the role of logistics corridors in pollution-related mortality. Cities along major highways, such as Feira de Santana (33) and Rondonópolis (15), similarly showed substantial potential health benefits. Results are summarised in Table 1.

This study provides an evidence-based assessment of the potential national health benefits of air pollution reduction by extrapolating results from São Paulo to other Brazilian cities. While the current methodology does not directly quantify these localised effects, the results serve as an indicator of the health impacts that could have been experienced in those regions.

TABLE 1 - POTENTIALLY AVOIDABLE DEATHS ASSOCIATED WITH HEAVY-DUTY TRUCK EMISSIONS IN KEY BRAZILIAN TRANSPORT HUBS

Regions	Deaths (2017)	Avoidable Deaths	Highways Information
North			
AMAZONAS			
Manaus	4119	82	(BR-174) – Industrial and logistics hub
PARÁ			
Belém	6201	124	(BR-316, BR-010) – Port city
Marabá	505	10	(BR-222) – Mining transport hub
Santarém	860	17	(BR-163) – Soy export corridor
RONDÔNIA			
Porto Velho	1257	25	(BR-364) – Agribusiness and transport hub
Northeast			
BAHIA			
Salvador	7676	154	(BR-324) – Major port city
Feira de Santana	1636	33	(BR-116, BR-101) – Strategic truck stop
Vitória da Conquista	1271	25	(BR-116) – Key inland logistics hub
CEARÁ			
Fortaleza	9841	197	(BR-116) – Major industrial and logistics center
MARANHÃO			
São Luiz	3958	79	(BR-135) – Key port for agribusiness exports
PERNAMBUCO			
Recife	10972	219	(BR-101, BR-232) – Logistics and industrial hub
Caruaru	1978	40	(BR-232) – Major distribution center

Central-West

DISTRITO FEDERAL			
Brasília	6647	133	(BR-040, BR-060) National transport convergence point
GOIÁS			
Goiânia	5917	118	(BR-153) – Logistics hub in Central-West
Anápolis	1555	31	(BR-153) – Major distribution center
Rio Verde	605	12	(BR-060) – Strong agribusiness sector
MATO GROSSO			
Cuiabá	2269	45	(BR-364, BR-163) – Transport huab for agriculture
Rondonópolis	725	15	(BR-163) – Major grain logistics center
Sinop	298	6	(BR-163) – Agribusiness center
Sorriso	209	4	(BR-163) – Largest soybean producer in Brazile
MATO GROSSO DO SUL			
Campo Grande	3407	68	(BR-262, BR-163) – Central transport hub
Dourados	988	20	(BR-163) – Important agribusiness city

Southeast

ESPÍRITO SANTO			
Vitória	1799	36	(BR-101) – Port and industrial area
Cariacica	650	13	(BR-262) – Major logistics zone
MINAS GERAIS			
Belo Horizonte	9081	182	(BR-381, BR-040) – Logistics hub
Uberlândia	864	17	(BR-050) – Agribusiness distribution center
Contagem	1258	25	(BR-381) – Industrial zone
Betim	2491	50	(BR-381) – Major automotive and logistics hub
Juiz de Fora	2088	42	(BR-040) Strategic transport link between Southeast and Northeast
RIO DE JANEIRO			
Rio de Janeiro	31044	621	(BR-101, BR-116, BR-040) – Logistics and port hub
Volta Redonda	1218	24	(BR-393) – Steel industry center

SÃO PAULO			
São Paulo	45248	905	(BR-116, BR-381, SP-330, SP-348, Rodoanel)
Campinas	4692	94	(SP-330, SP-348) – Major logistics hub
São José dos Campos	2071	41	(BR-116, SP-070) – Aerospace and industrial area
Sorocaba	2508	50	(SP-280, BR-374) – Industrial zone
Ribeirão Preto	3224	64	(SP-330) – Agribusiness hub
Santos	3300	66	(SP-150) Major port city, destination for truck traffic
South			
PARANÁ			
Curitiba	6096	122	(BR-116, BR-376) Major logistics and industrial hub
Londrina	2646	53	(BR-369) – Agricultural transport hub
Maringá	1678	34	(BR-376) – Grain production corridor
Paranaguá	543	11	(BR-277) – Key port city for export
RIO GRANDE DO SUL			
Porto Alegre	7390	148	(BR-290, BR-116) – Regional logistics hub
Caxias do Sul	1537	31	(BR-116) – Industrial and transport hub
Pelotas	1918	38	(BR-116) – Key link for southern transport
SANTA CATARINA			
Blumenau	1106	22	(BR-470) – Industrial zone
Joinville	1642	33	(BR-101) – Industrial and logistics hub
Itajaí	798	16	(BR-101) – Major port for container transport
Total	**209784**	**4196**	

3. BIODIESEL AND ALTERNATIVE FUELS: THE ROLE AND LIMITATIONS OF BIOFUELS IN BRAZIL'S TRANSPORT SECTOR

77 billion litres

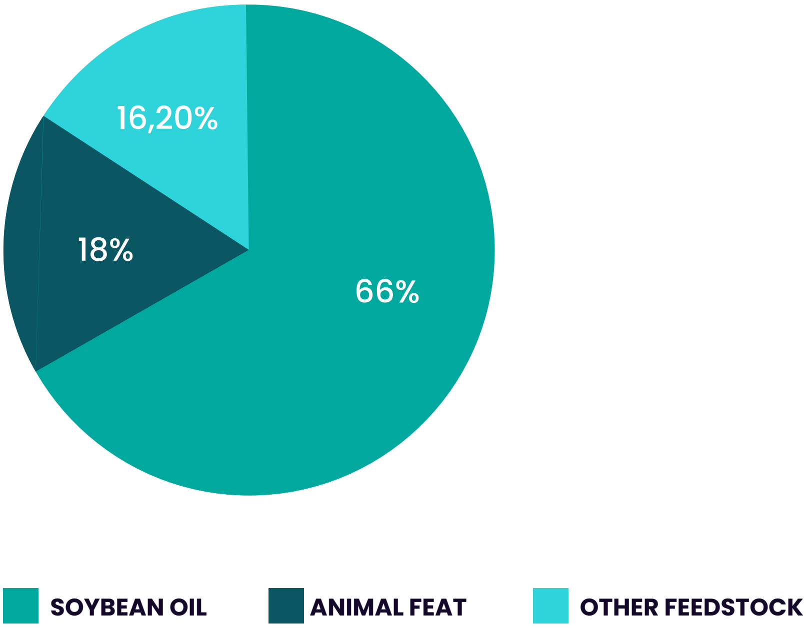
of biodiesel were produced over two decades through the program, preventing the emission of 240 million tons of CO_2 and saving approximately USD 38 billion in diesel imports.

As Brazil seeks to enhance efficiency and reduce emissions in its freight transport sector, alternative fuels have become an integral part of the national strategy. With one of the world's largest biofuel industries, Brazil has long promoted biodiesel, biomethane and ethanol to diversify its energy mix and lessen its dependence on fossil fuels (IEA Bioenergy, 2023). The country's abundant agricultural resources, coupled with robust government policies, have historically positioned biofuels at the forefront of efforts to achieve fuel diversification and lower emissions. Nonetheless, despite ambitious programs such as RenovaBio and the Future Fuels Program, uncertainties persist regarding the long-term sustainability and effectiveness of biofuels. Critical issues—such as land use, deforestation, food security, and full life-cycle emissions accounting—continue to foment debates about whether biofuels can serve as a viable long-term alternative to fossil fuels. At the same time, while Brazil remains heavily invested in biofuels, other global economies are increasingly prioritising vehicle electrification and efficiency improvements, thereby challenging Brazil's emphasis on biofuel expansion as the primary pathway for decarbonization (International Council of Clean Transportation (ICCT), 2018).

Biodiesel, in particular, has been widely adopted in Brazil through mandatory blending policies. By 2021, the biodiesel blend mandate had reached 13% (B13), with the government's initial plans to increase to 15% (B15) (Ministry of Mines and Energy, 2021). The current blend mandate is 14% in 2025. Brazil's National Biodiesel Production and Use Program (PNPB), established in 2004, has significantly advanced the biodiesel industry, leading to reduced petroleum imports and bolstering domestic agriculture. Over two decades, the program facilitated the production of 77 billion litres of biodiesel, preventing the emission of 240 million tons of CO2 and saving approximately USD 38 billion in diesel imports. However, challenges persist regarding feedstock dependency and environmental impacts, necessitating ongoing evaluation and adaptation of the program (Government of Brazil, 2025). For instance, according to the National Agency of Petroleum, Natural Gas, and Biofuels (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP)), soybean oil constituted approximately 65.8%

of Brazil's biodiesel production in 2022, followed by animal fats (16.2%) and other feedstocks (18%) (Brazil National Agency of Petroleum, Natural Gas, and Biofuels, 2022), as shown in Figure 1.

FIGURE 1. FEEDSTOCK COMPOSITION OF BIODIESEL IN BRAZIL IN 2022.



The predominance of soy-based biodiesel raises concerns about land-use expansion, deforestation, and competition with food production, especially as global demand for soy increases. Lapola et al. (2010) utilised a spatially explicit simulation model to demonstrate that indirect land-use changes associated with biofuel production could negate carbon savings, with soybean biodiesel contributing to 59% of projected indirect deforestation in Brazil (Lapola et al., 2010). Efforts to diversify feedstocks through waste-based biodiesel, used cooking oil, and algae-derived biofuels are underway but have not yet reached the scale required to supplant first-generation biodiesel. The Energy Research Company (EPE) has analysed market conditions and public policies related to sustainable aviation fuels, indicating ongoing initiatives to promote alternative biofuels; however, these alternatives have not yet achieved the necessary scale to replace first-generation biodiesel (Energy Research Company (EPE), 2024).

