Climate Transparency

ENERGY TRANSITION IN BRAZIL:
PARIS AGREEMENT COMPATIBLE SCENARIO FOR THE TRANSPORT SECTOR UP TO 2050

POLICY PAPER

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EXECUTIVE SUMMARY

Transitioning from a carbon-intensive development path to a low-carbon economy requires an understanding of emission sources and its drivers. To achieve the 1.5°C target discussed under the Paris Agreement, countries must develop studies that not only estimate baselines based on historical data of GHG emissions and energy consumption but also project them considering different levels of ambition and political commitment. This policy paper provides scenarios of energy use and GHG emissions from the transport sector up to 2050, considering Brazil´s national pledges and climate action. Two scenarios are developed based on different political commitments. The results show that if Brazil pursues highly ambitious and concrete mitigation goals, it is possible to reduce 2050 emissions by up to 25% compared to 2005 levels (against a 101% increase in the conservative scenario). Also, the cost analysis evidences that cars, trucks and buses electrification are mitigation actions with interesting prospects for 2050. However, barriers related to financing, concession models and standards and regulations for new technologies and business models need to be overcome.

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Abbreviations

Agriculture, Forestry and Other Land Use (AFOLU)
Activity–Structure–Intensity–Fuel (ASIF)
Fifth Assessment Report (AR5)
Battery Electric Vehicle (BEV)
Brazilian Forum on Climate Change (FBMC)
Greenhouse Gas (GHG)
Global Warming Potential (GWP)
Hybrid Electric Vehicle (HEV)
Internal Combustion Engine (ICE)
Marginal Abatement Cost Curves – (MACC)
Nationally Determined Contribution (NDC)
Growth Acceleration Program (PAC)
Plug-In Hybrid Electric Vehicles (PHEV)
Investment Partnership Program (PPI)
Transport-Energy-Emissions Multi-Tier Analysis (TEMA)
United Nations Framework Convention on Climate Change (UNFCCC)
Vehicle Kilometres Travelled (VKT)

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The paper has been produced as part of the efforts of Climate Transparency, an international partnership of 14 research organizations and NGOs comparing G20 climate actions, and is part of a series examining the status, opportunities and challenges in decarbonizing the transport sector in G20 countries. Papers can be downloaded at:
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INTRODUCTION

In the past decade, Brazil has achieved a leading position in reducing greenhouse gas (GHG) emissions among the countries who have submitted Nationally Appropriate Mitigation Actions (NAMAs) and Nationally Determined Contributions (NDCs). The Brazilian NDC is notably one of the most ambitious, pursuing 37% cuts in GHG emissions by 2025 and 43% by 2030 compared to 2005 levels. However, the quantitative contribution of the transport sector in this abatement is not clear, due to the non-existence of specific targets in such commitments.

To date, Brazil has reported three national communications to the United Nations Framework Convention on Climate Change (UNFCCC) and four annual GHG estimates. Brazil's historical anthropogenic GHG emissions show that abatements have already been accounted, especially from the Agriculture, Forestry and Other Land Use (AFOLU) sector. However, recent estimates evidence an upward trend in emissions, mainly due to a resumption of deforestation rates and the legal expansion of planting areas (Goes et al., 2020). From 2005 to 2010, net carbon emissions were reduced by 53% (from 2.8 Gt to 1.3 Gt), although from 2010 to 2015 emissions increased by 15% (to 1.5 Gton) (Brazil, 2017).

There is still no prognosis for reversing this pattern, as the federal government has waved to halt or delay ongoing low-carbon development policies. Meanwhile, economic incentives are at work behind the exploitation of the Legal Amazon and the contraction in titling and demarcation of indigenous lands. Under these circumstances, stakeholders from other economic sectors, such as transport, are likely to increase their efforts in mitigation actions over time in order that Brazil's contribution to mitigation efforts remains within the temperature target range of 2°C and 1.5°C by 2050, reached under the Paris Agreement.

Long-term climate-energy scenarios for decarbonizing the transport sector involve not only understanding the nature of millions of mobile sources but also how these variables are affected by several transport-related issues, such as policies, infrastructure investments and market penetration of new technologies.

This policy paper develops a Paris Agreement compatible scenario for the transport sector up to 2050, considering Brazil´s national pledges and climate action. To this end, two scenarios of energy use and GHG emissions are modeled, considering the highest level of sector detail available. The first scenario, the 'Government scenario', is based on the fulfilment of Brazilian NDC and other historical trends. On the other hand, the '1.5°C scenario', a Paris Agreement compatible scenario, is based on disruptive mitigation actions, focusing on transport decarbonization, and thus going beyond the targets set by the current NDC. Then, a set of barriers for the transition to more efficient and cleaner energy is presented, and then recommendations for climate action to overcome them are discussed.

The remainder of this paper is organized as follows. Section 2 provides information on the technical approaches considered to estimate energy use and GHG emissions baselines. Section 3 describes the assumptions, technologies and pathways for each scenario. Section 4 analyses all investments and operating costs required for the projected transitions, presenting results by subsector, mitigation action and transport mode. Conclusions and policy implications are presented in section 5.

1. ENERGY-ENVIRONMENT MODEL AND DATA

This section presents the models adopted for estimatin energy use, carbon emissions and abatement costs over time. This is an important activity due to the existence of several methods in literature that seek to estimate the same results, but with unacceptable levels of accuracy. In these cases, estimates are usually made by projecting fuel consumption and socioeconomic variables, disregarding transport activity variables, such as energy intensity or average load factors in this process.

Here, we employed the 'Transport-Energy-Emissions Multi-Tier Analysis' (TEMA) model, derived from Gonçalves et al. (2019). It covers three technical approaches: (i) bottom-up; (ii) top-down; and (iii) 'Activity–Structure–Intensity–Fuel' (ASIF). The application of each depends on data availability.

Essentially, the bottom-up approach quantifies disaggregated emissions, thus allowing the individual management of each energy source. This requires detailed local data, which varies according to technology and emission factors (i.e. by technology and energy source).

In contrast, the top-down and ASIF approaches calculate aggregate emissions. For the top-down case, emissions are calculated with the use of national energy balances and default emission factors. This procedure does not allow for in-depth assessments of carbon emission drivers. However, it permits fast accurate measurements and leaves little room for error when it comes to the country's emissions, as fewer variables are considered in the process. In the ASIF case, despite being essentially an aggregate, this approach can addres some level of detail as it considers transport activity, energy intensity and emissions factors in a wide-range equation to calculate emissions.

