A pathway design framework for national freight transport decarbonization strategies

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Abstract:

National and international freight transport emissions represent about 40% of global transport emissions, with demand expected to triple by 2050, which will increase emissions further. However, to meet the 1.5°C climate goal, a rapid decrease in transport emissions is required, along with the achievement of zero emissions as soon as possible around mid-century. Given this context, long-term low-emission national development pathways provide a strategic instrument to align short-term action with long-term objectives and to reduce national freight transport emissions.

However, current transport-energy modelling studies often exclude the structural and systemic mitigation options that influence the industrial production and supply chain structure, as well as modal and logistics choices, and instead focus mainly on the technological options related to road freight vehicles and fuels. In addition, such studies lack relevant policy and stakeholder-oriented explanations of the barriers and enablers associated with these options.

In this paper, we introduce a new framework to design and compare long-term national and sectoral decarbonization pathways for freight transportation, facilitating the consideration of all decarbonization options and the organization of stakeholder-oriented policy dialogues. The development of this sectoral framework builds on the general Deep Decarbonization Pathways (DDP) framework and a first implementation in France. It is then applied and tested in three emerging countries: Brazil, India and South Africa and the results show that the linking of systemic and technological changes could reduce emissions per tonne-km by at least 60%, and up to 100% by 2050, while also reducing energy consumption and supporting national development.

Key policy insights:

- National mitigation strategies currently overlook the reduction of national freight transport emissions, so it should become a higher priority in future revisions.
- Deep decarbonization is possible but requires systemic changes in logistical and industrial organizations consistently linked with the necessary technological changes towards zero-emission vehicles.

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- In addition to road hauliers, road vehicle manufacturers and energy providers, national strategies must not forget to drive changes among freight owners and shippers, customers, infrastructure developers and operators, as well as logistics service providers.
- Policy-relevant strategies should be adapted to national development, industrial and logistics contexts.

Key words (7): freight, transport; decarbonization; pathways; emerging economies, developing economies

1. Introduction

To limit global warming to 1.5°C and avoid facing unmanageable climate impacts, societies will need to reach global carbon neutrality by 2050-70. This however requires far-reaching systemic and technological changes on an unprecedented scale in the main emitting sectors (IPCC, 2023). Existing scenarios compatible with the 1.5°C target with no or limited temperature overshoot show global CO_2 emissions from the transport sector decreasing by 60% on average between 2020 and 2050. However, the most ambitious scenarios (about one quarter of all scenarios) call for emissions reductions of more than 68%, reaching up to 90% (IPCC, 2022b).

Currently, annual transport sector emissions amount to 9 $GtCO_2eq$, accounting for about 15% of total greenhouse gas (GHG) emissions. Transport-related emissions have shown continuous growth since 1990, with an annual average of 2%, increasing faster than for any other end-use sector (IPCC, 2022b). This is mainly due to accelerating demand and global supply chains, which could lead to an almost tripling of tonne-kilometres by 2050 (ITF, 2021a), and a strong dependency on fossil fuels. National and international freight-related emissions account for about 40% of all transport GHG emissions (ITF, 2021a; SLOCAT, 2021).

Current medium-term objectives and strategies for freight as reported in Nationally Determined Contributions (NDCs) under the United Nations Framework Convention on Climate Change, are far from sufficient. Recent analyses highlight that measures affecting freight transport are largely overlooked and very limited in comparison to action on passenger transport (ITF, 2021b; SLOCAT, 2021), while also underlining the need to strengthen sectoral granularity as a priority (Gunfaus & Waisman, 2021; Hermwille et al., 2022). Most freight decarbonization measures focus on the development of low-carbon fuels, such as advanced biofuels or low-carbon electricity and the reduction of fuel consumption. However, they neglect the development of infrastructure and the use of incentives for rail, waterways, and specific actions to transform the structure and length of supply chains (SLOCAT, 2021).

Created under article 4.19 of the Paris Agreement, the "long term low greenhouse gas emission development strategies", also known as Long-Term Strategies (LTSs), could represent a powerful policy tool to revise NDC ambitions. Indeed, these strategies could help align the medium-term actions of NDCs with the broader transformations and mid-century objectives described in the LTSs (Waisman et al., 2019). The development of country-driven backcasted long-term deep decarbonization pathways could play a key role in describing the economy-wide and sectoral systemic transformations required by 2050-70 that would be compatible with the development priorities of all countries, and associated policy strategies over the next decades (Bataille et al., 2016; Waisman et al., 2019).

However, it is evident from the literature that long-term national sectoral pathways often exclude some important decarbonization options such as those related to the systemic changes influencing the demand and supply chain structure, as well as modal choices (Tavasszy et al., 2012), while deep decarbonization requires a broader set of options (de Blas et al., 2020). Pathways also often lack relevant details about the barriers and facilitators associated with these options, hence limiting the potential for public and private actors to further align their sectoral decisions and close the above-mentioned implementation gap.

