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# The role of the transport sector in climate change mitigation: An interdisciplinary approach to mobility innovation

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**ABSTRACT**
This article addresses the relevance of the transport sector in climate change mitigation and adaptation strategies, with a special focus on the Brazilian scenario, in which it represents 65% of energy consumption. Road transport, responsible for 13% of total carbon dioxide equivalent (CO2e) emissions in the sector, stands out as the main emitter. In addition to emphasizing the importance of urban planning, the potential for reducing emissions through an interdisciplinary approach that combines multi-level governance and low-carbon technologies are explored. Solutions such as more compact cities, the use of clean energy, and the integration of different modes, with an emphasis on public transport, are discussed as smart and sustainable strategies. This article also conducts a theoretical review of the current literature on smart mobility and its climate impacts, analyzing opportunities and challenges from the perspective of multilevel socio-technical transition. To illustrate the application of these ideas, we present a case study focused on the mobility system of the city of São Paulo, with the aim of understanding the barriers and opportunities towards a transport permeated by innovative and carbon-neutral technologies.

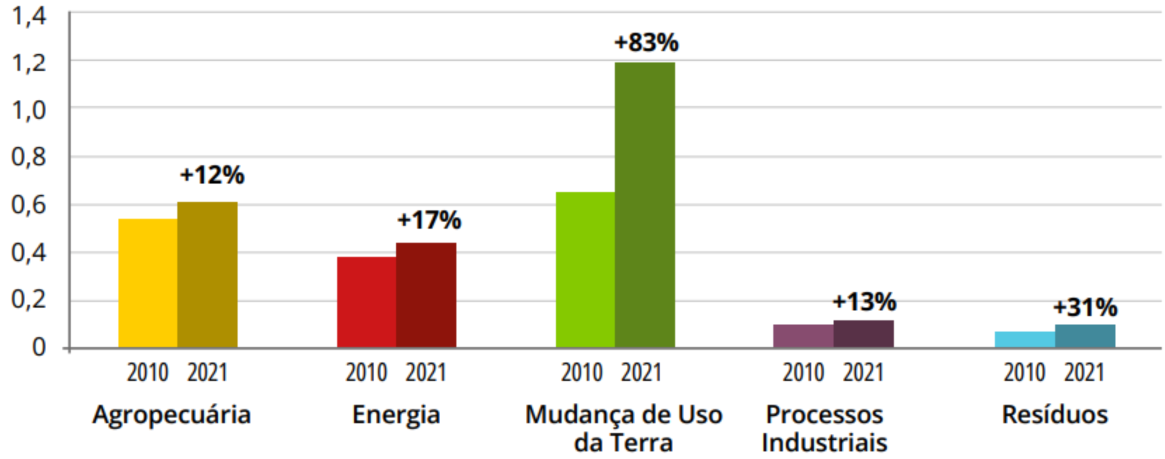
**Keywords:** Socio-technical transition, Smart mobility, Urban transport, Climate change, Innovation.

## 1 INTRODUCTION

Throughout the twentieth century, the automobile industry developed based on the production of vehicles for private use powered by fossil fuels. As a result, in 2021 the transport sector was responsible for 64.5% of global oil consumption and 37% of CO2 emissions from end-use sectors, even though it was one of the segments most affected by the COVID-19 pandemic in that period (IEAa, 2022). In Brazil, according to the Greenhouse Gas Emissions Estimation System (SEEG), of the Climate Observatory (OC), emissions have grown 40% since 2010, from 1.7 to 2.3 billion tons in 2021 (figure 7), when the country regulated the National Policy on Climate Change (PNMC). These results should make it difficult to meet the Nationally Determined Contributions[1] (NDC) targets, which will be updated in 2022 to 37% emissions reductions by 2025, and 43% by 2030.

[1] Brazil has defined that the NDCs – voluntary commitments of each signatory country to the Paris Agreement – will be defined based on the most recent Brazilian Inventory of Anthropogenic Emissions and Removals of Greenhouse Gases with progressive and more ambitious targets, indicating absolute values for emission reductions through sectoral mitigation and adaptation plans. Source: Senate Agency. Available in https://www12.senado.leg.br/noticias. Accessed March 13, 2022.

Figure 7. Brazilian emissions by sector before and after the PNMC




Source: SEEG (2023).

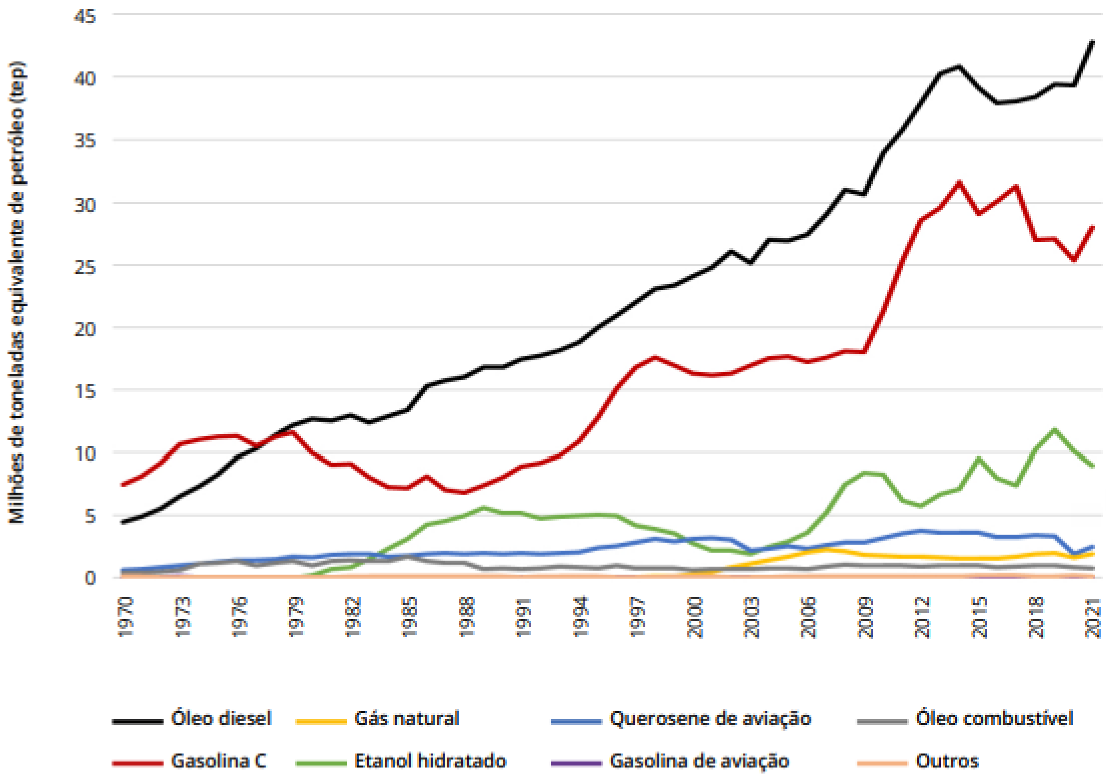
When it comes to urban mobility, the transition to decarbonisation in developing megacities is even more complex. In November 2022, the world reached the mark of 8 billion inhabitants at a time of multiple crises, such as the COVID-19 pandemic, which killed more than 6 million people (UNFPA, 2023). In this scenario, urban centers account for about 75% of global energy consumption and 70% of GHG emissions, [2]even though they occupy only 2% of the globe's mass. There are 4.5 billion people living in cities, with the prospect that by 2050 this number will be doubled. This means that by the middle of the century more than 1.6 billion people will suffer from temperatures that can reach up to 35 °C in urban perimeters (UN, 2021).

As a result, the dense movement of goods and passengers in the city highlights the role of mobility in meeting global emission targets and the Sustainable Development Goals (SDGs). In line with SDG 11 (Sustainable Cities and Communities), which aims to make cities and human settlements inclusive, safe, resilient and sustainable, the Climate Conference (COP21) in 2015 in Paris and the New Urban Agenda, approved in 2016 at the Habitat III Summit in Ecuador, emphasized the role of cities in implementing local climate action to limit global warming to 1.5°C.

The 2022 Synthesis Report of the Energy Research Company (EPE, 2022) points out that transportation is the sector that uses the most energy in Brazil (32.5%). Of this total, 95% correspond to road transport, with almost half (45.1%) using diesel fuel as a source (figure 8).

[2] GHGs covered by the Kyoto Protocol include carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF6), nitrogen trifluoride ($NF_3$). Source: UNEP (2022).

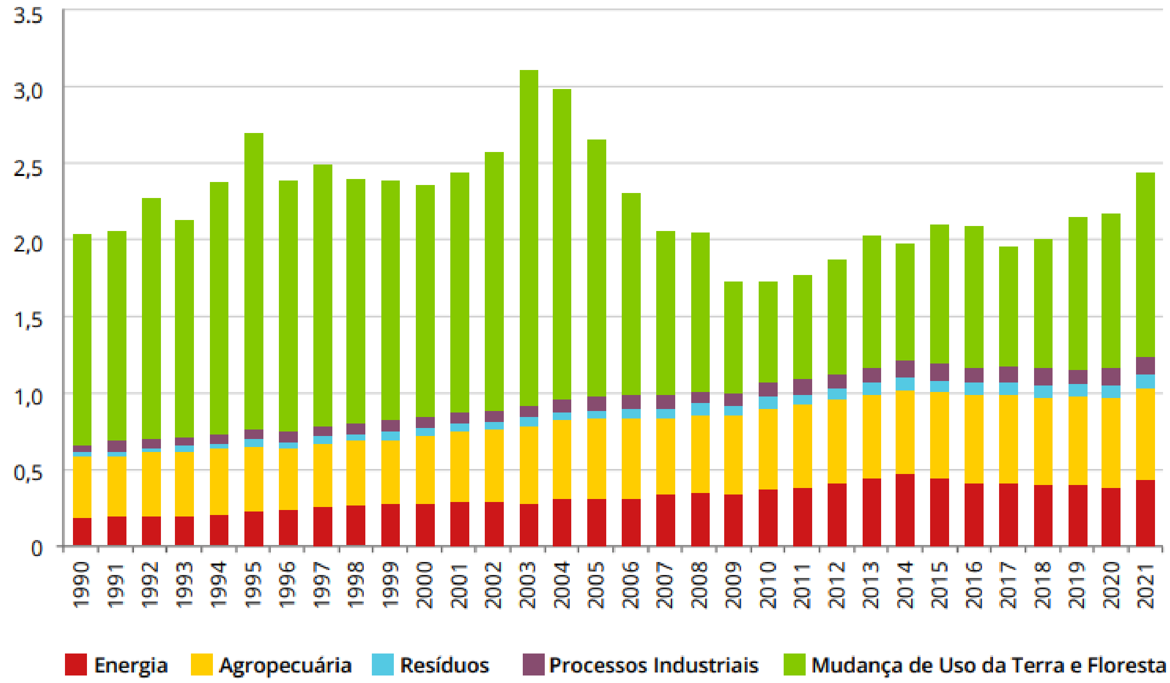
Figure 8. Fuel consumption in the transport activity




Source: SEEG (2023).