The distinctiveness of the TEMA is that not only all transport modes are modelled (including pipelines), but road transport is divided into 31 technology variations, including vehicle categories (automobiles, buses, trucks etc.) and powertrains (hybrid electric vehicles – HEV, battery electric vehicles – BEV, Flexible Fuel ICE, Ethanol ICE, Gasoline ICE, etc.). This is especially important as it provides the disaggregated demand for biofuels by technology over time (e.g. hydrous ethanol, and blends of gasoline-anhydrous ethanol and biodiesel-diesel)[1], and points out the pace and possible implications of the transition to alternative development paths (market penetration of electric/hybrid vehicles etc.).

Considering these approaches, we adopt bottom-up Tier 3 (for non-carbon dioxide – CO_2 gases) and Tier 2 (for CO_2) approaches to calculate GHG emissions from road transport, since country-specific technology-based emission factors and carbon contents are available. In parallel, a top-down approach is employed to refine results, reducing uncertainties. Where

1. Because of the lack of literature on the subject.

the calculated energy from the bottom-up approach for each type of fuel differs from the top-down (which is the reference approach), gaps can be solved by adjusting the values of VKT and vehicle occupancy. As the other transport modes have limitations on consistent and reliable activity data (fleet, vehicle kilometres travelled – VKT, emission factors per model-year etc.), we use ASIF and top-down approaches.

The baseline is modelled using macroeconomic data as proxy variables to project transport activity (and modal split) over time. The outputs from this process are the resulting modal split, energy use and GHG emissions. The consistency is assessed by examining the expected value of variables such as energy intensity (kJ/t-km or kJ/pass-km), vehicle occupancy etc.

The results from the energy-climatic model, together with the investment requirements and operating costs of key mitigation actions, are used as inputs to estimate marginal abatement cost curves – MACC (Goes et al., 2020). Hence, the model provides the corresponding marginal abatement cost and the cumulative CO2 emission reduction achieved by all mitigation actions adopted in the most ambitious scenario (Valenzuela et al. 2017).

The model requires annual data on transport activity (t-km and pass-km), investments, operation costs, licensing, VKT and fuel economy, collected from sectoral associations, private operators and the literature. Macroeconomic (gross domestic product – GDP, population etc.) and energy-related data (fuels and biofuels demand and properties) are collected from ministries. Finally, energy intensity and national fleet (per technology and energy source) are calculated.

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2. ASSUMPTIONS AND PATHWAYS

To define global and local assumptions that best represent governmental policies, private initiatives and society's demands by 2050, it is important to raise national commitments that have already been made and the possibility of meeting them.

To this end, the NDCs that could be applied to transport are:

(i) 18% share of bioenergy in the energy mix (encompassing ethanol supply, biofuel blends etc.);

(ii) promotion of efficiency measures; and

(iii) infrastructure investments in urban areas.

As a first analysis, this shows that Brazil has indicated a transition path based on the intensive use of bioenergy and marginal energy efficiency gains (especially from conventional internal combustion engines, ICE). For instance, the RenovaBio[2] and Rota 2030[3], launched in 2018, were designed with this purpose.

Furthermore, historical trends, alongside prospective policies, and infrastructure investments and technologies (whether foreseen or unforeseen) applied in specific areas, were studied and discussed with stakeholders[4] at the Brazilian Forum on Climate Change (FBMC) and transport-related workshops. As an outcome, a set of long-term mitigation actions that could be employed based on the Brazilian background are listed as follows: (i) Railway network expansion (passenger and freight); (ii) Railway electrification (freight); (iii) Road vehicle fleet electrification (passenger and freight); and (iv) Increased blend ratios of biofuels.

Taking these assumptions into account, two scenarios are then modelled based on different ambition levels and sector performances:

(i) The **'Government Scenario'** considers the historical trend of several variables, such as investments, policies and efficiency gains. Although compatible with the targets set out in the NDC, it does not result in declining emissions in the transport sector.

(ii) In contrast, the '**1.5°C pathway Scenario'** bets on more ambitious performances, aligned with the 1.5°C compatible range for 2050.

Both scenarios consider similar economic, social and demographic performances such as GDP, population growth, urbanization, aging of the population, spatial distribution of activities in cities etc. Table 1 presents the assumptions and pathways by scope[5.]

2. Attempts to reduce carbon intensity by 10.1% by 2028 compared to 2017 levels (considering the well-to-wheel – WTW – approach).
3. Attempts to increase the competitiveness of domestic industry by encouraging efficiency improvements.
4. Key actors from the Federal and State Government, public and private companies, academia and civil society.
5. The ongoing infrastructure investments are mapped from the PPI, Avançar and PAC government programs. These programs consist of massive investments in infrastructure and institutional actions, encouraging credit and financing. Additionally, potential expansions were designed based on a literature review and expert consultation. The penetration of emerging technologies is estimated from market research surveys with manufacturers, literature review and expert consultation. During this process, the relatio'nship between city profiles (for urban mobility and last-mile deliveries), industrial assets and market trends (domestic and international) are analyzed.