To address emissions concerns from biofuels, Brazil introduced RenovaBio in 2017 (Brazil Ministry of Mines and Energy, 2017), a policy designed to promote carbon efficiency in the transport sector. This program established a carbon credit trading system for biofuels, requiring fuel distributors to purchase Decarbonization Credits (CBIOs) based on the carbon intensity of the biofuels they distribute (Tiburcio et al., 2023). Despite these intentions, the effectiveness of RenovaBio remains uncertain. The program has faced several challenges, including fluctuations in CBIO prices, difficulties in enforcement, and inconsistencies in measuring carbon intensity across different biofuel production pathways (Grangeia et al., 2022). These issues have raised concerns about whether the system can provide the necessary long-term incentives for sustained decarbonization in Brazil's transport sector. Additionally, while biofuels generally produce lower tailpipe emissions than fossil fuels, questions persist regarding their full life-cycle emissions, particularly the indirect effects of land-use changes. The expansion of soy-based biodiesel production, for example, has been linked to deforestation and ecosystem degradation, offsetting some of the climate benefits biofuels were meant to provide. As a result, some experts argue that biofuels alone may not be a sufficient long-term solution for decarbonizing transport, and a broader transition toward zero-emission technologies such as electrification, may be necessary (International Energy Agency (IEA), 2021).

Beyond traditional biodiesel, Brazil has also initiated the Future Fuels Program (Combustível do Futuro) to promote next-generation biofuels, including ethanol-powered fuel cells, and to encourage a gradual shift toward electric mobility. This program aims to help Brazil maintain its competitive advantage in biofuels while integrating electrification into its transport mix where feasible (Brazil Ministry of Mines and Energy, 2024a) . A key area of focus is the development of ethanol-powered fuel cells—a technology advanced in collaboration with Brazilian research institutions and international automakers—which offers the possibility of generating electricity from ethanol. Proponents argue that this technology could serve as an alternative to battery-electric vehicles, particularly in regions where charging infrastructure is limited (União da Indústria de Cana-de-Açúcar (UNICA), n.d.). However, the rapid improvements in battery efficiency and the falling costs of renewable energy globally cast doubt on whether ethanol fuel cells can ultimately compete with direct electrification.

Data from 2023 indicate that Brazil's biodiesel production exceeded 7.5 billion liters—a 20.9% increase from the previous year—with projections for 2024 estimating production will rise to 8.9 billion liters, representing an 18% increase (Brazil Ministry of Mines and Energy, 2023). Furthermore, new legislation—commonly referred to as the "Fuel of the Future" bill, signed in October 2024—mandates a gradual increase in biodiesel blending, targeting a 25% blend by 2035, up from the current 14% (Brazil Ministry of Mines and Energy, 2024a). On the investment front, major industry players are also driving the transition; for example, Grupo Potencial recently announced an investment of approximately 600 million reais (around US$108.9 million) to expand its biodiesel plant in Paraná state, increasing annual production capacity from 900 million liters to 1.62 billion liters and positioning it as the world's largest soy oil–based biodiesel facility (Reuters, 2024a). Additionally, the Brazilian Association of Vegetable Oil Industries (ABIOVE) anticipates total investments of roughly 52.5 billion reais by 2030, with plans to construct at least 10 new biodiesel plants and expand existing facilities (ABIOVE, n.d.). These developments underscore the role of both government policy and industry investments in driving the transition while also highlighting challenges such as feedstock competition and environmental sustainability.

Despite the historical reliance on biofuels, the potential for full decarbonization of Brazil's heavy-duty transport sector will likely require a shift beyond biofuels toward zero-emission technologies. Although biofuels can reduce certain emissions compared to diesel, they still produce tailpipe pollutants—including particulate matter and nitrogen oxides—that pose risks to public health. Moreover, the resource-intensive nature of biofuel production, which demands significant agricultural inputs, may lead to unsustainable competition with food production and contribute to deforestation. As technological advancements in electric trucks, battery storage, and hydrogen fuel cells continue to accelerate, Brazil faces a strategic crossroads: whether to continue emphasizing biofuels as the primary pathway for transport decarbonization or to diversify its approach to align with global trends favoring low-carbon electrification.

The Environmental and Socio-Economic Implications of Soy-Based Biodiesel in Brazil

Brazil's biofuels sector has long been hailed as a cornerstone of the nation's strategy to diversify its energy mix and reduce fossil fuel dependence. In particular, biodiesel has been widely promoted due to Brazil's extensive agricultural resources and well-established production systems. However, the predominance of soy-based biodiesel now raises significant concerns about land-use expansion, deforestation, and the potential competition with food production, especially as global demand for soy continues to rise.

Soybean cultivation in Brazil is not solely driven by domestic energy policies but also by international market forces. As the largest global producer and exporter of soy, Brazil has seen its soy acreage expand rapidly to meet the surging demand for animal feed and biofuel production. This expansion has been linked to direct and indirect deforestation—particularly in biomes such as the Amazon and the Cerrado. The planned expansion of soybean biofuel plantations could lead to significant indirect deforestation, with long payback periods for carbon savings. Recent supply chain transparency data indicate that while direct deforestation linked to soy in the Amazon has been reduced—thanks in part to voluntary measures like the Soy Moratorium—the Cerrado remains highly vulnerable to land conversion (Reuters, 2024b; Stockholm Environment Institute, 2022). The environmental trade-offs of soy-based biodiesel are further exacerbated by global market pressures. Rising international demand—particularly from major importers like China and the European Union—has led to increased land speculation and conversion (European Comission, 2025). As prices for soy escalate, producers are incentivized to clear additional land, often encroaching upon areas that were previously preserved for food production or natural ecosystems. This trend not only heightens the risk of deforestation but also intensifies competition between biofuel production and food security.

Brazil's government policies have played a crucial role in shaping the biofuels landscape. Blending mandates have significantly boosted biodiesel production, yet they have also reinforced reliance on soybean oil. While biodiesel from soy offers a renewable alternative to fossil diesel and contributes to energy independence, its environmental footprint is not negligible. The heavy reliance on soy-based feedstock is now under scrutiny due to its association with indirect land-use changes, which may negate some of the greenhouse gas benefits of biofuels.

In summary, while soy-based biodiesel remains a key component of Brazil's renewable energy portfolio, its environmental and socio-economic implications are complex. As global demand for soy continues to grow, there is an urgent need for robust policy interventions and market-based mechanisms that not only enhance supply chain transparency but also safeguard native vegetation and ensure that biofuel production does not come at the expense of food security and ecosystem integrity. Addressing these challenges will require coordinated efforts among policymakers, industry stakeholders, and international partners to promote sustainable agricultural practices, enforce deforestation safeguards, and diversify energy solutions toward truly low-carbon alternatives.

Estimating Land Requirements for Soy-Based Biodiesel Production in Brazil: Current Use, Future Projections, and Comparisons with Food Crops

Brazil currently consumes approximately 40 billion liters of diesel annually (Brazil Ministry of Mines and Energy, 2024b). Under the current 14% biodiesel blend mandate, this translates to roughly 5.6 billion liters of biodiesel produced each year. However, because only about 70% of Brazil's biodiesel is derived from soybean oil, the actual volume of soybean-based biodiesel is approximately 3.92 billion liters per year. With an average yield of 400 liters of biodiesel per hectare from soybean-based feedstocks, this level of production requires around 9.8 million hectares of soy. This area accounts for about 26.5% of Brazil's total soybean cultivation area, which is estimated at 46 million hectares (EMBRAPA, 2024). For context, staple food crops such as rice, wheat, and beans are grown on a combined area of about 6.1 million hectares, meaning that the land used for soybean-based biodiesel production is nearly 7.5 times larger than that used for these key food crops.

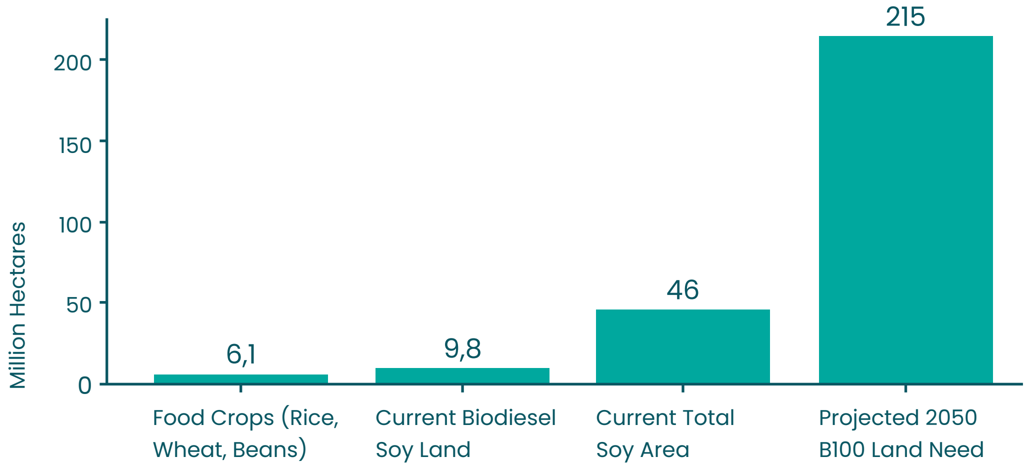
Looking ahead to a future scenario in which Brazil fully transitions to B100 biodiesel by 2050, it is assumed that diesel consumption will grow at an annual rate of 3.9% (Machado et al., 2020) from 2030 to 2050. Under this growth

25.3%

of Brazil's total land area would be required for a complete transition to B100 biodiesel using soy-based feedstocks, representing a massive scaling challenge.

rate, the annual diesel consumption is projected to increase from 40 billion liters to approximately 86 billion liters by 2050. In a full B100 transition scenario, this entire 86 billion liters of diesel would be replaced by biodiesel. At the same yield of 400 liters per hectare, producing 86 billion liters of biodiesel would require about 215 million hectares of land. This represents an increase of roughly 205 million hectares compared to current soybean-based biodiesel production. To put this in perspective, 215 million hectares is about 4.7 times the current total soybean cultivation area of 46 million hectares and constitutes approximately 25.3% of Brazil's total land area of 850 million hectares. The bar graph in Figure 2 presents these disparities.