The road segment (goods and passengers) is the most used in Brazil. With a length of 110,333 km, it represents 6% of the Gross Domestic Product (GDP) and generates 1.2 million direct and indirect jobs and an installed capacity of 4.5 million units, placing the country in the 8th position in the global *ranking* of automotive production (CNTb, 2022; ANFAVEA, 2023). In 2021 alone, 2 million new light vehicles were licensed in the country, 1.1% more than in 2020, revealing the strength of this market and the preference of this modal by Brazilians (EPE, 2020). As a consequence, 13% of national emissions originate in this segment, showing a growth of 5% per year (figure 9). The majority of this energy is consumed by heavy-duty trucks and buses (55%), followed by automobiles (36%).

Figure 9. Brazil's greenhouse gas (GHG) emissions from 1990 to 2021 ($GtCO_2e$)




Source: SEEG (2023).

In response to the high demand for energy for the movement of people and goods in cities, international organizations increasingly recognize the role of technology in the potential for mitigating and adapting to climate impacts. The UNEP-Copenhagen Climate Centre, in collaboration with the OECD's Directorate for Development Cooperation, has identified the priority climate technologies, their level of maturity and the financial flows required for their transfer in the report *Technology Transfer for Climate Mitigation and Adaptation*[3]. In addition, the United Nations Environment Programme (UNEP) launched *The Climate Technology Progress Report 2022*, focusing on the development and progress of technologies for climate action from a local and global perspective. In Brazil, UNEP teamed up with the Ministry of Science, Technology and Innovation (MCTI) in 2021 to launch the first *Technology Needs Assessment Report for the Implementation of Climate Action Plans in Brazil,*[4] divided by sectors. In common, these reports emphasize the climate technology needs in developing countries:

> "All parties [...] (c) Promote and cooperate in the development, application and dissemination, including the transfer of technologies... controlling, reducing or preventing anthropogenic emissions of greenhouse gases [...]" – Article 4, paragraph 1.
>
> "Developed country Parties shall take all possible measures to promote, facilitate and finance, as appropriate, the transfer of or access to environmentally sound technologies and *know-how*

[3] The IPCC Special Report on Methodological and Technological Issues on Technology Transfer (SRTT) refers to the term "technology transfer" as a set of processes covering the flows of experience and equipment to mitigate and adapt to climate change, not just patented knowledge, but diffusion and technological cooperation between and within countries and the learning process, use and replication of technology. Available at https://archive.ipcc.ch/publications_and_data/ar4/wg3/en/ch2s2-7-3.html.
[4] Available at: https://repositorio.mcti.gov.br/handle/mctic/4973.

> to other Parties, particularly developing country Parties, so that they can implement the provisions of the Convention [...]" – Article 4, paragraph 5 (UNFCCC, 2022).

On the impacts of technology on society, the Social Sciences have focused on the development, diffusion and, mainly, the consequences of specific technologies, such as the steam engine (Industrial Revolution) or the computer (Digital Revolution). But an important feature of modern technology is the existence of large and complex spatially extended and functionally integrated systems (socio-technical networks), such as the mobility system, which have played a central role in the process of industrialization and economic development, contributing to a significant change in society's behavior and lifestyle. In addition to the benefits, these systems generate negative externalities that have influenced the field of research in which social scientists have come to analyze their functioning and evolution (HUGHES, 1989).

But in the contemporary world, technology has become a cross-cutting component of modern life, influencing all social practices, from work to interpersonal relationships, from education to health. Climate catastrophe is not immune to this influence, given technology-driven misinformation. Six out of seven people around the world say they are insecure about the future (UNEP, 2022), suggested by gloomy news about climate change conveyed by social media and messaging apps, while climate denialism can be used as a justification for inaction and the delegitimization of scientific knowledge on the topic (NICHI, 2021).

From an interdisciplinary perspective, understanding the institutional and political dynamics associated with the process of decarbonization of transport through climate technologies requires a more accurate analysis of the best path for structural and systemic changes (KERN, 2012; BANISTER, 2008). For example: even with a high socio-environmental impact, an average car is unused for more than 90% of the time, carries an average of one person and occupies 15m² of urban space, in addition to the high cost of maintenance and taxes, and is still a mode that attracts most transport users due to the perception of *status* and convenience (BONDOROVÁ; ARCHER, 2017).

Based on social, economic and political aspects, in addition to the potential for climate mitigation and adaptation with the introduction of new technologies in the transport sector, this article investigates the elements and favorable conditions for regulation, investment and adoption of policies based on carbon emission scenarios in Brazil. The objective is to synthesize the recent literature on smart mobility and climate change and to understand the opportunities and challenges of this approach to address climate impacts in urban passenger transport. To this end, the focus will be on solutions that fit into the "avoid-change-improve" approach (DALKMANN; BRANNIGAN, 2007), being:

> – Avoid: reducing travel through demand management and urban planning, and automation and data technologies that allow travel avoidance;
> – Change: measures that encourage collective and more efficient modes, such as public transport and walking or cycling;

– Improve: use of more efficient fuels and vehicles or their electrification.

## 1.1 TRANSPORT ADAPTATION AND MITIGATION STRATEGIES

Effects resulting from climatic events, such as flooding and flooding, rising or falling temperatures, winds, rains, and landslides, in addition to the greater propensity for deaths and accidents, tend to be a greater challenge in cities, where 61% of the population (124.1 million people) of more than 203 million Brazilians is concentrated (IBGE, 2022).

Difficulties in the movement of passengers and in the flow of products, added to the instability in signaling services, equipment and transit facilities, harm the logistics system, with a high impact on economic activities (Chart 3). In addition, the costs of rehabilitating damaged infrastructure burden and delay the financing of climate solutions.

Table 3. Potential impacts of climate on infrastructure and urban mobility

| Impacts Climate | Impacts on infrastructure | Impacts on mobility |
|---|---|---|
| ***Temperature Rise*** | Deterioration and deformation of pavements and rails, bridges and viaducts;<br>Slope instability; Overheating and overloading of equipment. | |
| ***Increased rainfall and of extreme events*** | Damage to infrastructure;<br>Damage to electrical equipment and systems;<br>Deterioration of structures;<br>Slips;<br>Tree falls;<br>Signaling and control drop-off;<br>Overloading of drainage systems;<br>Reduction of visibility and grip of vehicles; Restrictions on navigability. | Reduction of the safety and/or performance of transport modes;<br>Reduced comfort for passengers, pedestrians and cyclists;<br>Increased travel time;<br>Road blocking;<br>Restrictions on the logistics of products and services;<br>Increased operating costs;<br>Reduction in the share of collective and non-motorized modes of transport. |
| ***Lifting and over-elevation from sea level*** | Damage to infrastructure;<br>Erosion and corrosion of structures and materials;<br>Damage to track support layers. | |
| ***Reduced rainfall*** | Restrictions on navigability. | |

Source: Adapted from the National Plan for Adaptation to Climate Change (2016) and BRAZIL 2040: scenarios and alternatives for adaptation to climate change (2015).

As for adaptive capacity in the transport sector, the diversification of modes, the quality of the transport system, road planning and land use and occupation are some of the most recognized adaptation measures. Technical solutions that minimize the impacts of extreme events, such as weather warning systems and route alternatives, are also configured as adaptive, as well as the qualification of public transport and non-motorized modes as travel alternatives (LAH, 2019). The author points out that these measures, alone, are insufficient for the transition to low-carbon mobility and that policies that include taxes on fuels and vehicles integrated into compact urban planning are needed. In addition, large investments in transport infrastructure generally have shorter shelf lives and, given the rapid advance of climate impacts, may be poorly resilient (KOETSE; RIETVELD, 2012).

The Bogotá Declaration for Sustainable Transport (BOGOTA, 2011), of which Brazil is one of the signatory countries, adopts the "avoid-change-improve" approach to align transport with the Principles of Sustainable Development and implies solutions similar to those of the *Working Group on Sustainable Urban Transport* (WGSUT): avoid inefficient or unnecessary travel, change the mode of transport to less polluting options and generate low-carbon transport solutions through improvements in technology, regulation, operation and infrastructure to make the offer more environmentally efficient.

## 1.2 SMART CITY AND MOBILITY

Although the definition and conceptualization of smart cities emerged in the 1990s, the scientific literature does not provide a consensus (NEIROTTI *et al.*, 2014). However, reducing the idea of smart to [5]technological tools does not translate the potential of this model of urbanity into sustainable and socially inclusive initiatives. Still, Information and Communication Technologies (ICTs) represent the foundation of a smart city (CARAGLIU; DEL BO, 2019; KITCHIN, 2015; BATTY *et al.*, 2012; NAM; PARDO, 2011). ICTs have even made it possible for the world to be structured as a networked society, in which economic and social phenomena occur almost instantaneously (CASTELLS, 2007). A recent example of this digital revolution was the COVID-19 pandemic, which accelerated new habits, such as remote work (telecommuting or *home office*) and flexible working hours, the main reason for daily commuting, also configuring a paradigm shift made possible by technology.

Even so, the technological integration with socio-environmental aspects was only deepened after Giffinger *et al.* (2007), which amplified the characteristics of a smart city from six approaches: i) smart economy, ii) smart people, iii) smart governance, iv) mobility, v) smart environment, and vi) smart life (Table 4). The authors also point out the need for accessible and sustainable transportation, as well as the balanced use of natural resources in this sector.