Table 1: **Assumptions and pathways by scope**

Scope		Assumptions and pathways	
		Government scenario	**1.5ºC**
Transport patterns	Passenger	■ Marginal increase in the share of rail and water transport in the modal split ■ Shift from private vehicles to public transport (buses) ■ The historical growth rate for active transport	■ Analogous to the Government scenario, but with more ambitious estimates
	Freight	■ Increase in rail and water transport activities (t-km) based on infrastructure investments in progress	■ Analogous to the Government scenario, but with an additional estimate of 14%
Vehicle licensing	Light vehicles	■ End of ICE vehicles sales by 2045 ■ Sales growth of HEV (especially with flexible-fuel engine) and BEV, reaching 100% share in 2045 ■ Sales growth of BEV motorcycles, reaching 35% share in 2050	■ End of ICE vehicles sales by 2040 ■ Sales growth of alternative vehicles (BEV and HEV), reaching 100% share by 2040 ■ Sales growth of BEV motorcycles, reaching 34% share by 2040 and 70% in 2050
	Heavy vehicles	■ Decrease of diesel-fueled buses share from 99% in 2018 to 22% by 2045, being replaced by PHEV and BEV buses ■ Electrification of trucks is restricted to tests in waste collection and a fraction of the light truck licensing	■ 20% share of fossil diesel-fueled buses by 2040 ■ 10% share of BEV light trucks (less than 10 tonnes) by 2030 and 50% up to 2050 ■ 12% share of BEV and HEV heavy trucks (more than 10 tonnes) by 2050
Energy use	Biofuels	■ Biodiesel blend at 15% (B15) from 2025, maintaining this share up-to 2050 (for road, rail and water transport) ■ 27% blend (E27) of anhydrous ethanol in gasoline ■ The historical growth rate of hydrous ethanol	■ Biodiesel blend at 20% in 2030, 25% by 2040 and 30% up to 2050 ■ 27% blend (E27) of anhydrous ethanol in gasoline ■ 90% hydrous ethanol market share by 2050 ■ Bio-oil blend at 20% up to 2050 ■ Biokerosene blend at 20% by 2040
	Electricity	■ Railways electrification at a slow pace (freight transport)	■ Analogous to the Government scenario, but with more ambitious estimates
Energy efficiency	Road	■ Engine technology improvements and use of heat recovery technologies (10% by 2030 and 20% by 2050) ■ Operational improvements (maintenance) (5% by 2030 and 10% by 2050)	■ Engine technology improvements and use of heat recovery technologies (15% by 2030 and 25% by 2050) ■ Operational improvements (maintenance) (10% by 2030 and 15% by 2050)
	Air	■ Aircraft design and operational improvements (10% gains by 2030 and 15% up to 2050)	■ Aircraft design and operational improvements (10% gains by 2030 and 25% up to 2050)
	Water	■ Ships design, weight and engines improvements (7% by 2030 and 12% up to 2050)	■ Ships design, weight and engines improvements (10% by 2030 and 20% up to 2050)
	Rail	■ More efficient propulsion systems and regenerative braking (5% by 2030 and 7% up to 2050) ■ Operational improvements (5% by 2030 and 10% up to 2050)	■ More efficient propulsion systems and regenerative braking (5% by 2030 and 10% up to 2050) ■ Freight: Operational improvements (7% by 2030 and 25% up to 2050)
	Pipelines	■ Increased capacity and operational improvements (up to 5% by 2050)	■ More ambitious estimates (up to 10% by 2050)
User behaviour	Road	■ A shift from private automobiles to buses ■ Shift from buses to transport-related apps ■ The historical growth rate for active transport (non-constrained trips) ■ Car/ride-sharing, pooling etc. are mainly electric and restricted to selected cities	■ A shift from private automobiles to buses and transport-related apps ■ Significant increase in active transport1 ■ Motorization rate reduction ■ Consumers opt for more efficient vehicles ■ The growth of tele-activities, reducing trips
Financing	Electromobility	■ Credit facilities for financing electric buses	■ Analogous to the Government scenario, but with more ambitious estimates ■ Development of new regimes for passenger transport concession, especially in metropolitan areas

[6] Non-motorised forms of transport involving physical activity (e.g. walking and cycling).

The Government scenario represents the maintenance of national plans and current trade agreements. Therefore, this scenario maintains the policy of stimulating biodiesel (started in 2005 with a 2% biodiesel blending ratio), but does not consider the establishment of a market for new biofuels such as bio-oil and biokerosene. In addition, this scenario maintains the pace of modal shift towards more efficient modes such as water and rail, albeit at a slow pace. Electromobility is restricted to ride-hailing drivers, offering economic advantages for users with high utilisation rates. The government does not offer significant incentives to switch to this technology (from ICE to BEV), despite isolated efforts in financing electric buses. For this reason, the market for vehicles equipped with internal combustion engines (ICE or HEV) remains predominant until 2050, especially for heavy vehicles.

In the 1.5° C scenario, Brazilian society experiences a transformation in consumption habits (choosing more efficient vehicles), use of public transport, intermodality and clean fuels. For example, new models of concessions for public passenger transport stimulate electromobility and reduce dependence on private transport. Moreover, the government encourages the use of new biofuels, such as bio-oil and biokerosene, while increases the mandatory mixture of biodiesel in mineral diesel (up to 20%) and stimulates the production and consumption of hydrated ethanol in flex-fuel and PHEV vehicles. Finally, this scenario presents gains in energy efficiency in all modes of transport through technological advances and operational improvements.

3. BASELINE AND SECTORAL CARBON PROJECTIONS IN BRAZIL

Historical information on transport activity dates from 1970 to 2018 (baseline). Despite this, the analysis is focused on 2005, since it is the base year of the first Brazilian NDC (2016).

According to Figure 1, one can conclude that the 1.5°C scenario presents a 25% emissions abatement when comparing to 2005 levels. This is critical to note, given the strong correlation between transport activities and GDP worldwide (Tob-Ogu et al., 2018), indicating the difficulties of implementing low-carbon policies without compromising economic performance.

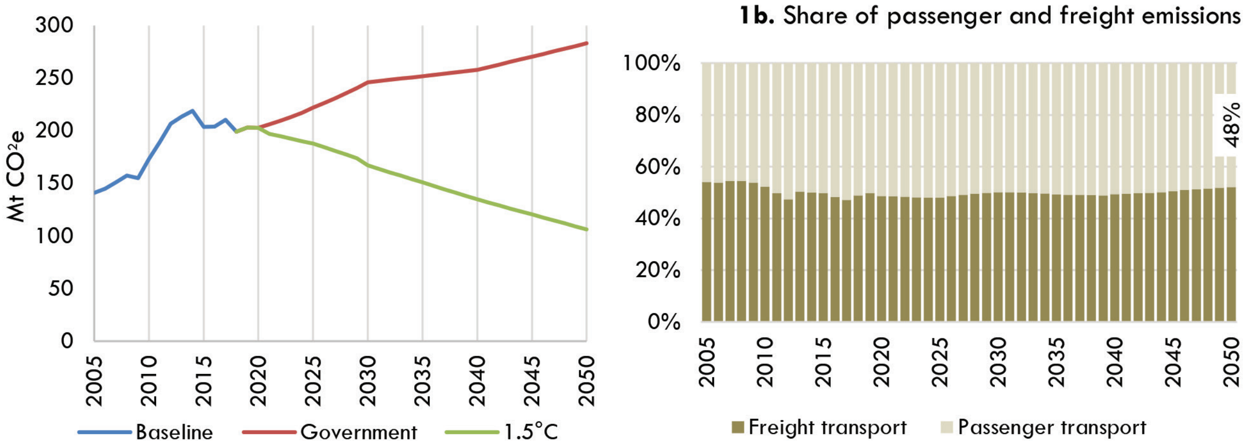
Though the 1.5°C scenario emits 2.7 times less by 2050 than the Government scenario. Even not representing the decarbonization of transport, this scenario is relevant for limiting end-of-century warming to below 1.5ºC, especially considering a favourable performance of the AFOLU sector[7].