FIGURE 2. LAND USE COMPARISON: CURRENT VS 2050 B100 SCENARIO



These calculations illustrate the massive scaling challenge that a complete transition to B100 biodiesel using soy-based feedstocks would entail. The dramatic increase in land requirements underscores the critical need for sustainable intensification, significant yield improvements, and the strategic use of previously deforested or degraded lands. Such measures are essential to mitigate adverse environmental impacts and ensure that food security is not compromised.

Case Study: Economic Analysis of the implementation of new technologies in the State of São Paulo

Researchers from Imperial College London and the University of São Paulo (Machado et al., 2020) conducted a comprehensive assessment of greenhouse gas (GHG) and pollutant emissions in São Paulo's road freight transport sector under different scenarios. The study, using the Low Emissions Analysis Platform (LEAP) model (Stockholm Environment Institute, 2025) to estimate emissions from fuel combustion in vehicles (demand-side emissions), fuel production and processing (transformation emissions), and imported fuel emissions, particularly for scenarios dependent on external fuel sources. The model integrates multiple inputs, including fleet composition and transitions across scenarios, emission factors for each vehicle type, and the energy source mix for electricity-based alternatives. Additionally, it accounts for vehicle survival rates and degradation factors over time to ensure an accurate representation of real-world emissions.

The analysis contrasts a Baseline Scenario, where diesel trucks remain dominant until 2050 without significant investment in alternative fuel infrastructure, against Alternative Technology Scenarios, in which cleaner technologies progressively replace diesel vehicles from 2030 onwards. These alternatives include Liquified Natural Gas (LNG), Compressed Natural Gas (CNG), biodiesel, hybrid diesel, hydrogen fuel cell electric, and battery electric trucks, with the assumption of infrastructure expansion to support fuel supply.

The study models Brazil's truck fleet evolution and emissions by incorporating projections for energy system evolution and economic growth. Fleet growth follows GDP trends, while São Paulo's electricity mix remains predominantly renewable (~60% hydropower). The study assumes crude oil refining capacity will remain unchanged until 2050. Additionally, it includes an annual 3.9% increase in biodiesel production capacity and a steady expansion of renewable electricity generation from hydropower, wind, and solar sources.

Scenario-Specific Assumptions

The baseline scenario assumes a diesel-dominated fleet until 2050, whereas alternative pathways introduce battery electric (BEV), hydrogen fuel-cell (FCEV), hybrid diesel-electric, liquefied natural gas (LNG), compressed natural gas (CNG), and biodiesel as substitutes. Each scenario accounts for fuel infrastructure expansion, shifts in energy production, and reductions in crude oil refining demand, as seen in Table 2.

This framework provides a strategic basis for evaluating emissions reductions, infrastructure needs, and policy interventions required for freight decarbonisation in São Paulo.

The transition to low-emission truck technologies in São Paulo's freight sector can have significant implications for air quality and climate change mitigation. Table 3 and 4 summarize the expected pollutant reductions for different fuel and powertrain options compared to a diesel baseline, providing insights into both short-term (2030) and long-term (2050) effects. The pollutants considered in the study are GHG, NO_x, $PM_{2.5}$, CO, HCs.

TABLE 2- SUMMARY OF THE MAIN ASSUMPTIONS FOR EACH SCENARIO

Scenario	Fleet sales	Crude Oil Refining	Biodiesel Share	Electricity Generation	Natural Gas Infrastructure
Diesel Baseline	100% diesel until 2050	No increase	Gradual B20 by 2050 (+3.9% per year)	No change	No change
Battery Electric (BEV)	100% electric by 2030	Large decrease	No change	Electricity demand increases significantly, requiring grid expansion and investment in charging infrastructure	No change
Hydrogen Fuel-Cell (FCEV)	100% hydrogen fuel-cell by 2030	Decrease	No change	Minor increase for hydrogen production	Hydrogen plants added in São Paulo from 2030
Hybrid Diesel-Electric	50% hybrid, 50% diesel by 2030	Moderate decrease	B30 by 2050 (+3.9% per year)	No change	No change
Liquefied Natural Gas (LNG)	100% LNG by 2030	Moderate decrease	No change	No change	LNG plants built from 2030
Compressed	100% CNG by 2030	Moderate decrease	No change	No change	CNG processing expands by 2040 (+10 million m^3/day)
Biodiesel	100% biodiesel (B100 by 2050)	No decrease	B100 by 2050 (+3.9% per year)	No change	No change

TABLE 3 - PERCENT REDUCTION IN POLLUTANTS IN 2030 AND 2050 PER SCENARIO. NEGATIVE VALUES REPRESENT REDUCTIONS IN EMISSIONS, WHILE POSITIVE VALUES REPRESENT INCREASES

Scenario	Year	GHG (%)	NO_x (%)	$PM_{2.5}$ (%)	CO (%)	HCs (%)
Battery Electric	2030 2050	-30% -46%	-15% -30%	-30% -43%	-11% -21%	-70% -89%
Fuel-Cell Electric	2030 2050	-15% -27%	-5% -10%	-15% -26%	-10% -19%	-65% -80%
Hybrid Diesel	2030 2050	-4% -8%	-12% -23%	-20% -30%	-9% -18%	-15% -30%
LNG	2030 2050	-1% -1%	5% 10%	-20% -30%	15% 30%	10% 20%
CNG	2030 2050	20% 35%	2% 5%	-8% -15%	38% 76%	5% 10%
Biodiesel	2030 2050	1% 2%	5% 10%	10% 20%	500% 1000%	25% 50%

TABLE 4 - ABSOLUTE CHANGES IN 2030 AND 2050 (IN TONS). NEGATIVE VALUES REPRESENT REDUCTIONS IN EMISSIONS, WHILE POSITIVE VALUES REPRESENT INCREASES

Scenario	Year	GHG (tons)	NO_x (tons)	$PM_{2.5}$ (tons)	CO (tons)	HCs (tons)
Battery Electric	2030 2050	-3,584,400.0 -5,496,080.0	-1,647.6 -3,295.2	-29.1 -41.7	-122.5 -245.0	-67.9 -86.4
Fuel-Cell Electric	2030 2050	-1,792,200.0 -3,224,000.0	-549.2 -1,098.4	-14.6 -25.2	-116.7 -221.6	-63.1 -77.7
Hybrid Diesel	2030 2050	-477,920.0 -955,840.0	-1,318.1 -2,525.3	-19.4 -29.1	-105.0 -210.0	-14.6 -29.1
LNG	2030 2050	-59,740.0 -119,480.0	549.2 1,098.4	-19.4 -29.1	175.0 350.0	9.7 19.4
CNG	2030 2050	2,389,600.0 4,181,800.0	219.7 549.2	-7.8 -14.6	443.3 886.0	4.9 9.7
Biodiesel	2030 2050	119,480.0 238,960.0	549.2 1,098.4	9.7 19.4	5,832.6 11,665.2	24.3 48.5

Economic analysis of alternative scenarios

Large-scale investment in charging infrastructure and electricity grid capacity remains a key challenge to their deployment. Building on the emissions assessment of alternative truck technologies proposed by (Machado et al., 2020), this session conducts an economic analysis to evaluate the economic, environmental, and health impacts benefits of transitioning São Paulo's road freight sector toward cleaner technologies. By quantifying both the financial benefits and emission changes, this analysis provides a framework to support decision-making. The study employs damage functions to estimate the societal gains from improved air quality and reduced climate impacts, linking lower emissions to avoided health risks, productivity losses, and environmental degradation.

This analysis quantifies the economic benefits of emission reductions in São Paulo by adapting internationally recognized damage functions to reflect local conditions. These adjustments account for Brazil-specific economic factors, public health impacts, population exposure, and infrastructure differences, leading to a more accurate estimation of benefits. Using an impact analysis framework, the study translates changes in emissions—namely greenhouse gases (GHG), nitrogen oxides (NO_x), fine particulate matter ($PM_{2.5}$), carbon monoxide (CO), and hydrocarbons (HCs)—into costs related to healthcare, productivity losses, and environmental degradation. This approach offers a comprehensive assessment of the long-term financial impacts from alternative freight transport technologies.

Damage Costs

The economic impact of emissions reductions was estimated using internationally recognized damage functions—adjusted for Brazil—and expressed in 2024 R$ values. The original damage cost estimates were derived from sources like the U.S. Environmental Protection Agency (EPA, 2023) the World Bank (World Bank, 2022), and the Organisation for Economic Co-operation and Development (OECD, 2012). Since direct damage cost estimates for carbon monoxide (CO) and hydrocarbons (HCs) are unavailable, a scaling approach was applied using pollutants with similar health and environmental impacts. For example, CO's damage cost was estimated as 15% of NO_x's cost based on studies suggesting that CO has roughly 10–20% of NO_x's health impact—primarily affecting respiratory diseases. Similarly, the damage cost for HCs was approximated at 15% of that for fine particulate matter ($PM_{2.5}$), because certain hydrocarbons, such as benzene, contribute to particulate matter formation and are linked to long-term cancer risks rather than to acute respiratory issues (WHO, 2004). These scaling factors were chosen based on comparative risk assessments to approximate damage costs.

These values were adjusted for Brazil using income elasticity, urban pollution exposure, healthcare cost ratios, and epidemiological data.

Methodology for Monetized Damage Costs in Brazil

To accurately estimate the economic benefits of emissions reductions in São Paulo's road freight sector, this study adjusts internationally recognised damage cost functions to reflect Brazil's economic, environmental, and public health conditions. The analysis incorporates income elasticity, urban exposure, healthcare costs, currency conversion, and economic growth projections to ensure reliable valuations for 2024, 2030, and 2050.

Economic willingness to pay (WTP) for pollution reduction is linked to GDP per capita. Since Brazil's GDP per capita is lower than the OECD average, an adjustment must be made. In 2023, Brazil's GDP per capita was estimated at $9,032 (World Bank, 2024a), while the OECD average GDP per capita was $30,490 (World Bank, 2024b). The difference in income levels requires a correction factor to align damage cost estimates with Brazil's economic reality.