Bai *et al.* (2018) define smart cities and ICTs as a new and important concept among the priorities to address the impacts of climate and global warming in cities. Among the disruptive technologies, the authors cite the digital control of resources, such as energy, water, and transportation, to prevent climate risks from hitting these systems simultaneously. For example, concomitant

[5] The expression *smart city* emerged in the 90s by IBM, when it was going through a period of crisis with the arrival of new technology companies, such as Microsoft and Apple. The company has seen the growth of cities as a potential for new business and innovation. Source: Söderström *et al*. (2014).

disruptions lead to shortages of food, money, and fuel, as happened in New York after Hurricane Sandy in 2012. Materials such as cement, which absorb CO2 – cement production is the third largest source of emissions in industry (5.6%), after the burning of fossil fuels and changes in land use – can be sustainable and low-cost solutions (BAI *et al.*, 2018).

Table 4. The six dimensions that characterize a smart city

| Dimension | Characteristics |
|---|---|
| **Smart economy (competitiveness)** | Innovative spirit;<br>Entrepreneurship;<br>Economic image and brand;<br>Productivity;<br>Flexible labor market;<br>International insertion;<br>Ability to transform. |
| **Smart people (human and social capital)** | Level of qualification;<br>Affinity with "*life long learning*";<br>Ethnic and social diversity;<br>Flexibility;<br>Creativity;<br>Cosmopolitan spirit and "open-mindedness";<br>Participation in public life. |
| **Smart governance (participation)** | Participation in decision-making;<br>Public and social services;<br>Transparency;<br>Political strategies and perspectives. |
| **Smart mobility (transport and ICT)** | Local accessibility;<br>International accessibility;<br>Available ICT infrastructure;<br>Safe, sustainable and innovative transport systems. |
| **Smart environment (natural resources)** | Attractiveness of natural resources;<br>Conditions;<br>Pollution;<br>Protection of the environment;<br>Sustainable management. |
| **Smart lifestyle (quality of life)** | Cultural services;<br>Health conditions;<br>Individual safety;<br>Housing quality;<br>Education services;<br>Tourist attractiveness;<br>Social cohesion. |

Source: Translated and adapted from Giffinger *et al.* (2007).

In developing this concept, other authors have highlighted the role of collaboration between public and private actors to encourage innovations in smart cities (AHVENNIEMI *et al.*, 2017) and civil society participation in decision-making (DEAKIN; AL WAER, 2011), with a more people-centered vision with technology as a support to improve the quality of life in cities (NEIROTTI *et al.*, 2014; ANGELIDOU, 2015).

Making, building or adapting smart cities seems to be a natural path for large urban centers. Inserting Information and Communication Technology (ICT) in the construction of an urban environment with more efficient services and infrastructure requires a socio-technical transition (TS). Broto and Bulkeley (2013) point to experimentation as a global trend in urban climate governance in this social paradigm, in which municipal governments formulate interventions, processes, and instruments that help accelerate climate action at the local level. In addition, Geels *et al.* (2018) argue that transformation can occur when actors alter the strategic direction to encompass a change, depending on organizational elements readjusted from underlying habits, beliefs, and values. Here, transformation is interpreted as a set of processes through which existing regimes are gradually modified in terms of technologies, institutions, and culture.

The Brazilian Charter for Smart Cities[6] is an initiative of the General Coordination of Support to Regional and Urban Management of SMDRU/MDR to define a concept of "smart cities" for Brazil and an agenda for the digital transformation of Brazilian cities in a sustainable way. The document was written collaboratively with the support of the German Cooperation Agency GIZ and in partnership with the Ministry of Science, Technology and Innovation (MCTI), the Ministry of Communications (MCom), as well as 126 public and private institutions involved in public policies for territorial, technological and environmental development, arriving at the following definition:

> "Smart cities are cities committed to sustainable urban development and digital transformation, in their economic, environmental and socio-cultural aspects, that act in a planned, innovative, inclusive and networked way, promote digital literacy, collaborative governance and management and use technologies to solve concrete problems, create opportunities, offer services efficiently, reduce inequalities, increase resilience and improve the quality of life for all people by ensuring the safe and responsible use of data and information and communication technologies."

One of the most discussed problems in smart cities concerns smart *mobility*, which is already changing the transport system with initiatives such as electrification, connectivity, ride-sharing and vehicle autonomy. But this field of study is permeated by controversy. Obringer and Nategui (2021), for example, in an article reviewing the concept of smart cities in the Anthropocene, [7]point out the challenges associated with the environmental footprint of smart technologies, such as the increased use of energy and the generation of electronic waste, such as batteries. Still, most research concludes that the technology is beneficial to the process of reducing carbon emissions in the sector (LAH, 2017; BONDOROVÁ; ARCHER, 2017; NAKAMURA; HAYASHI, 2013).

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[6] Available in https://www.gov.br/mdr/pt-br/assuntos/desenvolvimento-urbano/carta-brasileira-para-cidades-inteligentes/CartaBrasileiraparaCidadesInteligentes2.pdf. Accessed May 12, 2021.

[7] The term "Anthropocene" was proposed by Paul Crutzen and Eugene Stoermer to define the geological era that would succeed the Holocene. One of its premises would be that human beings have become a geological force and play a decisive role in climate change already underway (Crutzen and Stoermer, 2000).

## 1.3 DECARBONISATION TECHNOLOGIES IN TRANSPORT

### 1.3.1 Ridesharing

In the shared systems axis, Uber and 99 are the brands best known by Brazilians and operate systems called door-to-door transportation networks. Fulton *et al*. (2017) concluded that the global car fleet could be reduced by a third if sharing were widely adopted.

Some authors have questioned the effectiveness of this reduction, since sharing is directly associated with increased use of private and shared cars, in addition to reducing the impact of manufacturing and parking, but it is essential to integrate this mobility resource into a multimodal model of sustainable transport (BAI *et al.*, 2018; BONDOROVÁ; ARCHER, 2017).

### 1.3.2 Electric and autonomous vehicles

Electric car sales doubled in 2021 to a new record high of 6.6 million (IEAb, 2022). But the future of this market depends on diversifying batteries and mineral supplies, such as lithium, cobalt, graphite, and nickel, to reduce the risks of bottlenecks and rising prices. Although the international outlook is good, the electrification of the fleet in Brazil faces challenges. The provision of infrastructure for battery charging in cities and homes and the commercialization of the electricity needed to supply vehicles represent barriers to its implementation at scale.

The Brazilian vocation for ethanol is the main justification of those who defend the postponement of the entry of the electric vehicle in Brazil, and some bodies in the sector are beginning to support the idea of developing flex hybrid technology*, which would associate the electric motor with* the flex engine, making it possible to take advantage of the infrastructure of the sugar and alcohol industry already installed in the national territory.

A report by McKinsey and Bloomberg New Energy Finance supports an integrated vision for the future of mobility that points to three axes of innovation: sharing, electrification and autonomous, and predicts that changes will have to occur at the local level, in large urban centers (BOUTON *et al.*, 2017). In line with this trend, the main traditional automakers already have autonomous and electric vehicle projects. The main obstacle in electrification concerns the energy matrix of the countries that produce the batteries and their disposal, since their recycling is complex and requires specific technology.

Autonomous vehicles have the potential to reduce GHG emissions per kilometer by up to 94% by 2030, compared to conventional combustion-powered vehicles (LAH, 2019). They also generate repercussions due to records of fatal accidents that have occurred in recent years and require intensive data processing from multiple sensors in real time to perform tasks of perception of the external environment, and making this type of solution more expensive.

Still, the future for this market in Brazil is seen with optimism with the arrival of Chinese companies BYD, which announced an investment of [8] R$ 3 billion in three factories in Bahia to launch the first 100% electric car produced in the country, and TEVX Higer, an assembler of electric buses and trucks, which will have two factories in the country[9]. The National Bank for Economic and Social Development (BNDES) will also provide R$ 200 million for infrastructure and sustainable mobility, [10] under the Rota 2030 program, created by the Federal Government in 2018 to support the production of hybrid cars, electric buses and related products.

### 1.3.3 Renewable energy

The historical results show that the participation of renewable energy in the activity of passenger transport (automobiles and light commercial vehicles) in Brazil is significant, being the country a pioneer in the use of sugarcane for the production of fuel. As for biodiesel, the country has 59 plants, with an installed production capacity of 13.8 billion liters per year. The main feedstock for biodiesel produced in Brazil is soybean oil (70%), followed by animal fat (20%) and recycled cooking oil, and seasonally palm oil and cottonseed oil (10%) (EPE, 2020).

The emissions avoided by the use of first-generation ethanol, biodiesel, and sugarcane bioelectricity in 2021 were 47.9 Mt$CO_2$e, 19.0 Mt$CO_2$e, and 4.3 Mt$CO_2$e, respectively, adding up to 71.2 Mt$CO_2$e. As for biogas, it is noteworthy that its installed capacity in distributed generation reached 43 MW, with agro-industrial, animal and urban waste as input. In addition, its share in the domestic supply of energy (0.12%) grew by 22% per year in the last five years.

In 2021, the National Biofuels Policy (RenovaBio) completed its first full cycle of operationalization in the organized market. As of December 2021, 272 production units were certified, most of which were ethanol. Through CNPE Resolution No. 17, of October 2021, it defined mandatory annual GHG emission reduction targets for the sale of fuels. The government's approval to increase the blend of biodiesel in fossil diesel (from 10% to 12% in 2023), which is expected to reach 15% in 2026, is part of a program that sets mandatory targets for reducing emissions. As a result, the country must stop importing and burning 1 billion liters in 2023, reaching up to 4 billion in 2026 (EPE, 2020), in order to reach the goal set by RenovaBio[11]. But this solution also involves controversies regarding

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[8]Available at https://www.capitalreset.com/byd-sera-primeira-a-fabricar-carro-eletrico-no-brasil.
[9]Available at https://www1.folha.uol.com.br/colunas/eduardosodre/2023/07/fabricante-chinesa-de-onibus-eletricos-confirma-segunda-fabrica-no-brasil.shtml.
[10]Available in https://www1.folha.uol.com.br/colunas/painel/2023/07/bndes-disponibiliza-r-200-milhoes-para-cadeia-de-carros-hibridos-e-onibus-eletricos.shtml.
[11] RenovaBio is an initiative of the Ministry of Mines and Energy (MME), launched in December 2016, which aims to expand the production of biofuels, based on predictability and environmental, economic and social sustainability. It is guided by three strategic axes: 1) Decarbonization Targets, 2) Biofuel Production Certification and 3) Decarbonization Credit (CBIO).

the raw material, which requires a lot of water in the cultivation of its crops and, in addition, monocultures impoverish the soil.