The 1.5 Degree Scenario

All information presented below relates to the 1.5°C scenario, inasmuch as it is low-carbon path compatible with the Paris Agreement. The Government scenario is considered mainly to estimate the potential for carbon abatement from mitigation options (see section 'Investments requirements and cost analysis').

Figure 2a illustrates the energy use projections through to 2050. By 2050, electricity remains as an alternative energy source (2.5% share), while the use of biofuels continues to expand, reaching

Figure 1. **GHG emissions from Brazil´s transport sector**



[7] In this case, negative emissions from the AFOLU sector offset emissions from transport.

35% share at the end of the time series. From this, hydrous ethanol and biodiesel represent 90% of all biofuels consumed, with 70% and 20% shares by 2050, respectively.

Despite the international trend on electromobility and the Rota 2030 program, Brazil does not advance in this area at the pace of the main international players, such as China and Europe[8]. Nonetheless, significant advances in energy use derived from biomass reduce national dependence on diesel (from 51% in 2005 to 44% in 2050), which may improve energy security.

Energy security is an issue of critical importance to many stakeholders in Brazil. Most recently, this was evinced in the 2018 Brazil Truck Drivers' strike, undertaken by nearly 2 million self-employed truck drivers protesting protest diesel prices, which contributed to nationwide supply-side disruptions and shortages in food, medical supplies, and oil (Dantas et al., 2019). Moreover, almost 100% of buses are fueled with diesel, as are most trucks, freight trains, inland navigation and offshore support vessels.

In this context, Figure 3 represents energy use by source, taking into account the years 2005, 2020 and 2050. Unlike GHG emissions, energy consumption increases by 120% during the time series. This could be explained by the increased use of biofuels and the emerging market of electromobility (especially for light passenger vehicles).

As observed, gasoline consumption falls by 29% (from 13,638 toe to 9,720 toe), reaching 8% in participation. Consequently, the consumption of anhydrous ethanol (a biofuel blended with gasoline) also decreases. Disregarding external events (e.g. changes in transport patterns or user behaviour), gasoline is gradually replaced by hydrous ethanol and electricity in light passenger vehicles. In turn, dependence on diesel reduces until 2040, but returns to the levels of 2020 by 2050 due to the low performance of electromobility in the transport of heavy freight vehicles.

Figure 2. **Energy use estimates throughout 2050 for the 1.5°C scenario**

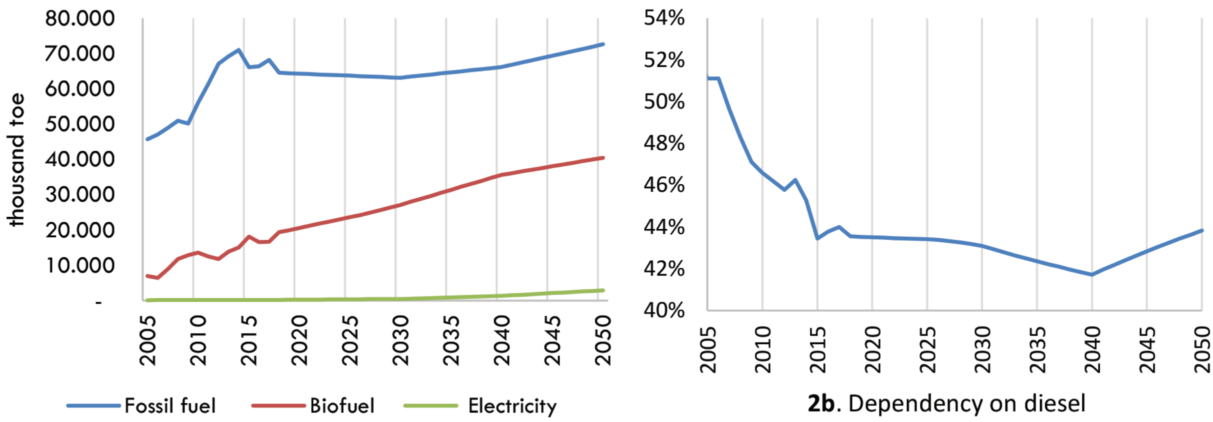
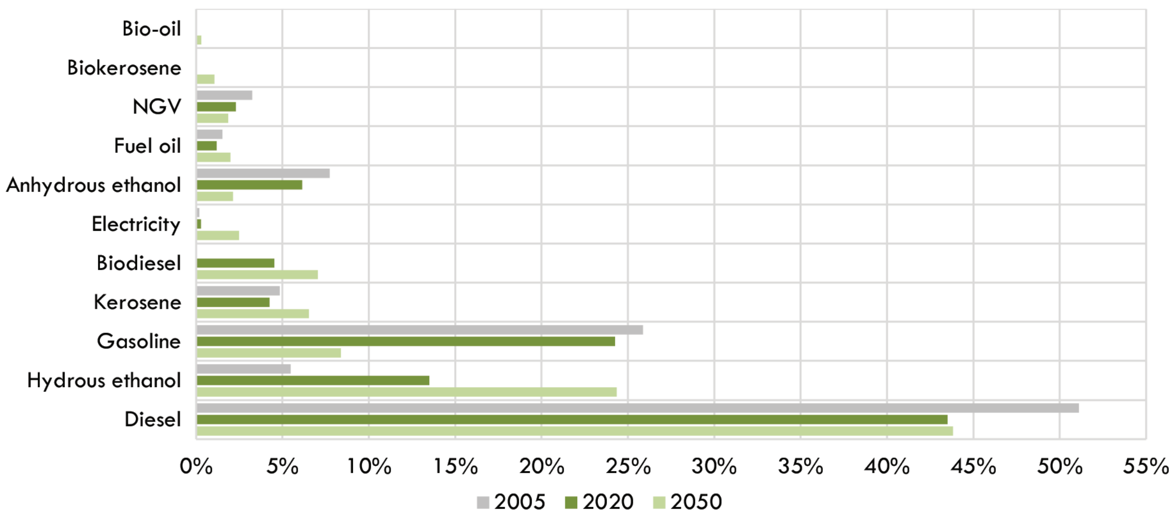


Figure 3. **Comparison of energy sources between 2005 and 2050**



8. The barriers to electromobility are shown in Table 3 (in the section 'Enabling deep decarbonization in transport').

As shown in Figure 4, road transport stands out as the main element of the Brazilian transport matrix, especially in the case of passenger transport. Although changes in transport patterns towards more energy efficient modes caused a decrease in the share of road transport from 93% in 2005 to 84% in 2050, this mode of transport is still far superior to air, rail and water transport (with 8.5%, 6.9% and 0.1% by 2050). In the Brazilian case, the infrastructure-related costs for expanding the metro and metropolitan railways are major impediments to increase rail activity.