To address these challenges, this paper introduces the Deep Decarbonization Pathways (DDP) framework for the freight transport sector, based on the generic DDP approach described in Bataille et al. (2016) and Waisman et al. (2019). Building on an initial application of the approach for France (Briand et al., 2019), the framework has been adapted and tested in three emerging economies: Brazil, India and South Africa (Ahjum, 2021; Gonçalves et al., 2022; Gupta & Dhar, 2022; Gupta & Garg, 2020). The paper is structured as follows: section 2 reviews the methodological challenges for policy-relevant DDPs in freight transportation; section 3 introduces the new framework to design national DDPs for the freight transportation sector; section 4 presents the results of the three country case studies; and section 5 discusses the findings. The emission sources reported in this work are the same as those used in the UNFCCC's national inventories, which do not include emissions related to international freight transport.

2. Literature review: methodological challenges for policy-relevant freight transport decarbonization pathways

This literature review highlights the limitations of existing studies associated with modelling all decarbonization drivers and options, as well as accounting for stakeholder-oriented information relevant for policy decisions.

Recent reviews (de Blas et al., 2020; Kaack et al., 2018; McKinnon, 2018; Meyer, 2020) highlight that freight transport decarbonization requires the consideration of systemic changes related to demand management, supply chain reorganization and modal shifts, in addition to technological changes focused on energy efficiency gains and low-emission vehicles and fuels. Indeed, a broad range of literature shows the effects of underlying drivers of transformations on the different emission factors of the sector:

- Changes in the cost, stock and time patterns of production, in consumption behaviours, trade economics and rules, and the effect on transport demand and supply chain structure (Barrientos et al., 2016; Dente & Tavasszy, 2018; Gereffi et al., 2005; Inomata, 2017; Raza, 2021a, 2021b; UNCTAD, 2020).
- Changes in infrastructure expansion, associated costs and time management, and effects on supply chain organization and modal choices (J. Havenga et al., 2012; Kaack et al., 2018; Shankar et al., 2019).
- Changes in the environmental and economic rules of logistics operations, delivery services and effects on modal choices, road vehicle choices and energy efficiencies (Marcilio et al., 2018; Pérez-Martínez et al., 2020).
- Changes in technological costs, battery life and energy density, or regulations such as fuel emission standards, and effects on the supply and adoption of low-carbon vehicles and fuels (Mahmoudzadeh Andwari et al., 2017; Malik & Tiwari, 2017; Tarei et al., 2021).

These studies illustrate the multiple potential drivers of decarbonization and that reaching global carbon neutrality will require broad consideration of these drivers as highlighted by the Intergovernmental Panel on Climate Change (IPCC) (2018 and 2022). However, while the IPCC acknowledges the importance of mitigating climate change through a broad range of options, the Sixth Assessment Report scenario database primarily consists of global analyses based on Integrating Assessment Models (IAMs), rather than global transport energy sectoral models (GTEMs). Out of a total of more than 100 models, only four global transport models were included: the Mobility Model (Fulton et al., 2009), the Global Transportation Roadmap (International Council on Clean Transportation (ICCT), 2012), MESSAGE-Transport V.5 (Huppmann et al., 2019) and GCAM (Mishra et al., 2013). While transport is the core focus of

GTEMs, this is not the case for IAMs, where transport is only one economic sector within the whole economy. GTEMs lack the integration of the transport sector with other sectors of the economy, while IAMs provide less detail on national and sectoral transport transitions (Yeh et al., 2017). Aspects such as drivers of demand generation and the spatial organization of logistics chains are poorly represented in all IAMs, and to some extent in GTEMs. This lack of sectoral detail means that models rely mostly on technological factors to reduce emissions, disconnected from the economic and spatial complexity of logistics chains and operations. While models offer different interaction representations, no single model can produce a comprehensive picture accounting for all drivers of freight transport demand, modal choices, logistics efficiency and low-carbon technology shifts, and they thus represent a simplified and incomplete perspective of the reality. The challenge in developing long-term DDPs is therefore to consider all of the existing research, models and analysis to enable a broader set of options to be examined, while at the same time ensuring the consistency of qualitative and quantitative pathway descriptions.