In the city of São Paulo, the Climate Change Law of 2009 determined that the entire bus fleet should be renewed to be powered by clean energy by 2018, but due to the justification that today only 1% complies with the legislation, this determination was waived and there is a new bill in the Legislature changing the deadline for gradual implementation until 2037 (NICHI; ZULLO, 2021). There are 13,945 collectives, considering the vehicles in operation and reserve, to transport an average of 7 million passengers per working day (SPTRANS, 2021).

## 1.4 TRANSITION TO SMART AND SUSTAINABLE MOBILITY IN SOCIO-TECHNICAL SYSTEMS

Problems such as climate change cannot be solved by incremental improvements, but require systemic changes, also called sustainable transitions, which encompass modifications in production and consumption patterns related to the energy and transport sectors (MARKARD *et al.*, 2012).

These changes imply the evolution of stable structures linked to political, economic, social, cultural, market and technical factors, and configure socio-technical systems. Lifestyles, regulations, and institutional arrangements stabilize these systems in regimes that can take decades to consolidate due to their non-linear, open character, and reveal the multidimensional character of sustainable transition processes (STRN, 2019; MARKARD *et al.*, 2012; DWYER, 2011; HUGHES, 1989).

Among the main dimensions of the socio-technical transition are agencies and policies, governance, and civil society participation. In addition to the analytical approaches associated with technological innovation as the central theme of analysis, institutional aspects and those related to the actors of the system are considered (MARKARD *et al.*, 2012; RIP; KEMP, 1998). The multilevel perspective in socio-technical systems understands innovation as a process shaped by broader social contexts, in which rules and institutions configure structures that are both the context and the outcome of actors' actions, including levels of government (GEELS, 2019; GEELS; SCHOT, 2007). This analysis is also strategic for public managers in transition processes that bring together various social groups (companies, users, and civil society organizations), with different preferences, strategies, and resources in the formulation of the agency, such as the creation of meaning, learning, collaboration, competition, investments, and purchase, in social structures shaped by rules and institutions (GEELS, 2019).

Thus, in order to understand how the technological transition converges with public climate governance, this article works with the concept of socio-technical governance complemented by the concept of multilevel governance converging with multi-scalar solutions to complex problems, such as climate change, and which, therefore, must be managed at the various levels of government with cross-cutting impacts (DEWULF *et al.*, 2015; NEWELL *et al.*, 2012).

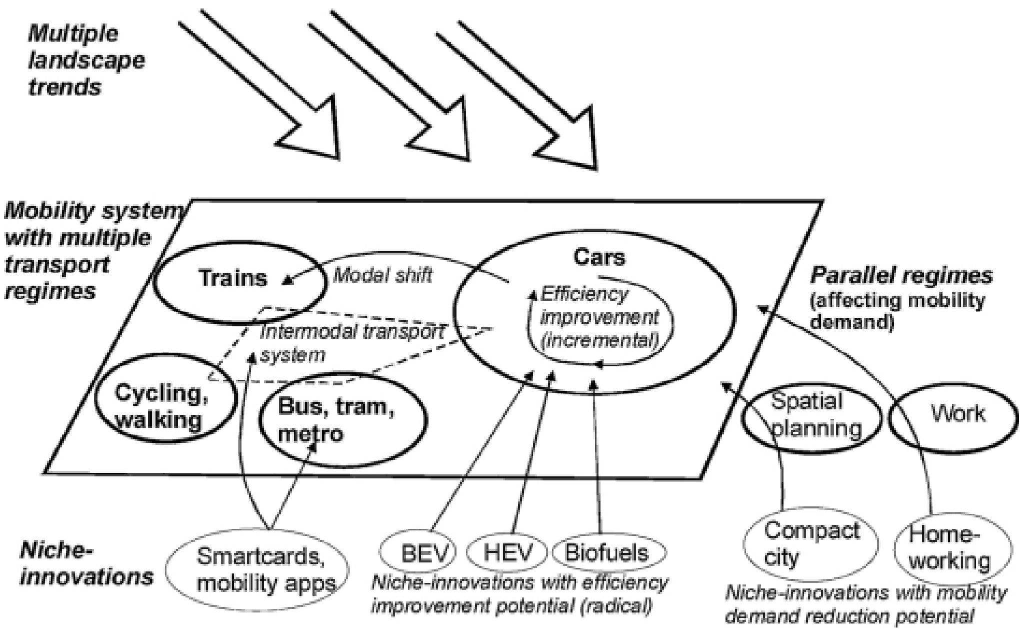
From a multilevel perspective, Geels (2018) comments that disruptions arise in niches (exogenous developments that influence the current regime), sociotechnical regimes (institutional structuring of systems through learning processes and support from power groups) or sociotechnical landscape (exogenous developments that influence niche and regime dynamics, creating windows of opportunity for innovations). Niche markets, for example, function as laboratories where users have special demands and are willing to support emerging innovations. Cities can also characterize laboratories, according to Broto and Bulkeley (2013), who call them "climate change experiments" imagined by (or on behalf of) an urban community to test technical and social interventions aimed at mitigating and adapting to climate impacts. Or even urban living labs, as spaces for experimentation for city planning (NICHI; CORTESE, 2022).

This process can be guided by three paths, according to Geels (2011): i) articulation of expectations and visions to attract attention and funding from external actors, ii) construction of networks to expand the base of actors and resources, and iii) learning and articulation processes that encompass market demands, user preferences, infrastructure, business models, public policies and symbolic representations, such as culture and beliefs. The author also points out that the participation of actors with political or socioeconomic power helps to legitimize innovations. Finally, the sum of the set of rules that guide the groups is the means and result of the action of actors who share practices, capacities, ways of life and values that configure institutional and regulatory arrangements (GIDDENS, 1984).

As an urban mobility system is also constituted by the interrelationship between technical and social processes, the transition to a future of sustainable urban mobility can be conceptualized as a socio-technical system (CANITEZ, 2019; NYKVIST; WHITMARSH, 2008). In this context, the analysis incorporates the rules and institutions that allow and constrain the actors that drive innovations. Marletto (2014) is one of the authors who approach urban mobility and transport from a socio-technical transition theory perspective to prove that the future of urban mobility depends on the participation of actors who support alternative transport systems.

The analysis of the results of this article follows the premise of Geels (2012), who suggests an analytical distinction between the socio-technical system, actors and institutions/rules to adapt the socio-technical map of the urban mobility system of São Paulo in order to represent the positioning of the actors (figure 10).

Figure 10. Multi-level approach adapted to the passenger mobility system

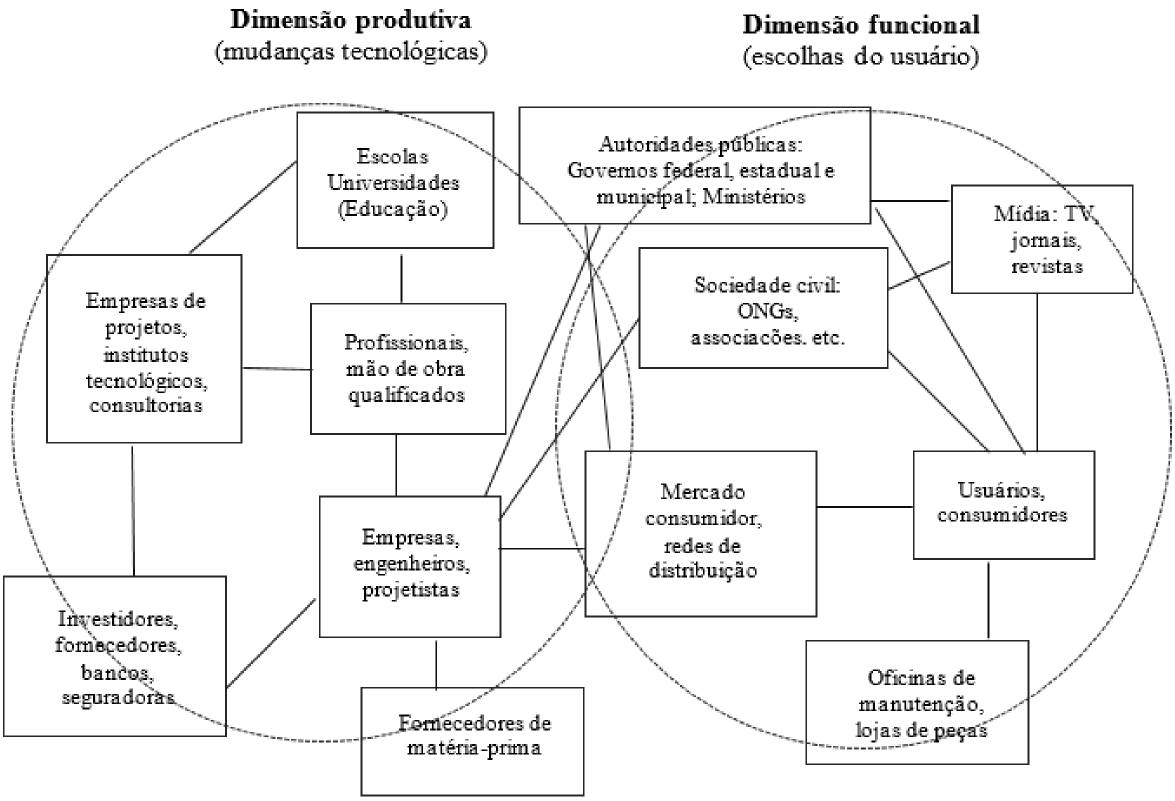



Source: Geels (2012).