The freight transport modal split tends to be more balanced over time, with crucial performance improvements on rail and water transport. During the time series, rail expands 9% in participation (from 25% in 2005 to 34% in 2050), whilst water transport achieves 25% in participation by 2050. Both performances are driven by commodities flows. Completing the list, pipelines and air transport account for 2% and 0.1%.

The modal split over the time series, per transport type (passenger and freight), is exhibited in Figure 5.

Figure 6 exposes the projected road transport freight vehicle fleet. There has been a significant increase in light[9] and heavy-duty[10] trucks stocks since the 2000s. This can be explained by the increased amount of parcel deliveries in Brazil, resulting from the rapid urbanization and manufacturing diversification (which used to produce only medium-sized trucks[11] for short and long-distance deliveries). As a matter of fact, the high share of heavy trucks is a result of the intensive use of road transport mode for long distances, competing with high capacity modes such as rail and water transport.

With respect to vehicle types, electric and hybrid propulsion systems are responsible for 30% of truck stocks by 2050. Overall, a fleet of 2 million trucks is expected. From this, over 600 thousand BEV and HEV trucks are foreseen. More specifically, light-duty trucks account for the largest share of BEV, and heavy-duty trucks account for the HEVs.

Road transport passenger vehicle fleet is presented in Figure 7. Results point to a fleet of 120 million passenger vehicles by 2050. BEV and HEV represent 88 million vehicles in the same period (73% of the total fleet).

Figure 4. **Transport activity estimates throughout 2050**

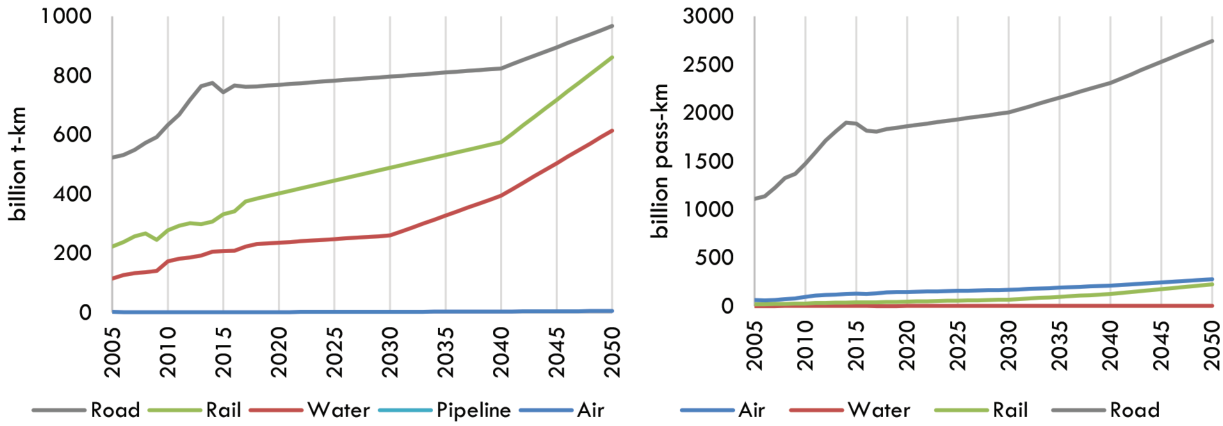
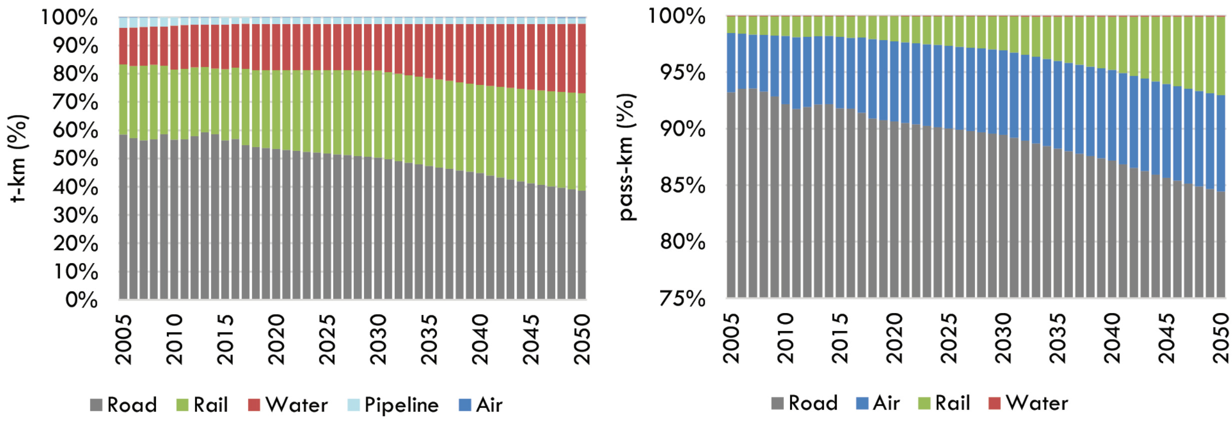


Figure 5. **Modal split by 2050 per transport type**



9. Vehicles with gross vehicle weight (GVW) between 3.5t and 10t.
10. Vehicles with GVW above 15t.
11. Vehicles with GVW between 10t and 15t.

