Navigating Technological Transition in Brazil's Automotive Sector: A Coexistence of Biofuels and Electrification

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ABSTRACT

This paper investigates the technological (re)configuration within Brazil's mobility sector, emphasizing the simultaneous development of e-mobility (EVs) and well established biofuels pathway. By applying the theoretical frameworks of path dependence and technological trajectories, the study examines how Brazil's historical investment in internal combustion engines (ICEs) and biofuels has shaped current technological landscapes. The analysis reveals that Brazil's transition is not confined to a singular technological path but involves a coexistence of EVs and biofuels. This dual approach, characterized by the integration of emerging technologies with established ones, presents both challenges and opportunities. The paper discusses the implications of this coexistence and provides strategic recommendations for policymakers and industry stakeholders to support and optimize the integration of these technological paths.

Keywords: Biofuels; Electric Vehicles; Innovation; Internal Combustion Engines; Path Dependence; Technological Lock-In; Technological Transition.

INTRODUCTION

Transportation and urban mobility are undergoing major transformations as global efforts to improve energy efficiency and reduce fossil fuel consumption gain momentum, supported by policies such as higher fuel efficiency standards and incentives for low-emission vehicles [1], [2]. In Latin America, particularly Brazil, this trend is shaped by a unique technological and historical context. Brazil's automotive sector has followed a distinctive trajectory, balancing its long-standing expertise in biofuels with the integration of hybrid and electric vehicle technologies, demonstrating the intersection of established and emerging innovations (Barassa, 2019).

Theories of technological change, such as path dependence [4] and technological lock-in [5], help explain why Brazil's internal combustion engine (ICE) technology, powered by biofuels like ethanol, has become so entrenched These frameworks emphasize how historical investments and complementary infrastructure, such as ethanol distribution networks, reinforce the dominance of biofuels, creating barriers to the widespread adoption of electric vehicles (EVs). This dynamic reflects a classic case of lock-in, where institutional and market forces make technological shifts difficult.

At the same time, the rise of electrified and hybrid vehicles offers new technological pathways for Brazil. In the past five years, more than 250,000 hybrid

and electric vehicles have entered the Brazilian market, according to the Brazilian Electric Vehicle Association (ABVE).

While there is a growing recognition of the need to diversify with EVs, significant challenges remain due to the strength of the biofuel sector and consumer preferences for ICE vehicles. The coexistence of biofuels and electrification illustrates a complex interaction of historical choices and emerging innovations, making it essential to understand how past technological decisions shape future developments.

This article analyzes the dynamics of Brazil's automotive sector, with a focus on how companies' strategic positioning and movements are influenced by technological trajectories, including the role of new entrants that are reshaping the market/industry. It explores how firms reinforce existing paradigms while also opening potential alternative technological routes. The findings aim to contribute to a deeper understanding of Brazil's technological transition, offering recommendations for policymakers and industry stakeholders on how to navigate this evolving landscape amidst the impact of emerging players.

The study adopts a systemic view, covering both light and heavy-duty vehicles, and analyzing different vehicular architectures, including biofuel-powered, hybrid, and electric platforms. By considering the full spectrum of technological solutions, the research highlights the various trajectories and challenges across these platforms, providing insights into the broader technological transition occurring in Brazil's transportation sector.

MATERIALS AND METHODS

This study adopts a qualitative research methodology to explore the complexities of technological transition within Brazil's automotive sector. The research integrates multiple approaches to provide a comprehensive understanding of the dynamics at play.

Firstly, the study involves a thorough review of the literature on path dependence, technological lock-in, and technological transitions [6], [7]. In addition to theoretical research, the methodology includes an analysis of industry reports, government policy documents, and market data specific to electric vehicles (EVs) and biofuels within the Brazilian context [8], [9], [10]. This analysis helps contextualize the theoretical frameworks within the realities of Brazil's automotive sector.

Furthermore, semi-structured interviews were conducted with key stakeholders, including industry experts, policymakers, and representatives from automotive companies. These interviews provide qualitative insights into the practical challenges and opportunities associated with the transition towards electric mobility and the role of biofuels.

RESULTS AND DISCUSSION

In the Brazilian automotive landscape, passenger cars have seen a growing presence of conventional hybrid models, particularly those utilizing flex-fuel technology. These hybrids have carved out a niche by leveraging Brazil's well-established ethanol refueling infrastructure and benefiting from favorable fiscal

policies . This reflects a path-dependent process, where historical technological choices—such as Brazil's deep integration of biofuels into its transportation system—continue to influence present innovations. The development of flex-fuel hybrids, led by Toyota, is a testament to how established knowledge and infrastructure can reinforce existing technological trajectories, creating a reinforcing mechanism that makes deviation toward new technologies more challenging [11]

In this case, the path established by Brazil's biofuel infrastructure not only supports the continued use of ethanol but also shapes the technological direction of hybrid vehicles. The flex-fuel hybrid models, combining biofuels with electrification, can be seen as an intermediary technology that consolidates Brazil's historical reliance on biofuels while integrating emerging electrification trends. This dynamic illustrates how the path dependence of biofuel technologies can serve as both a barrier and an enabler of technological innovation, locking in certain trajectories while allowing incremental transitions toward new technologies.