Income elasticity assumptions for environmental valuation were derived from existing literature. The income elasticity factor varies by pollutant, with carbon dioxide (CO_2) assigned a factor of 1.50, nitrogen oxides (NO_x) at 1.10, particulate matter ($PM_{2.5}$) at 1.30, carbon monoxide (CO) at 1.20, and hydrocarbons (HCs) at 1.10. These factors ensure that damage cost estimates scale appropriately based on income differences between Brazil and higher-income countries where original damage cost functions were developed.

Since economic conditions, willingness to pay, and healthcare costs evolve over time, the values were further adjusted to account for projected economic and inflationary trends. Brazil's GDP is expected to grow at an annual rate of 2.3% between 2024 and 2050, reflecting economic expansion. Simultaneously, inflation is projected at 3.8% per year over the same period, requiring adjustments to maintain the real value of estimated costs in future years.

The adjustment formula:

$$\text{Damage Cost}_{BR} = \text{Damage Cost}_{OECD} \times \left(\frac{GDP_{pc,BR}}{GDP_{pc,OECD}} \right)^{\text{Income Elasticity}} \times [(1 + GDP_{Growth})(1 + Inflation)]^{tt}$$

Where

- tt , years from 2024 (6 years for 2030, 26 years for 2050)
- GDP_{Growth} Rate = 2.3%
- *Inflation* Rate = 3.8%

Applying these factors, we obtain the damage costs in 2030 and 2050, as shown in Table 5.

TABLE 5 - DAMAGE FUNCTIONS CALCULATED FOR BRAZIL IN 2030 AND 2050, EXPRESSED IN 2024 R$ VALUE

Pollutant	Original Cost (USD/ton)	Adjusted Cost (BRL/ton, 2030)	Adjusted Cost (BRL/ton, 2050)	Source
CO_2	190	R$266.36	R$884.96	(EPA, 2023)
CH_4	2,800	R$3,925.24	R$13,041.46	(EPA, 2023)
N_2O	55,000	R$77,102.98	R$256,258.46	(EPA, 2023)
NOx	7,000	R$11,887.58	R$37,878.97	(Dang & Mourougane, 2014)
$PM_{2.5}$	30,000	R$43,512.69	R$146,509.09	(World Bank, 2022)
CO	1,050	R$6,456.32	R$20,569.98	Scaled from NOx
HCs	4,500	R$6,188.30	R$19,723.63	Scaled from $PM_{2.5}$

Since the emission data available report only total greenhouse gas (GHG) emissions without disaggregating individual gases, we calculated a weighted average damage cost to reflect the composition of CO_2, CH_4, and N_2O in diesel-powered vehicles. Based on emission factors from (Machado et al., 2020), CO_2 accounts for approximately 99.99% of total GHG emissions, with CH_4 and N_2O contributing just 0.005% and 0.002%, respectively. These shares were used to weight the individual social cost values for each gas (expressed in 2024 BRL), as shown in Table 6. This value ensures that the monetized impacts of GHG emissions are properly accounted for even when disaggregated data are unavailable, and it was projected to 2030 and 2050 using income-adjusted growth and inflation assumptions consistent with the methodology applied to other pollutants.

The economic impacts of emissions changes are assessed by applying damage cost functions to the quantified differences in pollutant emissions—whether reductions or increases. For each scenario, the difference in emissions between the baseline (diesel) and the alternative technology is multiplied by the relevant damage function for each pollutant. This method yields a monetary estimate of the avoided harms (such as lower healthcare expenses, reduced environmental degradation, and minimized productivity losses) or the additional costs incurred due to higher emissions. All results are expressed in present value terms to account for the time value of money. The values can be summarised in the following Table 7 and 8:

TABLE 6 - DAMAGE COSTS WITH WEIGHTED GHG FUNCTION, EXPRESSED IN 2024 R$ VALUE

Pollutant	Original Cost (USD/ton)	Adjusted Cost (BRL/ton, 2030)	Adjusted Cost (BRL/ton, 2050)	Source
GHG ($CO_2 + CH_4 + N_2O$	Composite	R$267.86	R$889.36	(EPA, 2023) and emission shares in (Machado et al., 2020))
NO	7,000	R$11,887.58	R$37,878.97	(Dang & Mourougane, 2014)
$PM_{2.5}$	30,000	R$43,512.69	R$146,509.09	(World Bank, 2022)
CO	1,050	R$6,456.32	R$20,569.98	Scaled from NOx
HCs	4,500	R$6,188.30	R$19,723.63	Scaled from $PM_{2.5}$

TABLE 7: ECONOMIC AVOIDED OR ADDED COST BY POLLUTANT IN 2030 AND 2050 (IN MILLIONS, EXPRESSED IN 2024 R$ VALUE)

Scenario	Year	GHG	NOx	PM2.5	CO	HCs	Total
Battery Electric	2030 2050	-960.9 -4895.1	-19.60 -124.8	-1.30 -6.1	-0.8 -5	-0.4 -1.7	-982.9 -5032.8
Fuel-Cell Electric	2030 2050	-480.4 -2871.5	-6.5 -41.6	-0.6 -3.7	-0.8 -4.6	-0.4 -1.5	-488.7 -2922.8
Hybrid Diesel	2030 2050	-128.1 -256.3	-15.7 -38.7	-0.8 -1.3	-0.7 -1.4	-0.1 -0.3	-145.4 -298
LNG	2030 2050	-16 -106.4	6.5 41.6	-0.8 -1.3	1.1 7.2	0.1 0.4	-9.1 -58.5
CNG	2030 2050	640.9 3726.2	2.6 20.8	-0.3 -2.1	2.9 18.2	0 0.2	646.1 3763.2
Biodiesel	2030 2050	32 213.2	6.5 41.6	0.4 2.8	37.6 239.9	0.2 1	76.7 498.5

TABLE 8 - ECONOMIC AVOIDED OR ADDED COST BY POLLUTANT IN 2030 AND 2050 EXPRESSED IN 2024 R$ VALUE, EXCLUDING GHGS

Scenario	Year	Total Impact (million R$)	Total Avoided Pollutant Emissions (tons)	Impact per Ton (million R$/ton)
Battery Electric	2030 2050	-22.06 -137.67	1,867.10 3,668.30	-11.82 -37.53
Fuel-Cell Electric	2030 2050	-8.31 -51.39	743.6 1,422.90	-11.17 -36.12
Hybrid Diesel	2030 2050	-17.28 -103.23	1,457.10 2,793.50	-11.86 -36.96
LNG	2030 2050	8.27 49.87	714.5 1,438.70	11.57 34.67
CNG	2030 2050	5.19 37.04	660.1 1,430.30	7.86 25.91
Biodiesel	2030 2050	44.72 285.32	6,415.80 12,831.50	6.97 22.23

Electric Technologies: Strong Long-Term Benefits

The transition to battery-electric and hydrogen fuel-cell freight systems offers significant long-term economic and environmental benefits. As observed in the analysis of the Battery Electric scenario, the economic benefits from avoided costs (i.e., the reductions in damage to public health and the environment) increase substantially over time. Specifically, the avoided cost per ton improves from -11.82×10^3 R$/ton in 2030 to -37.53×10^3 R$/ton by 2050. Similarly, the Fuel-Cell Electric technology exhibits a comparable trend, with its avoided cost per ton increasing from -11.17×10^3 R$/ton in 2030 to -36.12×10^3 R$/ton in 2050. These findings suggest that, as these technologies mature and scale, the cumulative reduction in NO_x, $PM_{2.5}$, CO, and HCs emissions translates into greater economic savings over time. The analysis indicates that the long-term benefit per ton of avoided emissions for electric technologies improves at a higher rate compared to other vehicle alternatives. The reduction in these pollutants yields not only environmental benefits but also public health savings in the form of fewer air quality-related diseases, further contributing to the overall reduction in economic costs associated with road freight emissions.

However, The joint policy paper "*Décarboner le transport routier de marchandises*", published in March 2025 by France's Conseil d'Analyse Économique (CAE) and Germany's Sachverständigenrat zur Begutachtung der gesamtwirtschaftlichen Entwicklung (GCEE), presents a clear position on the future of freight decarbonization in Europe. The report recommends prioritizing battery-electric trucks (BETs) as the main technological solution, citing their current cost-effectiveness, operational readiness, and alignment with the evolving structure of freight logistics. It emphasizes that BETs have already achieved total cost of ownership parity with diesel trucks in France and Germany, and that public investment should focus on rapidly deploying megawatt-scale charging infrastructure along major corridors. In contrast, hydrogen fuel cell trucks receive notably less support in the report, not because they are without potential, but because their deployment faces significant hurdles related to cost, energy efficiency, and infrastructure feasibility.

The document's cautious stance on hydrogen reflects a broader shift in European policy and market expectations. While hydrogen was once considered a promising alternative for long-haul freight, recent assessments—including those in our own analysis—show that real-world emission reduction benefits and economic performance are increasingly favoring electric drivetrains. In particular, our data demonstrate that battery-electric and fuel-cell technologies initially performed similarly in cost per ton of avoided emissions, but these findings are rooted in assumptions that are already evolving. Infrastructure costs, energy input requirements, and the limited availability of green hydrogen are altering the comparative landscape. The CAE-GCEE recommendation reflects this dynamic context: it is not a rejection of hydrogen, but an evidence-based prioritization of the most feasible path forward under current and foreseeable conditions. This reinforces the need to continually reassess scenario-based analyses as technologies mature and policy environments shift (CAE & GCEE, 2025).

From a policy perspective, these results strongly advocate for the strategic allocation of resources and incentives towards the electrification of freight transport. By transitioning to battery-electric and hydrogen fuel-cell technologies, governments can not only improve environmental outcomes but also foster long-term economic resilience by mitigating the costs associated with pollutant emissions.