Figure 6. **Road transport freight vehicle fleet prospects**

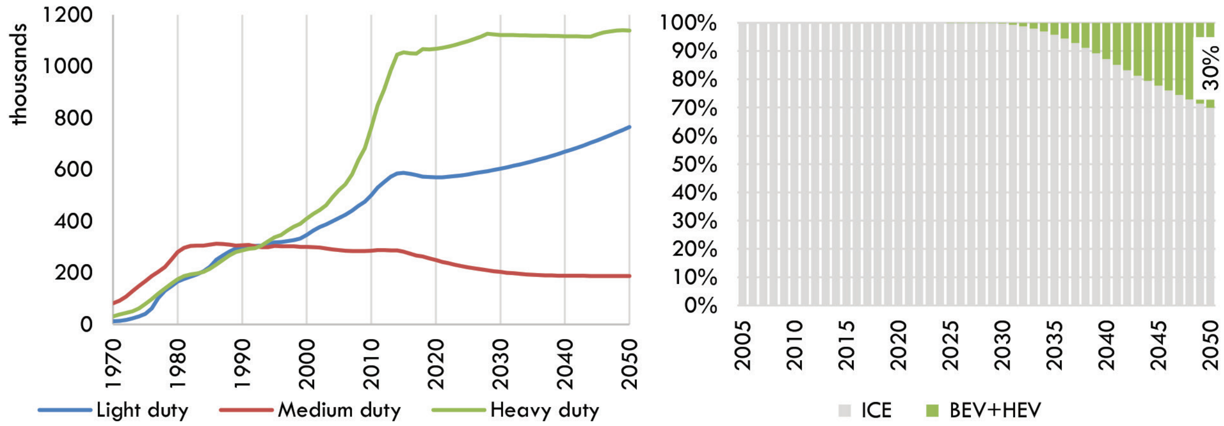
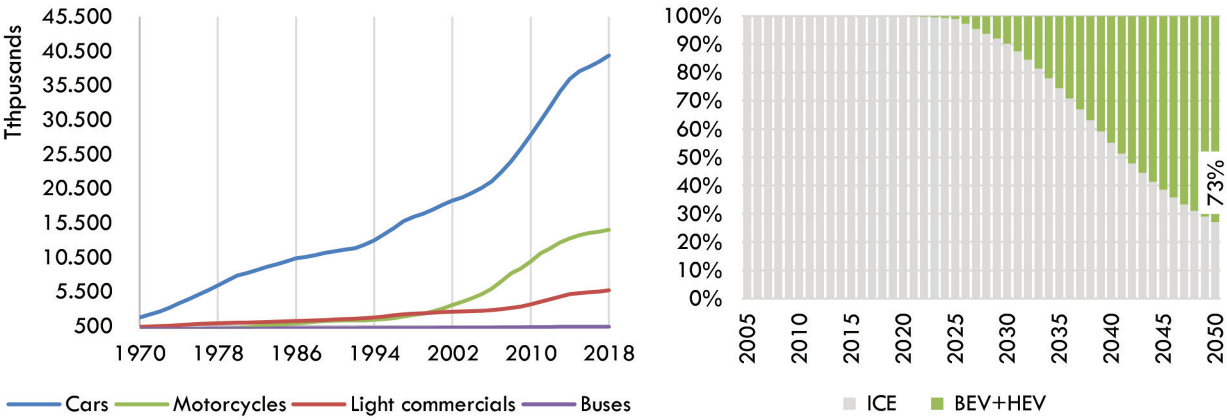


Figure 7. **Road transport passenger vehicle fleet prospects**



In Brazil, the fleet of battery electric vehicles will be predominantly composed of urban buses, light commercials, light trucks and ride-hailing drivers (taxi and mobile application). On the other hand, the fleet of hybrid passenger vehicles will be predominantly composed of private cars, heavy trucks and regional buses.

As discussed in section 3, the large share of passenger electric vehicles (EV) is a consequence of changes in user behaviour. This means users choose more efficient vehicles, not only for private trips but also for apps and bus travel.

Next section discusses the investments requirements, conducting a cost analysis of the main mitigation actions that drive emissions in the 1.5°C scenario.

Investments requirements and cost analysis

As presented in the section 'Energy-environment model and data', we apply a MACC model to analyze the costs and carbon abatement potential of the selected mitigation options compared to a business as usual scenario (Government scenario). In other words, a MACC analysis points out the cost-effectiveness of implementing a mitigation option over time.

The MACC analysis is conducted by mitigation option and scenario, which may be based on the introduction of a new technology or simply the increase in the penetration of some action, comparing mitigation options with a business as usual situation (e.g. investing on electric vehicles or maintain an conventional ICE fleet?). Results are expressed in cost of carbon avoided (US$/ $tCO_{2e)}$, being multiplied by the total amount of emissions avoided (tCO2e) to obtain the total cost of the mitigation action.

In this context, a government can only choose mitigation options whose cost per ton mitigated is negative, that is, there are savings after their implementation[12]). It is important to emphasize that not necessarily the best options for the transport system are those that have a negative mitigation cost (US$/$tCO_{2e}$). For instance, metro expansions in Brazil are not viable from this perspective, although they are fundamental for improving the transport system.

[12] By estimating the abatement cost (capital expenditure – CAPEX minus Operational Expenditure –OPEX) of a unit of GHG emitted in the 1.5°C scenario relative to the Government scenario

Table 2 summarizes the CAPEX required to implement each mitigation action contemplated in the 1.5°C scenario[13]. Two time-horizons are presented: 2021-2030 (NDC) and 2031-2050 (long-term prospects).

In the first period (2021 to 2030), only investments announced by the government are considered in both scenarios (with subtle differences in ambition between each scenario). This includes the RenovaBio, Rota 2030, PPI, Avançar and PAC government programs. Thus, the presented values represent the difference in costs between the Government and 1.5°C scenarios.

Between 2031 and 2050, while few mitigation options are launched in the Government scenario, the 1.5°C scenario experiences a wide range of mitigation options. Also, the country experiences economic recovery after the impeachment of the president (2016) and the Covid-19 pandemic. For this reason, the amount invested in the second period is substantially higher than in the first.

By 2050, the most expensive intervention is the metro network expansion, reaching 64.8 billion dollars invested. This mitigation action is followed by the light vehicles' electrification (41.8 billion) and rail network expansion (freight transport) (3.9 billion).