However, the rise of plug-in hybrids and battery electric vehicles (BEVs) is challenging the dominance of biofuels and flex-fuel hybrids. Chinese automakers, particularly BYD and GWM, have adopted aggressive strategies to introduce BEVs to the Brazilian market, thereby presenting an alternative technological pathway [12]. This situation introduces potential for a technological divergence, as BEVs are not reliant on Brazil's established biofuel infrastructure. The entry of these players signals a possible shift in technological lock-in dynamics, as new firms promote electrification and potentially disrupt the entrenched biofuel-based regime. Although Brazil's historical reliance on biofuels has created strong lock-in mechanisms, the increasing penetration of BEVs reflects how external pressures and market forces can open windows of opportunity for alternative technologies.

In urban mobility, the Brazilian bus sector is also undergoing significant transformation, marked by the entry of new players into the electrification domain. BYD, one of the leading global players in electric bus manufacturing, was a pioneer in Brazil by establishing its production plant in 2017. This initiative marked a significant milestone in the development of electric mobility in the country. Traditional manufacturers such as Mercedes-Benz, Volkswagen, and Volvo are expanding their participation in e-mobility, while local firms like Eletra and Marcopolo have been proactive in developing electric bus technologies. For example, Eletra's establishment of a production facility in São Bernardo do Campo and Marcopolo's development of its own electric bus chassis, using domestic suppliers, exemplifies how incumbents are responding to the shift in technological trajectories by embedding new competencies within the existing industrial framework. [13]

Despite this shift towards electrification, biofuels remain relevant, especially with the development of biomethane-fueled buses, such as those produced by Scania. This technology taps into Brazil's established knowledge of alternative fuels derived from sugarcane by-products, representing another instance of path dependence shaping innovation. The adaptation of biomethane-powered buses within the existing fuel supply networks reflects the resilience of biofuel technologies, even in the face of rising electric alternatives. This suggests

that Brazil's technological trajectory in heavy-duty transport is not one of sudden transformation but of gradual diversification, where biofuels continue to play a crucial role alongside emerging electric technologies [14].

For heavy-duty vehicles, biofuels like biodiesel and synthetic fuels, such as hydrotreated vegetable oil (HVO), illustrate the continuing lock-in effects of the internal combustion engine (ICE) and liquid fuel infrastructure. Biodiesel's compatibility with existing diesel engines and the infrastructure necessary for its distribution underscores the persistence of established technological pathways in sectors where electrification faces significant barriers, such as long-haul trucking [15]. The technological lock-in created by existing infrastructure and the capital investment needed to replace it means that biofuels will likely remain a dominant part of Brazil's transportation mix for the foreseeable future.

Additionally, biomethane, a renewable fuel derived from organic waste, has emerged as a key component in Brazil's heavy-duty vehicle decarbonization strategy. Biomethane's integration into the fuel landscape, particularly for trucks, highlights an ongoing reliance on biofuel pathways that leverage Brazil's agricultural by-products. However, the successful adoption of biomethane depends on developing a dedicated refueling infrastructure [14]

CONCLUSION

The results of this study reveal a complex interaction between technological path dependence, lock-in mechanisms, and innovation trajectories in Brazil's transportation sector. Flex-fuel hybrid vehicles, particularly promoted by Toyota, exemplify how Brazil's integration of biofuels has shaped its current technological landscape. This path development, supported by the country's ethanol infrastructure, has led to technological lock-in, making it difficult for alternatives like battery electric vehicles (BEVs) to gain traction. However, new players like BYD and GWM are pushing BEVs into the market, signaling potential technological divergence and challenging the existing biofuel dominance.

In the urban bus sector, electrification is gaining ground, with companies like Marcopolo and Mercedes-Benz investing in electric buses. However, biofuels remain relevant, as demonstrated by Scania's biomethane-fueled buses, illustrating that Brazil's transportation sector is experiencing gradual diversification rather than disruption. In the heavy-duty vehicle segment, biodiesel and synthetic fuels like hydrotreated vegetable oil (HVO) continue to dominate due to the lock-in of internal combustion engine technology, with biomethane emerging as a complementary option.

For companies, navigating these multiple technological paths requires strategic investments and significant resources. Balancing biofuels and electrification positions Brazilian firms to lead in Latin America's decarbonization efforts. The government must support both established biofuels and emerging technologies through inclusive policies that foster a diversified path to decarbonization. Ultimately, Brazil's transportation sector will likely follow a hybrid model, where biofuels and electrification coexist in a path-dependent landscape.

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