A socio-technical transition, like climate environmental governance, requires multi-scale, multi-actor, and multi-level action. Multiscale governance refers to the different scales of the climate change adaptation problem, responsibilities at different levels of governance, and how to deal with the tension between scale and adaptation (BARBIERI; FERREIRA, 2018; DEWULF *et al.*, 2015; NEWELL *et al.*, 2012). With respect to technological changes, regulations and policies, road infrastructure, ICT use, user markets and practices, industry and structure and maintenance networks, and even the worldviews of actors, as well as the institutions that shape these visions, are equally relevant (CANITEZ, 2019; BANISTER, 2008).

It is worth mentioning that the reference to multiple actors refers not only to the public sphere, but also to companies, scientists, the media, civil society and NGOs (figure 11), all of which are fundamental in the conduct of environmental governance, sometimes acting in a network, through partnerships and coalitions (DEWULF *et al.*, 2015; GEELS, 2012).

Figure 11. Social groups that make up a multilevel socio-technical system




Source: Translated and adapted from Geels (2004).

Climate change experiments are sociotechnical because they attempt to intentionally change the material arrangements, cultures, norms, and conventions that determine GHG emissions and climate vulnerabilities in the city (BULKELEY *et al.*, 2011). In this way, the perspective of multilevel socio-technical transition presents a fruitful conceptual framework to understand the process of adoption of new technologies permeated by political, economic, social and cultural aspects and heterogeneous actors with particular interests at all levels (GEELS, 2012).

## 2 RESEARCH METHODS

Through a qualitative approach, this study makes a theoretical review based on secondary data based on the main sources of macroeconomic information from Brazilian and international public organizations on the transport and climate sector. The focus of the review was the nature of the process of developing and managing mobility in smart cities and its associated effects on climate mitigation and adaptation.

To empirically explore the potential of this approach, the characteristics and history of the low-carbon transition in passenger mobility in the city of São Paulo were analyzed based on the dynamics of the socio-technical regime and its actors (companies, government and civil society).

The main theoretical arguments were applied based on three objectives:

1) identify the characteristics of urban passenger transport technologies that aim to mitigate and adapt $CO_2$ emissions;
2) detect which actors and institutions are involved in this dynamic within the scope of the case study of the city of São Paulo;
3) understand the intersection of these technologies in the sustainable transition of the socio-technical mobility system.

## 3 RESULTS AND DISCUSSION

### 3.1 CASE STUDY: THE CHALLENGES OF URBAN MOBILITY IN SÃO PAULO

The Metropolitan Region of São Paulo (MRSP) is one of the largest urban agglomerations in the world, composed of 39 municipalities and more than 20 million inhabitants, concentrated in an urbanized area of more than 2,200 km². Due to its size and density, the region suffers from negative consequences inherent to the intensive use of motorized transport: pollution, congestion, road interventions, accidents and deaths.

The largest share of trips lasting more than 60 minutes is in public transport, totaling approximately 6,054 trips. In the city of São Paulo alone, between 2010 and 2022, the light car fleet increased from 5 million to more than 9 million (IBGE, 2022), representing about 7.4 vehicles for every 10 inhabitants of São Paulo (CET, 2018). Nationwide, the fleet reached 60.4 million automobiles in 2022 (MI, 2023). This growth is continuous and, between 2008 and 2018, the motorization rate in Brazil went from 19.6 cars per 100 inhabitants to 29.7 in 2018 (figure 12).

Figure 12. Historical series of increase in the car fleet in Brazil (2008-2018)

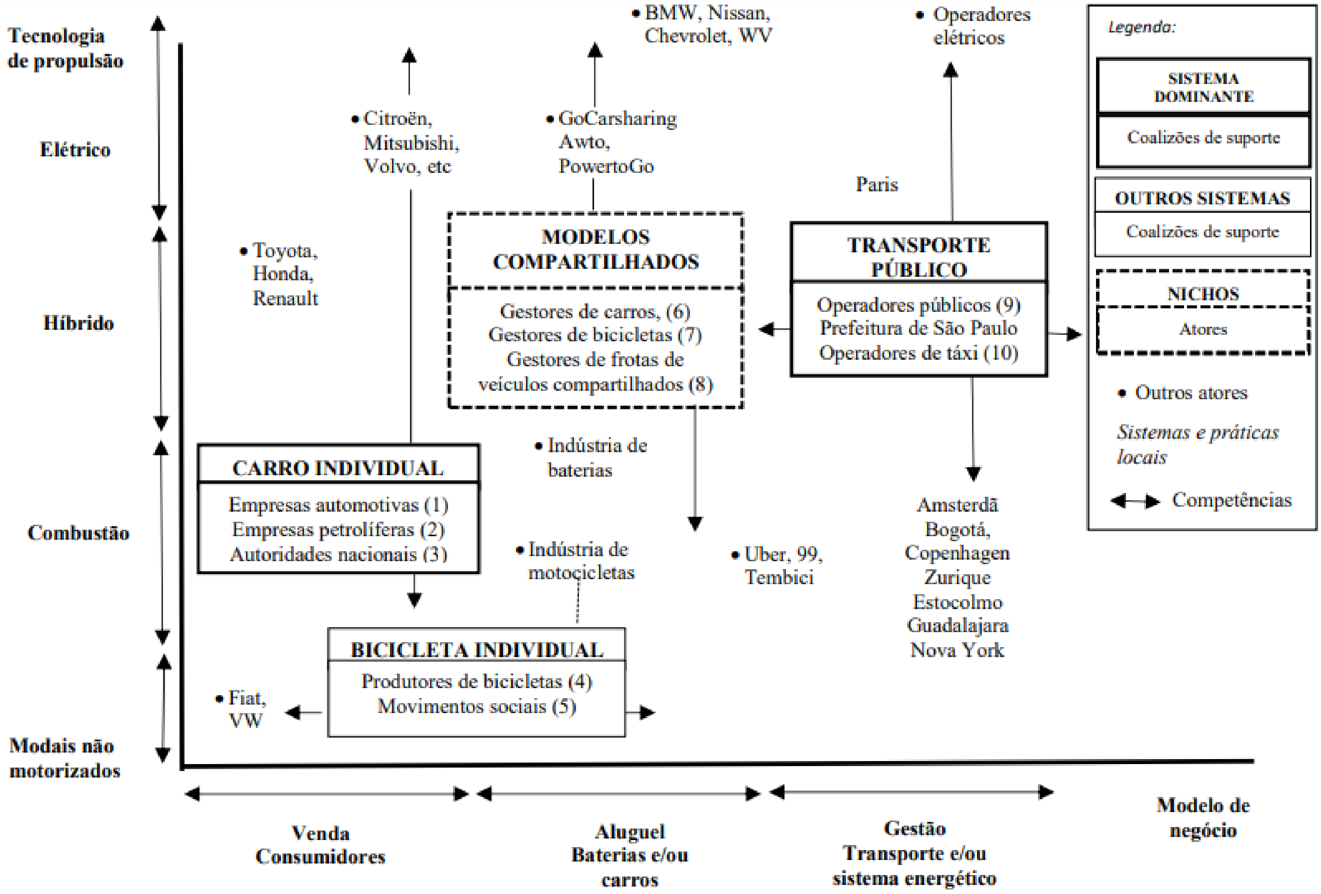

Source: Observatory of the Metropolis with data from Denatran (2019).

The discrepancy between the number of trips in the collective and individual modes reflects the territorial imbalance that reinforces social inequalities by "pushing" the poorest to the fringes of the city. Those with lower incomes, for the most part, use public transportation daily, traveling long distances in a long period of commuting to and from work, usually located in the expanded center of São Paulo, where economic activities are concentrated.

## 3.2 ACTORS AND INSTITUTIONS

This section uses the multilevel perspective to analyze the opportunities and barriers for a socio-technical transition from the reconfiguration of the low-carbon transport system in the city of São Paulo with the survey of actors and institutions that make up its mobility system. After this framing by actors, the multilevel perspective was configured to unveil the low-carbon mobility system according to the socio-technical transition approach (figure 13; table 5).

Figure 13. Sociotechnical map of São Paulo's mobility system




Source: Authored by the authors, adapted from Geels (2017).

Table 5. Survey of organizations and actors by modal complementary to figure 13

| System/Modal | Actors/Institutions | Companies/Organizations |
|---|---|---|
| **CARRO INDIVIDUAL** | (1) Automotive companies | AGCO, Caterpillar, CNH New Holland, Chery, Chevrolet, Honda, Great Wall, Hyundai, Komatsu, Mercedes-Benz, Scania, Toyota, Valtra, VW, John Deere. |
| | (2) Oil companies | Petrobras, Ecogen, Grupo Sol, Equinor, Karoon, Total, Shell, Cosan, BP do Brasil, Chevron, Engevix, Exxon Mobil, Maersk Oil, OGX, Nord Oil and Gas, Repsol Sinopec. |
| | (3) National authorities | National Secretariat for Mobility and Regional and Urban Development, Department of Mobility Projects and Urban Services, National Department of Traffic (Denatran), Ministry of Cities, Detran (Department of Traffic). |
| **SINGLE BIKE** | (4) Bicycle Producers | Alvoteq, Athor Bikes, Dream Bike, GTSM1, KSW Bikes, Track Bikes, Vela Bikes, Vzan. |
| | (5) Social movements | Go by Bike, Bicicletada, CicloBR, Ciclocidade, Pedal Verde, Pedalinas, União de Ciclistas do Brasil, Bike dos Anjos, Ciclistas do Brasil, Bike Tour SP, Ciclocentro, Sampa Bike, Bike Amigo. |
| **SHARED TEMPLATES** | (6) Car Managers | Uber, 99, MobilizaSP, PrimeYou, Lyft, BlaBlaCar, Waze Carpool, Zazcar, MoObi, Letz, Turbi, Lady Driver, inDrive. |
| | (7) Bicycle Managers | Yellow, Chica, MoBike, Tembici, BikeSampa, CicloSampa/PegBike, Jump, Tembici, Bike Itaú, Scoo. |
| | (8) Shared Vehicle Fleet Managers | Turbi, Ostengo, BMW i3, Awto, Beepbeep, Joycar, Golfleet, Fleet Mobility, Plantech, NEXTFleet, Fleety, PegCar, ALD Sharing, Ucorp, Scoo, Riba Share. |
| **PUBLIC TRANSPORT** | (9) Public operators | Companhia Paulista de Trens Urbanos (CPTM), Metrô SP – Companhia do Metropolitano de São Paulo, ViaQuatro, Empresa Metropolitana de Transportes Urbanos (EMTU), Companhia Brasileira de Trens Urbanos (CBTU); bus concessionaires: Sambaíba, Consórcio Bandeirante de Mobilidade, Viação Metrópole Paulista, Via Sudeste, Viação Metrópole Paulista, Viação Gatusa, etc. |
| | Sao Paulo City Hall | Municipal Secretariat of Mobility and Traffic: Executive Secretariat of Transport and Urban Mobility (SETRAM), Department of Public Transport (DTP), Inspection and Inspection Division (DIF), Division of Registration and Control of Differentiated Transport (DTD), Division of Free School Transport (DTEG), Division of Cargo Transport (DTC), Division of Support to Traffic Inspection (DSUP), Municipal Council of Traffic and Transport (CMTT), Traffic Engineering Company (CET), São Paulo Transport (SPTrans), among other divisions. |
| | (10) Taxi operators | Radio Taxi, Delta Association, UnionServ Cooperative, Top Taxi, Warning Taxi, Italtaxi, MT Cooperative, Use Taxi, Taxi Warning, Teletaxi, Jowal, CooperTax. |

Source: Prepared by the authors, adapted from Geels (2014, 2018).