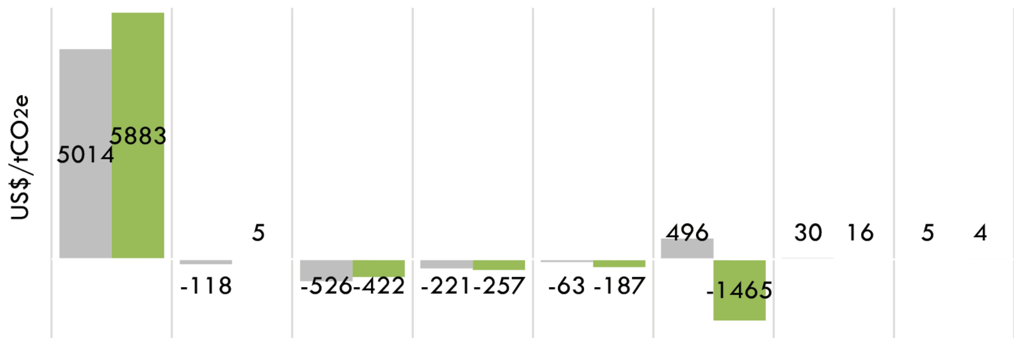
Figure 8 shows the average abatement cost from mitigation actions of the 1.5°C scenario.

As expected, in the MACC analysis, the expansion of the metro network does not compensate for investments costs over time, when compared to a conventional situation of using road transport (by cars, buses, etc.). Regarding the electrification of

Table 2: **Additional CAPEX of the key mitigation actions in the Scenario 1.5°C (million US$)**

Mode	Activity	Mitigation action	2021 to 2030	2031 to 2050
Rail	Passenger	Network expansion	2,452	62,349
Road	Passenger	Light vehicles' electrification	271	41,513
Rail	Freight	Network expansion	468	3,507
Road	Passenger	Buses' electrification	2	2,739
Rail	Freight	Railways' electrification	56	1,092
Road	Freight	Trucks' electrification	6	805
Air	Passenger and freight	Biokerosene blend	138	637
Water	Freight	Bio-oil blend	1	13
		Total	**3,394**	**112,655**

Figure 8. **Average abatement cost**



	Metro	Electric railways	Diesel railways	Trucks electrification	Bus electrification	Cars electrification	Biokerosene	Bio-oil
MAC 21-30 (PV)	5014	-118	-526	-221	-63	496	30	5
MAC 31-50 (PV)	5883	5	-422	-257	-187	-1465	16	4

[13] We considered a discount rate of 8% per year, discounted present values.

railways, initially profitable, it face competition from heavy-duty trucks (HEV) in the second period (which has lower acquisition and maintenance costs). This compromise its results from 2031 on. Currently, the entire fleet of urban trains in Brazil is already electric, and, therefore, the focus would be on freight railways.

In the same way, the electrification of cars does not compensate in the first period (2021 to 2030). However, lower battery prices, higher payload capacity (for light commercials), powertrain improvements (for the local industry), along with energy efficiency gains, reward investments in the second period (2031-2050). The introduction of biokerosene and bio-oil mixtures also does not compensate for investments in this time series.

Under different circumstances, cars and buses electrification in Brazil are mitigation actions with interesting prospects for 2050. Positive externalities of their implementation compensate for the initial investment (CAPEX). These results could support governments and institutions to study and implement sustainable development paths in their countries. Again, it is also necessary to assess potential benefits that go beyond the acquisition cost and maintenance savings (e.g. metro expansion).

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4. ENABLING DEEP DECARBONIZATION IN TRANSPORT

Inasmuch as each mitigation action requires certain economic, political and social bases, we discussed with experts from the FBMC and external transport-related stakeholders the means for its implementation. In other words, we attempt to investigate which conditions allow the 1.5° C scenario and which barriers must be overcome. Table 3 summarizes this analysis.

In the case of road fleet and railways electrification, the lack of a local industry and providers on electromobility, standards, regulations, concession models, knowledge about the economic benefits of an electric fleet, together with expensive assets and ICE automakers' lobbying are the main barriers that still slow the progress of this mitigation option. These barriers reflects the lack of awareness, interest and involvement of the people in charge of its implementation. For instance, a parliamentary front in favor of electromobility was dissolved in 2019.

However, some advances in this field have been observed in recent years, with several studies being developed by the academy and supported by federal institutions that propose roadmaps to accelerate electromobility in Brazil. These studies include improving standards, regulations and, concession models, as well as stimulating new business models and communication. In addition, the implementation of credit lines for hybrid electric and plug-in vehicles is being studied and local regulatory initiatives (cities) are already in place to expand low-carbon transport.

Despite massive investments through government programs such as PPI, Avançar and PAC government programs, expansions of the rail and water transport networks are still limited. This is due to the lack of assertive technical, economic and environmental studies, lack of supervision and control of works in progress, and congestions of trains and vessels at port stations. To overcome these barriers, it would be necessary to encourage competition for these modes of transport, and also to change political thinking towards long-term and sustainable investments.

Finally, for the introduction of bio-oil and biokerosene in the transport energy matrix, it would be necessary to reduce their production costs through investments in Research and Development (R&D) and political mobilization, as is already the case with biodiesel and ethanol.

Table 3: **Summary of main barriers and recommendations**

Mode	Activity	Action	Barriers	Current policies	Desirable 1.5°C policies
Road	Passenger	Light vehicles' electrification	Restricted market (all vehicles are imported) – Expensive assets – Lack of awareness, interest and involvement of the people in charge of its implementation – Lack of local EV manufacturers – ICE automakers' lobbying – Lack of standards and regulations	Tax reduction for EV – Toll-exemption policies – Initiatives for electromobility regulation (Promob-e Project) – R&D projects	Development of a national EV powertrain – Deadline to end ICE vehicle sales – Credit facilities for financing electric taxis and transport drivers by application
		Energy efficiency gains for light vehicles	Automakers are not meeting their goals under the Rota 2030 program – Current national eco-labeling program is not accurate	Rota 2030 program	Introduction of a more ambitious program after 2030 – Improvement of the national eco-labeling program
		Buses' electrification	Concession model are often poorly designed and structured – Bus quality improvement – ICE automakers' lobbying – Lack of knowledge about the economic benefits from electric buses – Lack of standards and regulations	Credit facilities for financing electric buses (Refrota program) – Investments in BEV fleet in the city of São Paulo – Local regulatory initiatives for low carbon vehicles	New business models and concessions - Change in legislation - Revision of tariff modalities - Government financial incentives (subsidies)
	Passenger and freight	Energy efficiency gains for heavy vehicles	Lack of specific heavy-duty target programs	Rota 2030 program	Introduction of a more ambitious program after 2030 – Improvement of the national eco-labeling program
	Freight	Trucks' electrification	Restricted EV market – expensive assets – Lack of awareness, interest and involvement of the people in charge of its implementation – Lack of local EV manufacturers – ICE automakers' lobbying – Lack of standards and regulations	Joint initiatives between multinational companies	New business models – Investments and financing of prospective technologies – development of accreditation systems (certification/labeling efforts) – government grants
Rail	Passenger	Network expansion	Cost overruns in infrastructure works – Lack of assertive technical, economic and environmental studies – Decision based merely on financial aspects	Delayed works planned for World Cup and Olympics that are still in progress – Other investments are restricted to São Paulo	Access to international financing (Green bonds) – Changing political thinking towards long-term and sustainable investments – Investment and Financing of prospective technologies
	Freight	Railways' electrification	Lack of studies and political commitment – Lack of local railway builders and providers – Lack of standards and regulations	-	Access to international financing (Green bonds) – Changing political thinking towards long-term and sustainable investments – Investment and Financing of prospective technologies – International bids, including for abandoned and underused network links