Hybrid Diesel: Limited Economic Benefit

The Hybrid Diesel scenario presents a mixed economic picture. The results show that the avoided cost per ton in 2030 is -11.86×10^3 R$/ton, which is comparable to the electric alternatives in the short term. However, by 2050, this benefit significantly diminishes, with the avoided cost per ton decreasing to -36.96×10^3 R$/ton. This represents a much smaller benefit compared to fully electric solutions, suggesting that the hybrid technology, while showing initial promise, does not offer the same long-term advantages as electrification.

Despite its ability to reduce emissions relative to conventional diesel, hybrid diesel does not fully capture the extensive long-term benefits realized by electric systems. The relatively modest improvement over time indicates that while hybrid solutions may serve as a transitional technology, they fall short of offering a sustainable and decarbonized freight transport solution. Consequently, policymakers should view hybrid technologies as an interim step rather than a comprehensive solution for achieving long-term decarbonization.

Fossil-Based Alternatives: Increased Economic Costs

In contrast to the more favorable performance of electric technologies, fossil-based alternatives such as LNG, CNG, and partially renewable fuels like biodiesel are associated with higher economic costs related to pollutant emissions. For example, the LNG scenario shows an impact of 34.30×10^3 R$/ton in 2030, increasing to 108.70×10^3 R$/ton by 2050. Similarly, the CNG and biodiesel scenarios present positive per-ton costs, suggesting that these fuels generate higher environmental and public health damages when compared to the diesel baseline. These results are primarily driven by continued emissions of pollutants such as NO_x, $PM_{2.5}$, CO, and hydrocarbons, which are less effectively mitigated in combustion-based technologies.

While these fuels may offer incremental improvements in specific operational contexts, the data suggest that they are less effective in reducing long-term economic and environmental burdens. If such alternatives remain part of the freight transport mix, their use may require the application of complementary control measures to manage pollutant exposure and health impacts. At the same time, the broader transition to low-emission freight solutions involves addressing several barriers—including high upfront investment, infrastructure readiness, and technology availability. In this context, electric technologies appear to provide more consistent reductions in pollutant-related costs, particularly over the longer term. These trends may be useful in guiding future planning and investment decisions related to freight decarbonization.

The Case for Electrification: Brazil's Heavy-Duty Transport Sector

The global transition towards zero-emission vehicles (ZEVs) is accelerating, driven by environmental urgency, economic opportunities, and societal benefits. Yet, Brazil's integration of zero-emission heavy-duty vehicles (HDVs) into its freight transport system remains at a nascent stage. According to the ICCT (International Council of Clean Transportation (ICCT), 2025), as of 2021, zero-emission vehicles represented only 0.1% of new medium-duty truck sales and just 0.2% of new heavy-duty truck sales in Brazil. By comparison, China reached 1.9% for medium-duty trucks and 0.8% for heavy trucks, while the European Union achieved 3.3% for medium trucks and 0.2% for heavy trucks. Even the United States, a market heavily reliant on diesel, matched Brazil's modest level of heavy truck electrification. These statistics highlight the substantial gap between Brazil and leading global markets, underscoring the need for accelerated policy interventions and targeted investments to boost adoption rates.

Looking forward, the ICCT outlines three distinct scenarios for zero-emission truck adoption in Brazil by 2050. Under the current policy trajectory, only 18% of Brazil's new truck sales would be zero-emission vehicles by mid-century. However, with enhanced political momentum and stronger policy proposals, ZEV trucks could represent approximately 37% of sales. In the most ambitious scenario—assuming full policy commitment and robust regulatory support—Brazil could achieve a 100% share of zero-emission new truck sales by 2050. These projections clearly illustrate that without significant policy shifts, Brazil's adoption of ZEV technology will remain far below the thresholds needed to achieve substantial transport-sector decarbonization.

Several key barriers currently inhibit faster electrification of heavy-duty trucks in Brazil. One of the most significant barriers is the high upfront costs associated with electric trucks, which can be 50% to 70% higher than traditional diesel-powered trucks. Additionally, Brazil's underdeveloped charging infrastructure severely constrains the feasibility of adopting zero-emission trucks for long-haul operations. The lack of a robust national policy framework or legally binding mandates to phase out diesel trucks further contributes to market uncertainty, deterring manufacturers and fleet operators from investing in zero-emission technologies. Lastly, Brazil's continued dependence on diesel—a commodity often subsidized and priced competitively—further reduces incentives for fleet operators to transition towards electric trucks, reinforcing the status quo.

Addressing the key barriers to the adoption of zero-emission freight technologies in Brazil may involve a combination of regulatory, infrastructure, and financial measures. One possible approach involves the introduction of zero-emission vehicle (ZEV) sales targets, as seen in regions such as California, the European Union, and Canada. Establishing a timeline for the gradual phase-out of new diesel truck sales—potentially by 2040—could help provide market clarity and support long-term investment planning. Infrastructure development is another important element. Public-private partnerships might facilitate the deployment of highway charging corridors and hydrogen refueling networks to ensure adequate coverage for long-haul freight operators.

In parallel, financial mechanisms such as subsidies, tax incentives, or preferential financing could help reduce the initial cost barrier associated with fleet conversion. International examples, including those from China, suggest that such instruments can play a role in accelerating the adoption of electric freight vehicles. Additionally, adjustments to existing fuel taxation frameworks, including carbon pricing or the reallocation of diesel subsidies toward low-emission infrastructure, may influence the relative economic competitiveness of zero-emission options.

Beyond overcoming these barriers, electrification of the heavy-duty transport sector offers extensive environmental, economic, and social benefits for Brazil. From an environmental perspective, zero-emission trucks produce no local pollutants, improving urban air quality and reducing related respiratory illnesses. Additionally, considering Brazil's renewable-intensive electricity grid—approximately 80% supplied by hydropower, wind, and solar (IEA, 2023)—the lifecycle greenhouse gas emissions of electric trucks are significantly lower than diesel alternatives, providing an even stronger climate mitigation benefit as the grid continues to decarbonize. Studies have shown that a heavy-duty electric truck operating in Brazil can reduce GHG emissions by over 75% compared to a diesel truck when accounting for energy use and lifecycle emissions (IEA-EPE, 2021). Additionally, the quiet nature of electric drivetrains helps reduce noise pollution in urban areas, benefiting both drivers and local residents.

Electrification also offers substantial economic advantages. Electric drivetrains convert 70–90% of battery energy into motion, compared to just 30-40% for internal combustion engines (International Council of Clean Transportation (ICCT), 2021b). This superior efficiency, combined with lower maintenance and operating costs, results in a lower total cost of ownership (TCO) over the vehicle's lifetime, as demonstrated by multiple studies in Europe (International Council of Clean Transportation (ICCT), 2023a), the United States (International Council of Clean Transportation (ICCT), 2023b), and China (International Council of Clean Transportation (ICCT), 2021a). In addition, the stability of electricity prices and reduced dependence on imported diesel further contribute to economic resilience.

Fleet operators can also achieve substantial savings by implementing smart charging strategies, which optimize electricity use and reduce costs. The ICCT reports that fleet operators utilizing smart charging systems can save up to €15,000 per year, or approximately 10%-15% of total energy costs for a fleet of ten electric trucks (International Council of Clean Transportation (ICCT), 2021b). These savings are particularly relevant in Brazil, where energy price stability is a key concern for logistics operators. Unlike diesel and biofuels, which are subject to global price fluctuations and import dependencies, electricity in Brazil is largely generated domestically from renewable sources, ensuring a stable and predictable energy supply.

Furthermore, the growth of domestic industries in battery production and electric vehicle manufacturing presents significant opportunities for job creation and technological leadership in Brazil. These benefits align with global trends in sustainable transport and position Brazil to be competitive in international markets increasingly focused on low-carbon supply chains.

Transitioning to electric freight vehicles not only promotes direct cost savings, but also unlocks broader economic opportunities. Brazil, endowed with abundant lithium and nickel deposits, is poised to become a leader in battery and EV component production (SuplyChain, 2025). By investing in domestic battery manufacturing and electric truck production, the country can reduce its reliance on imports while creating new jobs in clean technology industries. Expanding electric charging infrastructure—such as highway charging stations and smart grid upgrades—will stimulate investments in the energy sector and boost employment in infrastructure development.

Therefore, socially, the transition to electric freight vehicles also supports job creation in emerging sectors, requiring comprehensive training programs for technicians, mechanics, and logistics professionals to develop expertise in electric drivetrains, battery systems, and charging infrastructure. Workforce development is essential to ensure a smooth transition and provide stable, high-quality employment in the green economy.

Aligning Brazil's freight sector with global electrification trends will strengthen its international competitiveness, as major markets like the European Union and the United States rapidly adopt zero-emission vehicles. Early adoption will position Brazilian manufacturers and fleet operators to meet global sustainability standards. To unlock the full potential of electrification, strong policy support, strategic investments, and collaboration among government agencies, industry leaders, and energy providers are needed, including zero-emission vehicle mandates, expanded charging infrastructure, and financial incentives.

Responsible Sourcing and Recycling of Battery Minerals in Brazil: Mining, Demand, and Sustainability

As the global transition to electric vehicles (EVs) accelerates, the demand for critical battery minerals—such as lithium, nickel, cobalt, and manganese—has surged. In Brazil, a country with substantial mineral reserves and a longstanding mining tradition, the need to scale up production while ensuring environmental and social sustainability has become increasingly urgent. A number of initiatives and studies underscore the importance of responsible sourcing and robust recycling strategies to meet this demand.

According to Lead The Charge (Lead the Charge, 2023), companies must adhere to stringent environmental, human rights, and governance standards, as well as invest in technologies that enhance recycling and recovery potential. This framework provides a valuable roadmap for Brazil's mining sector as it seeks to respond to global demand while safeguarding its rich ecosystems and vulnerable communities.