### 3.2.1 Companies

Automakers that have received tax and financial incentives in recent decades are struggling to stay competitive in the face of underutilization of factories and cost pressures, market saturation in developed countries, and new generations[12] less interested in buying a car. In response, these companies focused on costs, mergers, improvements in production efficiency, emerging economies, and technological innovation related to performance, comfort, and safety (GEELS, 2018). Automakers are also facing pressure from society and governments regarding the impacts of their actions on climate variability, especially at the local level, and seek to gradually improve their combustion engines and develop vehicles powered by alternative or electric fuels. Results of a survey[13] released in June 2023 with data from 2022 reinforce the role of governments in the climate agenda: 79% of Brazilians are concerned about climate change and 74% think that the main cause is human action, with the majority believing that the greatest contribution to solving the problem should come from governments and companies. More than half of the 2,600 respondents said they had voted for a politician because of his environmental proposals.

The relevance of the real estate sector in the economy of the city of São Paulo is the result of its urbanization model, marked by real estate speculation, in which central lots were left empty as investments and those located in peripheral regions were sold to the poorest population. This process resulted in the fragmented growth and spread of the city (BACELLI *apud* BARBOSA, 2001). As a consequence, spatial accessibility still generates congestion, overcrowding of public transport and lack of access to public facilities in the peripheries, driving "territorial exclusion" (ROLNIK, 1999), since the most vulnerable population faces long and uncomfortable journeys to work and access urban services.

From 1920 onwards, the road model became the focus of development policies in the city, privileging individual motorized transport. At the beginning of the twenty-first century, mass transit received an abundance of public investment, but much of it was spent on subsidies rather than increasing transport capacity (ROLNIK; KLINTONWITZ, 2011).

From the beginning, in the 1950s, the automotive industry in Brazil adopted the policy of "import substitution", which brought factories of multinationals instead of developing local technologies. Currently, the sector is going through a moment of crisis, symbolized by the departure of the American automaker Ford from the country, in 2019, where it had been since 1919. But the bet on the sector continues to guide political ambitions, such as the billionaire package of incentives for the automobile industry in São Paulo, IncentivAuto, which provides discounts of up to 25% on ICMS for companies that invest at least R$ 1 billion in factories and product development. Another recent example is the approval, at the federal level, of the Rota 2030 project, which grants tax exemption to

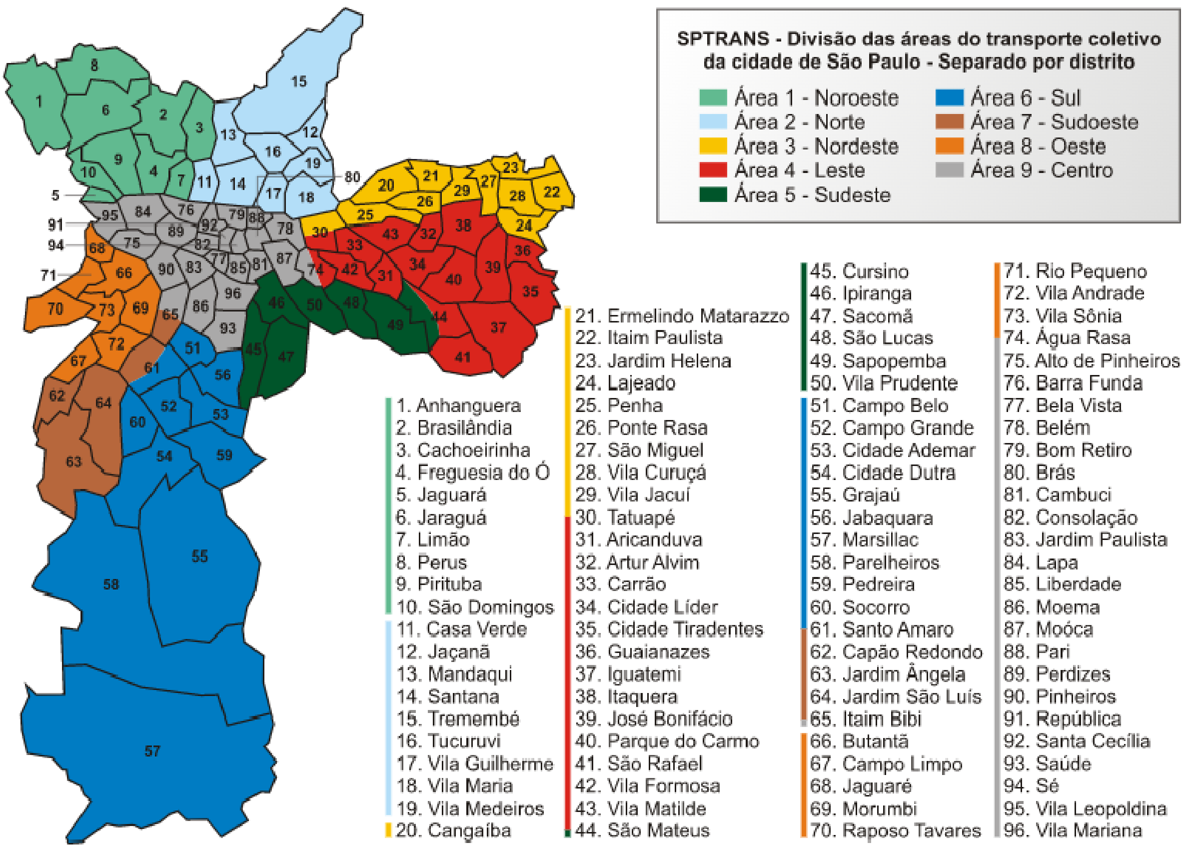
[12] Available at: https://automotivebusiness.com.br/pt/posts/noticias/geracao-z-deixara-de-comprar-250-mil-carros-em-2030/.
[13] Climate Change in the Perception of Brazilians – 2022 Survey, conducted by Intelligence in Research and Strategic Consulting (IPEC) at the request of the Rio Institute of Technology and Society (ITS). Available at https://itsrio.org/wp-content/uploads/2023/06/221715_PERCEP%C3%87%C3%83O-SOBRE-QUEIMADAS_R3_15.03.pdf. Accessed July 6, 2023.

the automobile industry, with the counterpart of investments in electric and autonomous vehicles. But it is relevant to point out that this type of solution addresses only one environmental problem: the burning of fossil fuels. Regardless of the technology, automobiles take up space, cater to the few, and encourage travel over long distances.

As for public transport, 11,312 buses circulate every day in the capital of São Paulo, transporting about 2.15 million passengers, corresponding to 65% of the demand registered before the arrival of the pandemic. Indicative of the impact of social distancing due to COVID-19 in terms of unemployment and change in the work model.

According to the Union of Urban Collective Passenger Transport Companies of São Paulo (SPUrbanuss), the city currently has 32 urban bus terminals and 23 public transport concessionaires authorized to operate in lots, which divide the 96 districts into 9 areas (figure 14).

Figure 14. Division of collective concessionaire lots by area and districts




Source: Denis Gomes with data from SPTrans. Creative Commons. Excerpted from https://pt.wikipedia.org/wiki/S%C3%A3o_Paulo_Transporte.

On the intercity lines, 500 routes serve the cities of the Metropolitan Region of São Paulo, managed by the State Government through the Metropolitan Company of Urban Transport (EMTU), with 19 thousand stopping points. In the train system, the Metropolitan Region has 74.3 km of railroad tracks, distributed in five lines connected by 64 stations (58 operated by the Metro and 6 by ViaQuatro), responsible for managing 150 trains, which transport almost 900 thousand people every year.

Regarding measures to restrict travel and improve mobility, the municipality instituted the rotation of vehicles, also called Peak Hour Operation (Municipal Law 12.490/1997), which limits the circulation of motor vehicles between 7 am and 10 am, and from 5 pm to 8 pm, divided by day of the week and number of corresponding license plates. But one of the most celebrated initiatives was the process of installing bike lanes in 2014, reaching the current 667.1 kilometers, although it is not a consistent policy throughout the city, since most of the collection points are concentrated in the expanded city center (figure 15).

Figure 15. Shared bicycles of the Bike Itaú program on the *campus* of the University of São Paulo


Photo: Marcos Santos/USP Images.

The Cycling Plan of the city of São Paulo foresees a network of 1,800 km by 2028, with priority for connection to public transport and the expansion of the network's capillarity to all regions of the city (CET, 2023). However, it should be noted that the intermodal strategy (car, subway and bicycle) is still limited to the central regions of the city.

### 3.2.2 Civil society

(I)mobility in the city of São Paulo is affected by poor quality and unevenness in sidewalks and asphalt, insufficient or damaged traffic lights, lack of accessible roads, safety problems for women, pedestrians and cyclists, among other infrastructure failures that make it impossible to fully use public space in active modes, such as walking and cycling.