Mode	Activity	Action	Barriers	Current policies	Desirable 1.5°C policies
Rail and water	Freight	Network expansion	Lack of competition in container cabotage and the National Waterway Transport Agency (ANTAQ) does not encourage it – aged fleet – Cost overruns in infrastructure works – Lack of assertive technical, economic and environmental studies – Decision based merely on financial aspects – lack of supervision and control of works in progress – Higher levels of bureaucracy, restricting intermodality	PPI, Avançar and PAC government programs	Equivalence of fuel oil and lubricants prices between coastal shipping and long-haul navigation – Access to international financing (Green bonds) for infrastructure expansion and fleet renewal – Changing political thinking towards long-term and sustainable investments – Investments and financing of prospective technologies (especially for electric railways) – Specific studies for water transport, including road access, licensing port works, dredging etc. – Tax reduction and bureaucracy simplification – Incentives to intermodality – Expand access to ports and railways – Legal framework for concessions for rail and water modes
Water	Freight	Bio-oil blend	High costs – Policies restricted to biodiesel and ethanol	RenovaBio program	R&D investments
Air	Passenger and freight	Biokerosene blend			R&D investments – Medium- and long-term investments aiming at meeting the national and international demands

5. CONCLUSION AND POLICY IMPLICATIONS

The search for a faster transition towards a low carbon economy needs to encompass multiple perspectives of performance from different sectors. This policy paper aimed at providing scenarios of the energy transition in Brazil by 2050, with a focus on transport. To this end, we considered Brazil's national pledges under the Paris Agreement, together with a wide range of assumptions, discussing them with experts from the public and private institutions, as well as civil society, at the FBMC and at transport-related workshops. As a result, assumptions such as market trends, government policies and society's demands are converted into mitigation actions at the highest level of detail to analyse investments costs and carbon abatement potential.

To estimate the baseline and projections of energy use and GHG emissions, we adopted the method developed by Gonçalves et al. (2019). With that said, we employed bottom-up/top-down (for road transport) and ASIF/top-down (for the other modes), providing detailed information on long-term performance. Moreover, the cost analysis, from MAC curves, was employed using the method developed by Goes et al. (2010).

Results show that Brazil is on track to meet its transport-related NDC targets, although more efforts are needed to be in line with a 1.5°C-compatible development pathway (with emission reductions compared to 2005 levels). It is important to emphasize that GHG emission reductions in the transport sector are politically significant, due to the close relationship between transport activity and GDP. In this manner, the 1.5°C scenario presents a 25% emissions abatement when compared to 2005 levels, while emissions in the Government scenario are 101% higher compared to the same year.

In short, the 1.5ºC development path demands a broad shift in local policy guidance, now restricted to biofuels incentives and energy efficiency gains (for light vehicles). Therefore, greater penetration of electromobility in passenger and freight transport would be needed, together with massive investments in infrastructure (even considering metro expansions), new public transport concession schemes and, finally, basic education on the benefits of sustainable transport.

Brazilian mitigation efforts will depend on which development path the current local government intends to follow. Up to now, it has shown a propensity for carbon-intensive policies, which may compromise even ongoing programs and environmental commitments.

Out of that, the MACC analysis reveals that the electrification of cars could be the mitigation action that best recovers investments (by reducing energy consumption and operational costs). In contrast, metro expansions, together with bio-oil and biokerosene investments, do not compensate investments, at least from GHG emission reduction point of view.

The methodology adopted in this study may be applied in countries with different characteristics.

6. RECOMMENDATIONS

This paper may support other studies from countries and regions with different backgrounds, providing benchmarks on key mitigation policies. This could contribute to a set of benchmarking studies that would provide determinative recommendations on the best actions for GHG mitigation in the transport sector, as relates to their influence on national pledges, under different political and economic contexts.

To promote the energy transition compatible with a 1.5°C scenario, we recommend that the Brazilian government, the private sector, academia and civil society develop roadmaps and climate actions that covers the following elements:

- **Changing political thinking towards long-term and sustainable policies**: reduce the number of short-term projects, for electoral reasons. Develop long-term roadmaps, focused on avoiding trips (e.g. teleactivities, distance learning), more energy efficient modes of transport and technological improvements. Also, the government must encourage the development of new regions, changing the spatial concentration of income and reducing poverty;
- **Development of a national EV industry, providing also components of commercial powertrains**: change of the current profile of manufacturers of lead-acid batteries (present in conventional vehicles and HEV) to lithium-ion batteries etc. (present in BEV). Development of a national powertrain, training professionals for this new EV market;
- **Improvement or creation of standards and regulations for new technologies and business models**: new standards for charging infrastructure, distributed storage, disposal or reuse of batteries and electric vehicle components, etc. Flexibility for the construction and operation of new electrified freight railways;
- **New business models and public transport concessions, revising tariff modalities with government financial support**: business models focused on charging infrastructure (charging stations, energy distribution, distributed and semi-distributed storage), electric vehicle sharing, etc. Concession models that require the expansion of the electric bus fleet in cities, with government subsidies for these fares;
- **Access to international financing, focusing on prospective low-carbon technologies**: development of partnerships between national and international banks for economic development, with different financing rates and payment terms for low carbon technologies. Robust actors, such as government and energy companies, would be the main guarantors of payment systems;
- **International bids to redeem low-yield rail links**: opening to foreign markets for the acquisition of underutilized or abandoned railways (approximately 67% of the Brazilian rail network);
- **Tax reduction and bureaucracy simplification, especially for water transport**: stimulating the competitiveness of water transport, reducing the price of fuel oil practiced in cabotage, as well as port tariffs.

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