In parallel, the International Council on Clean Transportation has published a detailed outlook on EV battery materials (International Council of Clean Transportation (ICCT), 2024) highlighting that the current and projected demand for these minerals will challenge existing supply chains. The report outlines that achieving sustainable growth in EV production depends not only on boosting primary extraction but also on mitigating supply risks through improved mining practices, transparent supply chains, and international collaboration.

Further complementing these perspectives, the Rocky Mountain Institute (Rocky Mountain Institute, 2024) has introduced the concept of the "Battery Mineral Loop," which advocates for a circular economy in battery production. RMI's analysis argues that enhancing recycling rates and recovering critical minerals from spent batteries could significantly reduce the pressure on primary mining operations.

In the Brazilian context, where mining operations have historically been associated with environmental challenges and social conflicts, these initiatives are especially critical. The country's regulatory authorities and industry stakeholders are increasingly aware that scaling up the production of battery minerals must be balanced with robust environmental safeguards and a commitment to responsible sourcing (Krenak, 2023).

In summary, to meet the rapidly growing demand for EV batteries while preserving its environmental integrity, Brazil must embrace responsible sourcing and recycling strategies. This means improving mining practices, enhancing supply chain transparency, and fostering a circular economy for battery minerals. With coordinated policy measures, industry-led initiatives, and international collaboration, Brazil can position itself as a key player in the sustainable energy transition while mitigating the adverse impacts of mining on its ecosystems and communities.

Global Trends and Success Stories in Heavy-Duty Truck Electrification

Global advancements in truck electrification provide a strong argument for the transition from diesel to electric vehicles, offering significant environmental, economic, and societal benefits. These advancements have been documented across multiple regions, and they offer valuable lessons for Brazil's heavy-duty transport sector as it seeks to accelerate its zero-emission vehicle (ZEV) transition.

In Germany, for instance, the "Power to the Road" initiative is underway to build a nationwide fast-charging network for heavy-duty electric vehicles. This ambitious project aims to establish 350 fast-charging sites along approximately 95% of the country's federal highways, with the goal of decarbonizing transport by 2045 (Riham Alkousaa, 2024). Germany's strategy also includes a target to power one-third of its road haulage with electric or synthetic fuels by 2030. Such a comprehensive approach not only demonstrates the technological viability of heavy-duty electrification but also underscores the critical role of coordinated public-private partnerships in building the necessary infrastructure.

Sweden offers another compelling example. Volvo Trucks is preparing to launch a new long-range version of its FH Electric truck in the second half of 2025. This new model is projected to travel up to 600 kilometers (373 miles) on a single charge—doubling the range of current electric truck models (Volvo Trucks, 2024a). The extended range addresses one of the key challenges in the heavy-duty sector, making electric trucks more suitable for interregional and long-haul transport and signaling a significant leap forward in electric truck technology.

In the United Kingdom, efforts to accelerate electrification have taken a prominent commercial form. Amazon, for example, has placed an order for over 150 electric heavy goods vehicles, including more than 140 Mercedes-Benz eActros 600 trucks and eight Volvo FM Electric trucks. With each vehicle capable of traveling approximately 500 kilometers (310 miles) on a single charge and recharging in about an hour, this initiative represents the largest zero-emission truck fleet ever established in the UK. This bold move is in line with Amazon's broader commitment to achieving net-zero emissions by 2040 and demonstrates how private-sector investment can drive progress in ZEV adoption (Chris Roe, 2024).

Meanwhile, in the United States, policy actions are also catalyzing the electrification of heavy-duty vehicles. The California Air Resources Board has implemented the Advanced Clean Trucks Regulation, which mandates a transition to zero-emission trucks and sets a goal for 100% ZEV sales by 2035. Similarly, New York State is investing heavily in incentives and charging infrastructure to promote the adoption of electric trucks for both medium- and heavy-duty segments. These regulatory and financial measures are intended to overcome high upfront costs and infrastructure gaps, and to reduce reliance on diesel—a critical component in shifting to more sustainable freight transport (New York State, 2023).

These global examples collectively illustrate that truck electrification is not only technologically feasible but also increasingly economically competitive. They emphasize the importance of robust infrastructure, supportive policies, and public-private partnerships. Moreover, these initiatives help to dispel misconceptions that electric vehicles are only as "dirty" as the power grid that charges them. In regions with a high renewable energy mix—such as Brazil, where approximately 80% of electricity is derived from renewable sources—the environmental benefits of electrification are even more pronounced. Electric trucks produce zero tailpipe emissions, thereby significantly reducing local air pollutants like nitrogen oxides (NOx) and particulate matter (PM), which are major contributors to urban smog and adverse public health outcomes (Kunak, 2023).

4. KEY MANUFACTURER CONTRIBUTIONS

Global manufacturers can play an important role in advancing truck electrification, and their international initiatives provide a range of lessons and challenges that are relevant for Brazil's heavy-duty transport sector. However, while these developments illustrate progress in certain markets, the experiences of manufacturers such as Volvo Trucks, Daimler Truck, Tesla and Scania also reveal a number of uncertainties and hurdles that need to be carefully considered.

Volvo Trucks, for example, has developed a range of electric truck models intended for urban, regional, and long-haul freight applications. The company has set a target for 50% of its global truck sales to be electric by 2030 (Volvo Trucks, 2024c). This commitment reflects both the potential for technological advancement and the market pressures for low-emission solutions. However, it is important to note that these ambitious targets depend on overcoming significant barriers such as high up-front costs and infrastructure limitations. While Volvo's plans indicate progress, their success in achieving widespread commercial adoption remains to be demonstrated. In Brazil, for instance, the company began testing ten 100% electric trucks in 2024 (Volvo Trucks, 2024b), deploying them within the logistics operations of its own industrial complex in Curitiba. Nonetheless, Volvo has not yet articulated clear plans to reach a target of 50% electric truck sales or to prioritize Brazil as a key emerging market for its electric vehicle strategy.

Daimler Truck has recently introduced the Mercedes-Benz eActros 600, a heavy-duty electric truck with an estimated range of about 500 kilometers per charge, with series production set to begin in late 2024 in Germany. In 2019, the company announced its strategy to include series-produced battery-electric vehicles in its portfolio across its main markets—Europe, the USA, and Japan—with the goal of achieving a completely CO_2-neutral fleet of new vehicles in these regions by 2039 (Daimler Trucks, 2019). With a domestic sale of 21% percent of the market share in Brazil in 2023 (HD + MD), the company is still to announce it electrification plans and targets for the Brazilian market (FENABRAVE, 2023)

Scania has focused on developing modular electric truck platforms, which can be adapted to various operational needs, including urban deliveries and regional distribution (Scania AB, 2019). This flexible approach may allow for more tailored solutions; however, market penetration in diverse operating environments remains uncertain. The effectiveness of modular designs in reducing total ownership costs and ensuring reliability across different freight applications is yet to be fully demonstrated in large-scale commercial operations.

Overall, the contributions of these key manufacturers reveal that while significant technological advancements have been made, challenges related to cost, infrastructure, and market uncertainties persist. The experiences of global manufacturers underscore that achieving widespread electrification in the heavy-duty transport sector is not solely a technical challenge but also requires coherent policy frameworks, substantial infrastructure investments, and careful economic evaluations. For Brazil, these global examples suggest that while the technological pathway for truck electrification is promising, replicating such progress will require addressing significant systemic barriers and aligning incentives across public and private sectors.

(MacDonnell, 2021) have done a Review of Commitments for Zero Emission Medium- and Heavy-Duty Vehicles as of 2021. The report highlights the main commitment, targets and strategies of the Global Manufactures, summarize in Table 9

TABLE 9: SUMMARY OF COMMITMENT TO ZERO EMISSION TARGET FOR THE TRUCK SECTOR BY THE MAIN MANUFACTURERS

Manufacturer	Target for 2040	Target for 2050
Daimler Truck	100% ZEV sales in key markets in 2039	CO_2-neutral fleet in key markets
Volvo Trucks	50% of global sales to be ZEVs	100% fossil-free vehicle sales globally
Scania	50% of global sales to be ZEVs	100% fossil-free fleet globally
MAN	No specific commitment for 2040	100% ZEV sales globally
Iveco	No specific commitment for 2040	CO_2-neutral fleet in key markets
Ford Trucks	100% zero-emission vehicle sales in Europe	No specific commitment for 2050
Volta Trucks	100% ZEV sales	No specific commitment for 2050

The commitments were established through a variety of public announcements, sustainability reports, corporate roadmaps, and active participation in global climate initiatives. Many manufacturers, including Daimler, Volvo, and Scania, have set voluntary corporate targets by announcing self-imposed sustainability goals in their corporate sustainability reports, investor presentations, and press releases. These commitments align with broader corporate net-zero strategies and ESG (Environmental, Social, and Governance) goals.

In addition to voluntary targets, several companies have joined industry-wide pledges and global initiatives. For instance, some have signed the Global Memorandum of Understanding (MoU) on Zero-Emission Medium- and Heavy-Duty Vehicles, aiming for 100% ZEV sales by 2040, while others, such as Volvo and Daimler, have participated in The Climate Pledge—a collaborative initiative led by Amazon and Global Optimism targeting net-zero carbon emissions by 2040.

Regulatory compliance and market requirements also play a significant role. In regions like Europe, the U.S., and China, stricter CO2 emissions regulations and ZEV mandates are driving manufacturers to accelerate their transition. As an example, Ford Trucks has committed to 100% ZEV sales in Europe by 2040 to meet the EU Green Deal objectives. Furthermore, increasing pressure from investors and institutional stakeholders has pushed companies like Volvo and Daimler to shift towards zero-emission vehicle sales, ensuring they remain competitive in a market where major fleet operators, such as Amazon and Maersk, demand cleaner transport solutions.

Technological advancements, driven by internal R&D investments and detailed technology roadmaps, are also critical to these commitments. Companies like MAN and Iveco are developing hydrogen and battery-electric truck platforms that directly influence their ZEV adoption targets, while some manufacturers are aiming for CO_2-neutral fleets by combining battery-electric, hydrogen fuel-cell, and biofuel-powered solutions.