The cost of travel is another critical component. Brazil is in the 36th position *in the ranking* of countries with the most expensive monthly buses, subways and trains in the world. Considering only the current cost of the municipal fare (R$ 4.40), the cost of round-trip public transportation in 20 working days represents about 17% of the minimum wage. Compared to large cities, such as New York (7.70%) and Paris (4.58%), transportation is one of the services that most burden Brazilian workers, according to data from Numbeo.[14] In addition, the quality of public passenger transport[15] requires improvements throughout the country, as it is overloaded and with records of routine accidents. The Institute of Applied Economic Research (IPEA) estimates a cost of R$ 50 billion in expenses related to traffic accidents and deaths, with 15% of admissions to public hospitals of victims of traffic accidents and 45 thousand victims every year (IPEA, 2015).

Between 2007 and 2021, the Atlas of Accidents in Brazilian Transport[16] counted 1.9 million accidents, with a total of 104,745 deaths, 4,716 in the State of São Paulo alone. At the municipal level, the death rate disclosed by the Safe Mobility Observatory in 2020 [17] was 806 deaths and traffic accidents (6.56 deaths per 100 thousand inhabitants), which motivated the City Hall to include in the 2021-2024 Goals Program[18] the objective of reducing this rate to 4.5 deaths per 100 thousand inhabitants.

Other losses resulting from the lack of adequate transport infrastructure affect productivity and health due to congestion levels, which in the metropolis reach 1% of the Brazilian GDP (CINTRA, 2014). The expenses generated by the loss of production due to traffic in São Paulo increased from R$ 17 billion in 2002 to R$ 40 billion in 2012. Although the city occupies the 48th position among those with the worst traffic in the world, the São Paulo resident spends an average of 56 hours a year stuck in traffic, at an average speed of 22.4 km per hour (38 km/h at peak times). Thus, far from the leader *in the ranking*, the city of London, where drivers can spend up to 156 hours per year in traffic jams (INRIX, 2022).

The anthropogenic effects on the climate in São Paulo could be verified from the COVID-19 pandemic. In the capital, migration to coastal and inland cities and the closure of shops and offices

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[14] Available at: https://www.numbeo.com/cost-of-living/.
[15] Public public passenger transport is an essential public service, and the organization and provision are the responsibility of the municipality, as provided for in the Federal Constitution (article 30, item V) and in the Organic Law of the Municipality of São Paulo (article 172). The organization of this service in the city of São Paulo is described in Law No. 13,241, of December 12, 2001, which considers that the Government is represented by the City Hall of the Municipality of São Paulo through the Municipal Department of Transportation (SPTrans, 2023).
[16] Available at: https://www.atlasacidentesnotransporte.com.br/.
[17] Available at: http://mobilidadesegura.prefeitura.sp.gov.br/.
[18] The Goals Plan is a planning and management instrument that helps municipalities define the government's priorities and strategic actions throughout the four years of the mandate. Available in https://www.prefeitura.sp.gov.br/cidade/secretarias/governo/planejamento/programa_de_metas_20212024/. Accessed April 21, 2023.

caused pollution to fall by 50% and the rate of pollutants that trigger respiratory diseases to be reduced by 30% (CETESB, 2020). In addition, there was a 31.3% drop in deaths in traffic accidents (68 deaths against 99) in the State of São Paulo between March 24 and 31, 2020, the beginning of the quarantine, as a measure to face the coronavirus, compared to the same period of the previous year (INFOSIGA SP, 2020).

The urban model of the city of São Paulo presents several examples of policies that favor the motor vehicle to the detriment of citizens. One of the most emblematic is the "Minhocão" (Elevado Presidente João Goulart), built in 1971 by the then governor Paulo Maluf to solve road problems in the East-West interconnection. With 2.8 km in length, the road is the subject of discussions about its relevance and problems generated for the residents of the region. Its overthrow was approved by the Constitution and Justice Commission in 2019 (PL 98/2018) and in 2021 the Court of Justice upheld a request made by the Public Prosecutor's Office to bar the construction of a park in the region due to a lack of urban planning in the City Hall project. The councilors then appealed and the case will be judged by the Federal Supreme Court (STF).

The creation of a park in the "Minhocão" is an indicator that São Paulo has advanced in policies of right to the city. In 2016, Avenida Paulista began to be closed to cars on Sundays and holidays, promoting cultural and leisure activities along its entire length. The Elevado itself (figure 16) is closed for the exclusive use of pedestrians on Saturdays, Sundays and holidays.

Figure 16. Traffic on the Presidente João Goulart Highway, in downtown São Paulo

Source: Rovena Rosa, Agência Brasil.

The transport sector has also catalyzed demands from social movements, many mediated by ICTs, such as access to information and data transparency, pressure to increase supply and reduce prices. The 2013 demonstrations organized by social networks emerged from the population's dissatisfaction with the increase in bus fares. The "June Days", as they became known, reveal new formats of popular participation and social control mediated by technology (GIARETTA; DI GIULIO, 2018). However, although the country has a high percentage of the population with access to the Internet, [19]there are barriers to the universalization of the service, either due to the cost of mobile Internet or technical weaknesses (FÓRUM MOBI, 2018).

The intensive use of technology, such as the digitization of services, applications, sensors, and cameras, especially on cell phones, generates a massive volume of data that helps to understand reality and identify new demands from the population for services and products. The interpretation and cross-referencing of these data, if used strategically, can support policy decision-making based on a systemic analysis updated in real time. However, the need to regulate the use of this data generates debate about the ownership of this information. In this context, the regulatory framework of the Data Protection Law (LGPD) – No. 13,709/2018 – aims to ensure the privacy and security of users. Similarly, Batty *et al.* (2012) indicate that government regulations should protect data and model development, appropriate interfaces, security of who can and cannot access online material, confidentiality issues, privacy, and intellectual property rights in a smart city framework.

### 3.2.3 Government

Transportation in Brazil is defined as a citizen's right in the Federal Constitution of 1988, which establishes that the public transportation system is an essential service, with its management transferred to the municipalities, but without mentioning the source of funds for any federated entity (VASCONCELLOS *et al.*, 2011).

The legislation clarifies the competences of the three levels of government: the Union is responsible for establishing traffic laws and regulations; to the States to license vehicles and drivers; and municipalities to be responsible for the construction and maintenance of public roads, regulate their use, manage the system and monitor compliance with traffic legislation and standards (OECD, 2014). The budget of the Municipal Secretariat of Mobility and Traffic is around R$ 5 billion and the Municipal Fund for Traffic Development is close to R$ 1.5 billion. In 2021, however, the operating cost of public transport was R$ 7.7 billion, an imbalance that reinforces the neoliberal logic that tends

[19] The number of households with Internet access in Brazil reached 90%, according to data from the National Household Sample Survey. In absolute terms, there are 65.6 million connected households. In the State of São Paulo, the percentage is 85% (13.2 million households). However, 28.2 million Brazilians (3.6 million of them students) are still not connected (IBGE, 2022).

to generate selective responses to climate risks and a limited interest in changing the structural conditions of the traditional automotive regime.

Still, climate change is part of São Paulo's agenda. In 2003, the city joined the Cities for the Climate campaign; in 2005, he joined the *Cities Climate Leadership Group* (C40), among the cities committed to reducing GHG emissions and mitigating climate impacts. Both networks encouraged the municipality to make other commitments, including a GHG inventory (SETZER *et al.*, 2015), which denotes that pressure from international organizations stimulates socio-environmental commitment at the local level.

As a global city, São Paulo is a source of innovation and major transformations, leading the adaptation processes in the country (BARBI, 2018; SETZER *et al.*, 2015; DI GIULIO *et al.*, 2017; MARTINS; FERREIRA, 2011). In 2009, it became the first Brazilian city to launch a Climate Change Policy with goals that include mandatory emission reductions. This initiative influenced the approval of the São Paulo State Policy, which, in turn, motivated the creation of the national policy on climate change (BARBI; FERREIRA, 2013).

Other environmental policies are added to this agenda: the Green Procurement Policy (2007), the Vehicular Pollution Control Plan (2007) and the Sectoral Transport and Urban Mobility Plan for Climate Change Mitigation (2013). More recently, it launched the Steering Committee of the Program for Monitoring Fleet Replacement by Cleaner Alternatives (2019) and, in June 2021, the Climate Action Plan of the Municipality of São Paulo (PlanClima), developed in partnership with C40, with 43 actions to zero GHG emissions by 2050, whose strategies include improvements in "walkability" on the way to the bus stop, to the increase in the attractiveness of the municipal bus system (Chart 6).

Table 6. Adaptation and mitigation measures in the urban passenger transport sector and guidelines of the Transport Sector Policy

| Adaptation measures | Mitigation measures | Local Initiatives – Sao Paulo |
|---|---|---|
| . New modes of transport and smarter infrastructure;<br>. Water emergency systems for tunnels and subways;<br>. Adaptation of roads and dikes to create compartments;<br>. Infrastructure protection;<br>. Design spatial planning – build new housing and infrastructure. | · More efficient fuels;<br>· BRT bus fast lines;<br>· Stagnation of the absolute volume of vehicles;<br>· Active management of vehicle traffic;<br>· Promotion of public transport;<br>· Increased use of alternative fuels;<br>· Technological improvement of vehicles and engines;<br>· Town planning. | · Vehicular Pollution Control Plan – PCPV (2011);<br>· Installation of intelligent traffic systems for vehicles and highways;<br>· Research Origin/Destination of Cargo and Passenger Movement in the Municipality of São Paulo, whose results support measures to optimize trips and traffic fluidity;<br>· Restriction on the Traffic of Motor Vehicles in the Municipality of São Paulo (Municipal Vehicle Rotation) – Municipal Law No. 12,490/97 and Decree No. 37,085/97;<br>· New modes of travel are being implemented, such as subway lines and BRTs;<br>· Expansion of the supply of public transport and encouragement of the use of means of transport with less polluting potential and emitter of greenhouse gases;<br>· ECOFROTA Program, which introduces buses that use less polluting technologies into the municipality's public transport fleet (Law No. 14,933/09);<br>· Encouragement of non-motorized transportation, with emphasis on the use of bicycles; |

| | | |
|---|---|---|
| | | · Implementation of exclusive lanes and lanes for collective buses and trolleybuses (570 km of exclusive lanes and 131.2 km of corridors by 2022) – SPTrans (2023);<br>· Regulation of circulation, stopping and parking of chartered buses through SMT ordinances;<br>· Exclusive lanes for vehicles with an occupancy rate equal to or greater than two passengers;<br>· PMSP only acquires or hires transportation services with *flex-fuel* vehicles and the use of ethanol;<br>· PMSP, through SMT, signed a memorandum of understanding with ELETROPAULO and RENAULT/NISSAN in order to study and enable projects that enable the introduction of electric vehicles in the city of São Paulo;<br>· SMT, through CET, has been replacing the lamps of the traffic light groups with LEDs;<br>· Vehicle Inspection and Maintenance Program for the entire fleet of motor vehicles, including motorcycles. |

Source: Adapted from Koetse and Rietveld (2012), Wolff *et al*. (2017); Sectoral Plan for Transport and Urban Mobility for Mitigation and Adaptation to Climate Change (PSTM, 2013); National Secretariat for Mobility and Regional and Urban Development (SEMOB, 2019).