Specifically, Volvo has committed to achieving 100% zero-emission vehicle sales globally by 2040, aligning with the Global MoU on ZEVs it signed, and aims to decarbonize its entire truck portfolio by replacing diesel-powered trucks with battery-electric and hydrogen fuel-cell electric vehicles. Its long-term objective is to achieve a completely fossil-free vehicle fleet by 2050, working towards a net-zero CO_2 emissions supply chain where both trucks and the production process are fully carbon-neutral. In a similar vein, Daimler Truck has pledged that all new trucks and buses sold in key markets will be zero-emission vehicles by 2039, as part of its strategy to align with climate goals and ensure long-term competitiveness in decarbonized transport markets. Daimler also aims for a 100% CO_2-neutral fleet of new trucks and buses worldwide by 2050—a commitment that extends beyond truck sales to encompass logistics operations, supply chains, and production sites. Their strategy includes launching battery-electric vehicles such as the Mercedes-Benz eActros.

Other global manufactors are beginning to demonstrate substantial momentum in the electrification of heavy-duty transport. One of the clearest indicators of this shift is the performance of Chinese manufacturer BYD, whose electric truck sales have grown rapidly between 2023 and 2024. According to (Carbon Tracker, 2024), BYD's electric truck deliveries now far outpace those of established European manufacturers such as Daimler and Volvo. This surge is attributed not only to a more aggressive product rollout but also to a vertically integrated manufacturing model that reduces costs and accelerates time-to-market. While the company's expansion into international markets has not been without controversy—including recent scrutiny over a factory project in Brazil (Annabelle

Liang, 2024)—their performance illustrates the pace at which newer entrants are reshaping the competitive landscape for zero-emission freight.

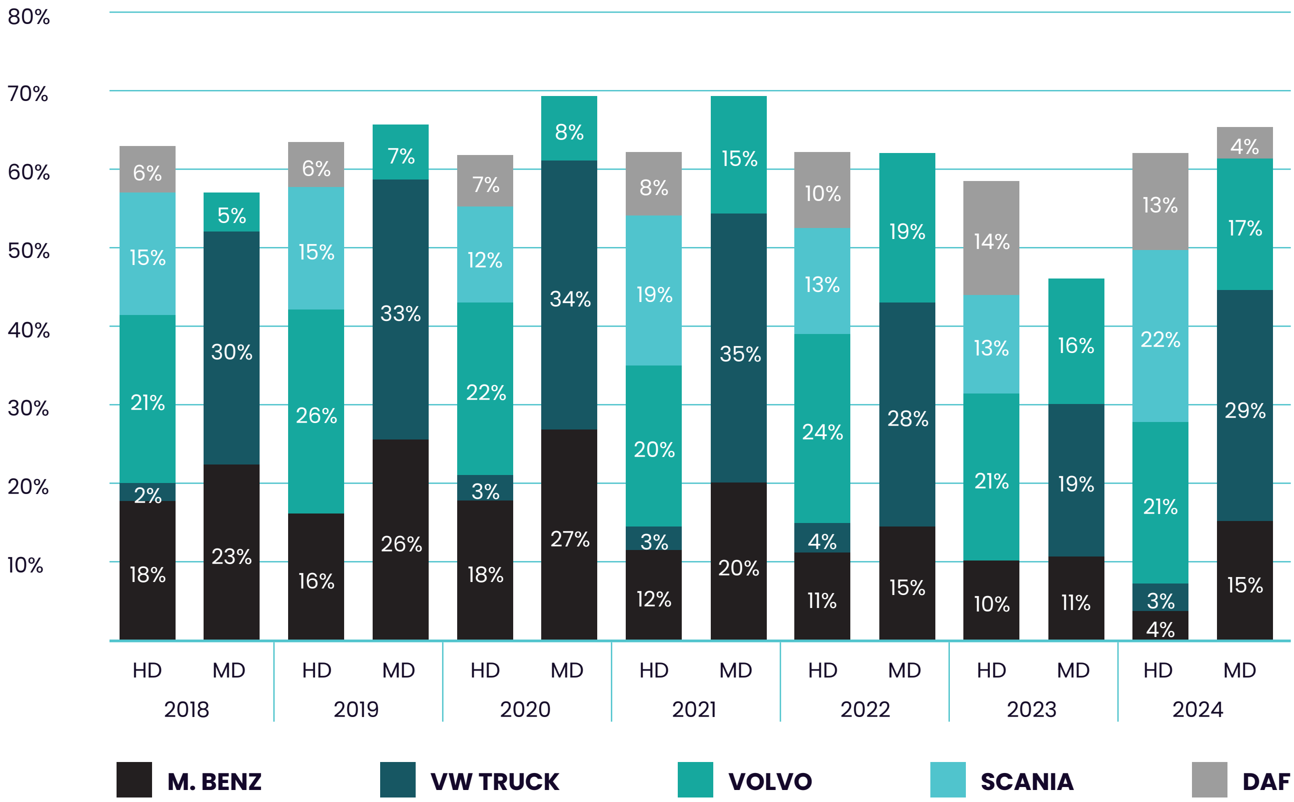
Another fast-emerging player is Windrose, a Chinese electric truck startup that has recently announced plans to establish truck assembly operations in the United States—a relatively rare move among Chinese EV manufacturers. (Reuters, 2024c) report notes that Windrose's order book for 2024 already exceeds the planned deliveries of e-trucks by traditional manufacturers such as Volvo Group and Daimler. Windrose aims to begin road deployment of its trucks within the year, signaling not only production readiness but also growing confidence among logistics operators in adopting non-legacy brands. The company's ability to scale quickly and secure contracts in both North American and European markets reflects an evolving dynamic in the heavy-duty vehicle segment, where innovation and supply chain agility are becoming increasingly decisive.

These developments contrast with the slower ramp-up observed among many incumbent manufacturers, who face legacy system constraints and higher transition costs. While traditional OEMs continue to invest in electrification, the market appears to be shifting more rapidly than some projections have anticipated. The cases of BYD and Windrose highlight how the landscape is being redefined not only by policy mandates or infrastructure readiness, but also by shifts in commercial strategies and customer demand. As emerging players demonstrate the ability to scale and deliver electric freight solutions at competitive prices, their role in shaping the decarbonization of road freight becomes increasingly relevant for policymakers and industry observers alike.

It is worth noting that Brazil is not listed among the leading countries with national ZEV policies for medium and heavy-duty vehicles, which highlights an area of potential development for the country. The analysis of market share trends among major truck manufacturers in Brazil from 2018 to 2024 (FENABRAVE, 2018, 2019, 2020, 2021, 2022, 2023, 2024) highlights the evolving dynamics in the heavy-duty (HD) and medium-duty (MD) truck segments. As illustrated in Figure 3, Mercedes-Benz, Volvo, Scania, DAF, and Volkswagen Truck have experienced significant fluctuations in market share across these categories. Daimler Truck (Mercedes-Benz) has shown a declining trend in the HD segment, dropping from 18% in 2018 to 4% in 2024. Conversely, Volvo has maintained a relatively stable position, fluctuating between 20% and 26% in the HD segment, while Scania has recently gained traction, reaching 22% in 2024. In the MD segment, Volkswagen Truck has consistently led the market, with its share varying between 28% and 35% over the analyzed period.

These trends reflect the competitive landscape in the sector and may influence the adoption of electrification technologies in Brazil. Companies such as Volvo and Scania, which are investing heavily in electric trucks globally, retain a strong market presence in the country, potentially facilitating future technological transitions. However, the lack of clear electrification commitments from some manufacturers in the Brazilian market suggests additional challenges for the decarbonization of freight transport in the country.

FIGURE 3: MARKET SHARE TRENDS IN THE HEAVY-DUTY AND MEDIUM-DUTY TRUCK SEGMENTS IN BRAZIL (2018–2024)



Theory of Change for Brazil

A transformative vision for Brazil's heavy-duty transport sector is emerging—one that envisions a fully electrified trucking system capable of reducing greenhouse gas emissions, improving public health, and driving economic growth. The ultimate goal is to create a sustainable and resilient freight system through electrification, but achieving this outcome requires coordinated action across multiple domains.

One key driver in this transformation is the leadership demonstrated by truck manufacturers. For instance, Volkswagen Caminhões e Ônibus (VWCO) has pioneered the production of heavy-duty electric trucks in Brazil through its e-Delivery lineup, which currently serves urban and short-haul logistics. Although these vehicles are primarily suited for city deliveries, the platform lays the groundwork for scaling up to heavier, long-haul models. Similarly, Volvo Trucks has delivered heavy-duty electric trucks in Brazil, including its FH Electric model that is tailored for regional freight operations. These models have been adapted for local conditions and have seen adoption in various Latin American markets, demonstrating Brazil's capacity to produce electric vehicles domestically (Volvo Trucks, 2023). Scania has also introduced its electric heavy-duty trucks, designed for regional distribution and even mining applications. Scania's modular approach allows for the customization of vehicles to suit different operational needs, though the broader market uptake remains to be proven (Scania AB, 2019)

Policy support and financial incentives represent another critical pillar for the transition. São Paulo's tax incentives for electric vehicles, which currently reduce taxes on EV purchases, could be expanded to cover heavy-duty electric trucks, thereby lowering the financial burden on fleet operators. Drawing inspiration from global best practices, such as California's Advanced Clean Trucks (ACT) Regulation, which mandates a progressive shift toward zero-emission truck sales—with a target of 100% by 2035 (California Air Resources Board, 2020)—Brazil could consider establishing legally binding mandates and setting a national goal to phase out new diesel truck sales. Similar frameworks are already in place within the European Union, where the recently adopted CO_2 emission standards for heavy-duty vehicles require a 90% reduction in fleet-average emissions from new trucks by 2050, effectively accelerating the transition to zero-emission freight technologies (European Commission, 2024). The introduction of such policies could help create a predictable regulatory environment and stimulate long-term investment and planning across the sector.

Infrastructure development is also essential for accelerating truck electrification. For example, expanding charging infrastructure along key freight corridors like BR-116 and BR-101 is critical to support long-haul operations. Initiatives such as Neoenergia's renewable charging stations, which integrate clean energy into charging networks, illustrate the potential for partnerships between utilities and government to ensure that the infrastructure supporting electric trucks is both extensive and sustainable (Neoenergia, 2024).

Public-private collaboration further reinforces this transformative effort. Notably, Ambev has begun integrating VWCO's e-Delivery trucks into its urban fleet and is exploring the use of electric trucks for regional distribution . This shift not only offers a practical model for other logistics companies but also signals that large private enterprises are beginning to internalize the environmental and economic benefits of electrification. Additionally, pilot programs led by Maersk in São Paulo and Santa Catarina have tested the viability of heavy-duty electric trucks for container transport. These initiatives, while still in the early stages, provide valuable data on operational performance and scalability, informing future policy and investment decisions (Maersk, 2023).

Consumer awareness and market development play a pivotal role as well. Highlighting the total cost of ownership (TCO) advantages—such as lower fuel costs, reduced maintenance, and enhanced operational efficiency—can help build a compelling business case for fleet operators to transition to electric trucks. Moreover, companies that adopt electrification can benefit from green branding, which appeals to eco-conscious customers and aligns with global sustainability trends. Workforce training programs are also needed to ensure that drivers and maintenance technicians are well-prepared to operate and service new electric vehicle technologies, supporting a smooth transition across the sector.

In summary, the theory of change for Brazil's heavy-duty transport sector relies on a multifaceted approach: leadership by manufacturers, supportive policies and financial incentives, robust infrastructure development, effective public-private partnerships, and active consumer and workforce engagement. Together, these drivers can create a sustainable, electrified heavy-duty trucking sector that significantly reduces emissions, enhances public health, and drives economic growth. While the challenges are substantial, aligning with global best practices—as demonstrated by key players in Europe, the United States, and other markets—can guide Brazil toward a resilient and low-carbon future.

How Can Brazil's Largest Manufacturers Help Accelerate the Transition to Electric Heavy-Duty Trucks?

Brazil's transition to a zero-emission heavy-duty transport sector hinges not only on robust policy frameworks and infrastructure investments but also on the proactive contributions of its largest manufacturers. By leveraging domestic capabilities, investing in research and development (R&D), forming strategic public-private partnerships, creating supportive policy conditions, and pioneering industry-led carbon-credit programmes, Brazil can markedly accelerate truck-fleet electrification. The sections below outline the principal levers available to major market players.

Battery Production and R&D Investment

One of the critical challenges in truck electrification is the supply and cost of batteries. Brazilian manufacturers such as Volkswagen Caminhões e Ônibus (VWCO), Mercedes-Benz, and Scania are well placed to direct capital into domestic battery production and R&D. Establishing local cell-manufacturing plants would reduce reliance on imports, lower production costs and generate technology tailored to Brazil's operating conditions. BYD's recent launch of a lithium-iron-phosphate battery factory for e-buses in Bahia shows that local production is both feasible and strategically valuable (BYD Company, 2023). Greater R&D spending could also improve energy density, charge-cycle performance and durability, all of which are crucial for heavy-duty applications. Enhancing battery technology in this way would further lower life-cycle costs, boosting market acceptance of battery-electric trucks relative to diesel.

Public-Private Partnerships for Charging Infrastructure

Charging infrastructure is another cornerstone of large-scale adoption. Major logistics and fleet operators—Randon, JSL and Gerdau, for example—can collaborate with federal, state and municipal authorities to co-invest in public fast-charging networks. In São Paulo, Enel X and bus OEMs have already partnered to deploy urban e-bus chargers, providing a template that could be extended to heavy-duty freight corridors (Enel, 2024). Rolling this model out along strategic highways such as BR-116 and BR-101 would mitigate range anxiety, streamline operations and create a foundation for national electrification. These joint ventures also have the potential to spur local job creation and facilitate technology transfer between the public and private sectors.

Policy Engagement and Supportive Regulation

Manufacturers can also shape the regulatory landscape that underpins long-term investment decisions. Supply-side instruments—such as binding vehicle-emission performance standards and zero-emission truck sales targets—create market certainty and encourage technological convergence on the most effective solutions. Brazil's truck makers could publicly endorse science-based pathways modelled on the Advanced Clean Trucks (ACT) Regulation in California (California Air Resources Board, 2020) and the EU CO_2 standards for heavy-duty vehicles (European Commission, 2024). Active support would contrast with past instances where parts of the global automotive sector have lobbied for weaker rules or for extended reliance on biodiesel and fossil gas (InfluenceMap, 2024). By aligning corporate advocacy with long-term decarbonisation objectives, manufacturers help establish a level playing field and reduce the risk of stranded investments in transitional combustion technologies.

Industry-Led Carbon-Credit Programmes

Beyond technology and infrastructure, manufacturers can internalise environmental benefits through carbon-credit schemes. Drawing on the precedent of RenovaBio in Brazil's biofuels sector and on Tesla's practice of selling zero-emission credits in California (Jennifer L, 2024), truck OEMs could establish an industry-wide platform that rewards early adoption of electric trucks. Credits generated from verified emissions reductions would offset higher upfront costs and create a transparent financial mechanism for decarbonisation across supply chains.

Final Takeaway and Regional Case Studies

Brazil's largest truck manufacturers therefore occupy a pivotal position in advancing freight electrification. Local battery production and R&D can remove a key cost barrier; public-private charging partnerships address infrastructure constraints; policy engagement can lock in clear, ambitious performance standards; and carbon-credit schemes can ease the financial transition for fleet operators. Experience from Europe, the United States and China shows that when supportive regulation and private-sector action coincide, total cost of ownership (TCO) parity between diesel and electric trucks is achievable. Applying similar strategies, Brazil could bring battery-electric trucks to cost parity—delivering lower emissions, better air quality and new economic opportunities.

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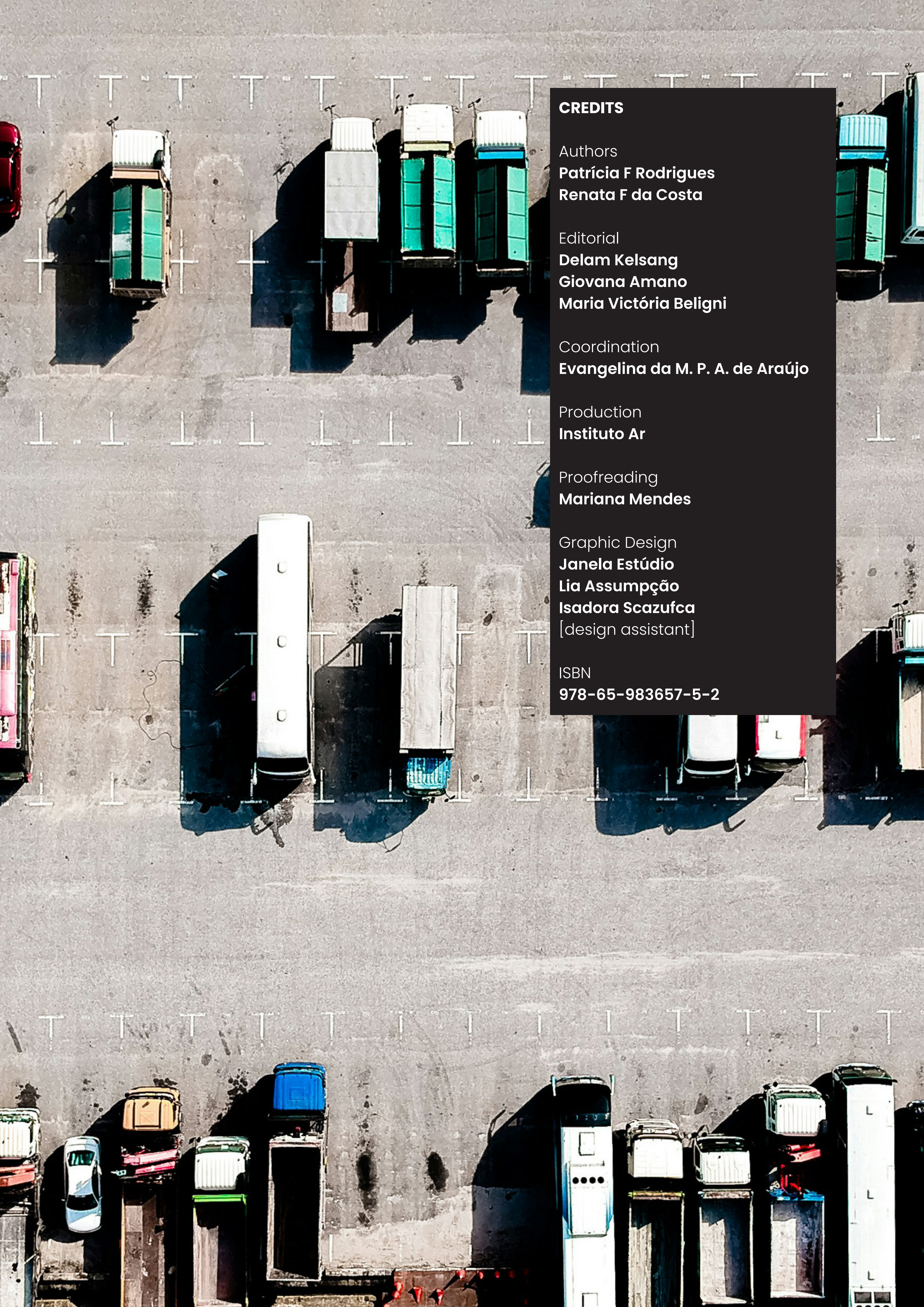

CREDITS

Authors
Patrícia F Rodrigues
Renata F da Costa

Editorial
Delam Kelsang
Giovana Amano
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Coordination
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Production
Instituto Ar

Proofreading
Mariana Mendes

Graphic Design
Janela Estúdio
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[design assistant]

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