In transportation, the City Hall also invests in connectivity, and among the most recognized solutions is the Single Ticket system, which allows the fare integration of public transportation in the Metropolitan Region. With the electronic control, it is possible to integrate four municipal buses free of charge in a period of up to three hours, in addition to a discount on integration with the rail system (SPTRANS, 2023). It is worth mentioning that this niche innovation is also blamed for the possible elimination of fare collector and subway jobs. In 2021, for example, the government announced the closure of the ticket offices of the Metro and CPTM stations with the expectation of saving R$ 100 million per year and modernizing the means of payment, which could be carried out via app, cell phone and self-service machines installed in the stations. However, there have been several complaints from passengers about technical problems and lack of paper to print the ticket, and even accusations of digital exclusion, as many of the users were unfamiliar with these devices. Other transportation services have been digitized with rapid adhesion by the population, such as CET's Digital Blue Zone in São Paulo (paid rotating parking by the City Hall) – which was previously controlled by paper and face-to-face inspection – and Sem Parar, a means of automatic payment of tolls, parking lots and gas stations.

To stimulate this innovation agenda, the City Hall created the Laboratory of Open Innovation in Urban Mobility (MobiLab+), through the Secretariat of Innovation and Technology and the Information and Communication Technology Company of the Municipality of São Paulo (PRODAM). The project works as a laboratory for new solutions, in partnership with *startups*[20], to incorporate new

[20] *A startup* is a new company with a scalable business model that is born around an innovative idea and in conditions of uncertainty to make a positive impact on society, either with a product or a service that solves a problem. Source: Sebrae. Available at https://www.sebrae.com.br/sites/PortalSebrae/artigos/o-que-e-uma-startup,6979b2a178c83410VgnVCM1000003b74010aRCRD. Accessed April 8, 2023.

technologies into urban mobility management. At the same time, the Metropolitan Urban Transport Company (EMTU) created the [E] LAB to research technological innovations focused on the efficiency of bus transport.

The exponential growth of technological solutions and applications (Exhibit 7) treats mobility from the perspective of a service *(MaaS), a term that defines the digital revolution in the transport industry, seen as an ecosystem of aggregated services to connect people and activities in the urban space efficiently (*Karlsson ET AL., 2020; KAMARGIANNI *et al.*, 2016) and user-centered (GOODALL *et al.*, 2017).

Table 7. Innovations in mobility

| Type of solution | Applications |
|---|---|
| Transportation monitoring and route planning | Moovit, Coletivo, CittaMobi, Where's my bus?, Where's the bus?, Bus SP, Go by bus, Urbanoide, ÔnibusSP and Trafi |
| Apps for people with disabilities informing the quality of accessibility of transportation and sidewalks | Wheel Guide, BioMob |
| More efficient use of the individual vehicle | Easy Taxi, 99, Uber, Sidecar, Lyft e Lady Driver, inDrive |
| Ride-sharing | Zipcar, Blablacar, Autolib, Caronets, Bynd and Zump |
| Private car rental | Moobie, Zipcar, Communauto, Zazcar, DriveNow, Lya, AutoLib, Car2Go |
| Bike Sharing Systems | Yellow, Girl, MoBike, Tembici, BikeSampa, CicloSampa |
| Reports of harassment in transportation | No more fiu fiu, Reception Map |
| Corporate Caronas | Bynd, Corporate Collective, WiiMove |
| Open data on transportation | Citymapper, OpenStreetMap, Google Maps, Waze |

Source: Own adaptation.

Research by Fórum Mobi (2018) indicates that the city of São Paulo has the largest number of users of mobility applications in the world (3.5 million). There are 500 million kilometers monitored monthly, which led the geotechnology company Waze to partner with the City of  São Paulo to make the data produced available for public monitoring, allowing, for example, users to report signaling problems, ensuring agility in the technical intervention of the City Hall.

This scenario suggests that a low-carbon transport policy should be more strongly encouraged at the local level, where it is possible to effect a more systemic and intense change in the integration of modes. This would require robust multi-level governance with the government, at the national level, more involved in debating policies and funding for municipalities. In this case, horizontality in decision-making between urban planners, transport, finance, environment, procurement and innovation managers has the potential to lead to the emergence of more effective public policies for climate action, while integrating multi-stakeholder governance so that the population has a voice in their demands for mobility. In this regard, digital technologies play a fundamental role in urban transformations, influencing new forms of governance, since expanded access to the Internet and to technological and open data platforms tends to strengthen participatory democracy and political action. A positive example of this practice is the São Paulo Strategic Master Plan[21] (PDE), which encourages popular participation, including heterogeneous groups such as social movements, market representatives, academics, and environmentalists.

Among the Brazilian cities that use technology to promote urban development closer to the citizen, São Paulo has ranked first in the *Connected Smart Cities 2021 ranking* [22] for two consecutive years (2020 and 2021). Prepared by Urban Systems, the *ranking* maps all 677 Brazilian municipalities with more than 50,000 inhabitants to identify the cities with the greatest potential for smart development in Brazil based on 75 indicators, such as connectivity, digitized public service and mobility.

In terms of Mobility and Accessibility, the municipality also stands out for the diversity of modes and innovations, such as the electronic ticket, smart traffic lights, 600 km of bike lanes, and a fleet of low-emission vehicles. In contrast, in the Governance axis, which considers participation, investments, and transparency, the city is in position 70, with a low score in Transparency and Zoning and Land Use Law, still in the updating phase (CONNECTED SMART CITIES, 2022). In March 2023, the City of São Paulo started registering drivers for mobizapSP,[23] a shared travel app based on artificial intelligence and with lower prices compared to other platforms.

It is concluded, therefore, that a profound reconfiguration in the local transport system is still hampered by asymmetric power relations between the national and local levels and that the mobility policy of São Paulo continues to be guided by the interest of large automotive companies for tax dependence. This pattern helps to explain, for example, the recurrent changes in environmentally favorable bills, with the extension of deadlines for regulating pollution levels in public transport. Thus, it is possible to infer that the mobility regime should remain strengthened and that the modal shift should remain limited, including more structural transport policies (bike lanes, hybrid buses, compact cities). One of the explanations for this trend is that the sector's funding is fragmented and often redirected to other priorities. These changes are often associated with changes in government management and diffuse political interests, preventing scale-up due to a lack of long-term planning and political commitment, as it makes it difficult for municipal authorities to plan decades in advance (BAI *et al.*, 2018).

[21]The Strategic Master Plan of the Municipality of São Paulo is a municipal law created in 2014 to guide the development and growth of the city until 2029. Elaborated with the participation of society, the PDE directs the actions of the producers of urban space, public or private, so that the development of the city is carried out in a planned manner and meets the collective needs of the entire population. Available in https://gestaourbana.prefeitura.sp.gov.br/marco-regulatorio/plano-diretor/. Accessed April 21, 2023.
[22] Available at: https://connectedsmartcities.com.br/.
[23] Available at: https://mobizapsp.com.br/.

## 4 FINAL THOUGHTS

The results of this article suggest that disruptive niche innovations, such as electric and autonomous vehicles, have not yet contributed to the reduction of emissions in the city of São Paulo, as they are far from being scaled. However, incremental innovations in biofuels, ride-sharing, and vehicle emission control regulations have brought effective improvements to mitigate and adapt mobility-related climate impacts in the municipality.

Still, in order to meet the long-term CO2 reduction targets, São Paulo's mobility system requires a structured transition, considering the technical dimensions at the intersection with actors and institutions impacted by the transport sector. Lah (2018) points out that much research on socio-technical transition focuses on niche innovations, which may erroneously infer that they are the ones that drive transformations in social structures converging with technology. Nevertheless, this is only one of the driving forces in the reconfiguration of the system as a whole, and not necessarily the most important. Some innovations that are not necessarily considered technological, such as 15-minute cities and [24] bike lanes, are still incipient in Brazil, but are already widely disseminated in countries such as France, the Netherlands and Denmark, which in a practical way have driven urban reorganization.

In terms of generalization, the structuring of a smart and sustainable mobility system can be applied to other systems that markedly affect climate variability, such as agriculture, construction, solid waste and sanitation. However, the empirical analysis was interpreted according to the specificities of the case study.

The article has limitations that future research can address. First, it is possible to delve into some niche solutions with the potential to reconfigure sustainable transport systems, such as shared cars and bicycles, autonomous cars, and mobility applications in the city of São Paulo. Other research questions in relation to co-benefits in the transition from low-carbon transport could be investigated, such as the correlation between health and air pollution, congestion and socio-economic impacts, accessibility and active mobility, or land use and parking, considering multiple scales and social and cultural practices.

In short, studies focused on the actors and institutions of a socio-technical system can drive changes in policies, regulations, and governance to support decision-making processes from networks and coalitions with the power to support or veto innovations (GEELS, 2014). Thus, multilevel governance has the potential to co-produce knowledge that can generate and redistribute resources and incentives that stimulate the scalability of niche innovations and mobilize public policies adhering to a carbon-neutral economy.

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[24] Moreno *et al.* (2021) define a "15-minute city" as an approach to building a new way of living in cities, in which most daily needs can be met on foot or by bicycle.

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