In addition, a rich literature is available on the relevance and value of scenario planning and the need to involve stakeholders to address profound, long-term transformations where information is incomplete and considerable uncertainties are present (Volkery & Ribeiro, 2009). The involvement of stakeholders is necessary for many reasons: they provide data that is otherwise largely unavailable; they contribute to generating ideas; they can prioritize trends and assess uncertainty levels; and they can assess scenario planning work. In addition, the knowledge that stakeholders can themselves derive from the scenario planning exercise is part of the expected outcome of the process (Andersen et al., 2021). However, current modelling approaches are often based on overly complex models and lack the flexibility to facilitate dialogues and to adapt to discussions around the implementation conditions of the transition. The challenge is therefore to provide a pathway design framework that sectoral stakeholders, such as shippers, carriers, infrastructure developers, vehicle manufacturers and energy providers can understand and use for expert interactions, based on a combined qualitative-quantitative method (Venturini et al., 2019). Stakeholders should be able to understand the impact of their decisions on certain key socio-economic and environmental parameters, and to share their own constraints and solutions, free from the technical limitations of quantitative tools. The question of how to involve stakeholders in scenario planning exercises is complicated (Burt et al., 2021), as well as how they should be represented - i.e. who should be their representatives (Cairns et al., 2013), but the issue is key to closing the above-mentioned implementation gap.

Our literature review suggests that no pathway design frameworks have been developed to explore, consistently and simultaneously, all of the freight decarbonization drivers that will be required for carbon neutrality, to facilitate the decision-making processes of all public and private actors to inform the revision of future LTSs and NDCs.

3. A pathway design framework for freight transport deep decarbonization

Based on the experience of the Deep Decarbonization Pathways research network (Bataille et al., 2020; DDP, 2021; DDPP, 2015; Lefèvre et al., 2020; Waisman H., Torres Gunfaus M., Pérez Català A., Svensson J., Bataille C., Briand Y., Aldana R. et al., 2021), the DDP framework has been developed around two main components to describe economy-wide and sectoral development pathways: (i) a semi-qualitative storyline and (ii) a quantitative dashboard. The pathway design process occurs in three steps (see Lefèvre et al., 2020; Svensson et al., 2021; and Waisman et al., 2019) which is described below regarding the freight sector.

3.1. Building a qualitative storyline considering the full set of decarbonization drivers

The first step provides a *storyline* framework to consider all possible areas of transformation and decisions which could support the mitigation of freight emissions. This framework encompasses elements related to the future of production, consumption, and trading systems; transport, storage and logistics infrastructure; logistics operations and delivery services; transport vehicles and fuels. For example, it is impossible to plan for the need to renew infrastructure or the vehicle fleet if there is no explicit description of the characteristics of materials and goods produced, imported, exported and transported over the territory, and no explicit description of the spatial structure of transport flows in relation to changes in national production, consumption and trading systems. This work builds a qualitative and semi-quantitative narrative according to the five main chapters of the *storyline* framework shown below (Annex 1):

(1) The future demographic, economic, spatial and socio-cultural structure of consumption, production and trade
(2) The development and management of transport and logistics infrastructure
(3) The development of vehicles and truck technologies and their market penetration
(4) The organization of logistics operations (supply and delivery), modal and vehicle choices
(5) The production and distribution of fuels

Within these chapters, the scenario developer describes the various drivers affecting the different elements of the sectoral Kaya identity (Bongardt et al., 2013; Schipper & Marie-lilliu, 2000a). These drivers are not independent and their interplay with emissions is complex. In combination they should contribute to the transformation of production, consumption and logistics organizations and flows to reduce unnecessary movements, trips and kilometres travelled, and facilitate the use of the most energy efficient and less carbon-intensive transport systems. The scenario developer has a certain degree of freedom to formulate these interactions and their contributions to emissions. Descriptions help to explain the underlying enablers of the transition: geophysical, environmental-ecological, technological, economic, socio-cultural and institutional feasibility conditions (IPCC, 2022a). This is complementary to the set of quantitative indicators contained in the *dashboard* and to supporting the implementation of policy dialogues.

Finally, the *storyline* can be enhanced through discussions with real-world actors to bridge the implementation gap and to help structure policy discussions between public authorities and specific actors. The different chapters (1) to (5) could support and inform discussions with freight owners and shippers, customers (1), infrastructure developers and operators (2), logistics service providers (3), transport carriers (4, 5), vehicle manufacturers (4) and energy providers (5) among others.

3.2. Deriving a fully quantified storyline for the dashboard

The method's second step consists in deriving a fully quantified pathway from the *storyline* elements and presenting this storyline in the *dashboard* framework. The *dashboard* provides data on a comprehensive and systematic set of quantitative indicators. It encompasses indicators on socio-economic logistic systems, transport demand, modal structure, road logistics, sectoral fuel consumption, sectoral fuel carbon content and related emissions (Annex 1). Contrary to most research on the topic, the DDP pathway design framework does not provide a quantitative model but rather a quantitative reporting framework known as the *dashboard*. This quantitative information can originate from different modelling or quantitative tools in a "model-agnostic" approach, which acknowledges that no single model can populate all information and represent real-world complexity.

The *dashboard* fulfils a number of primary objectives. First, it supports the analysis of the main emission factors and levers of decarbonization. It should gather all possible transformations of the demand and supply side, and not be limited to the description of conventional energy and emissions-related indicators. Second, it should support the expression of all drivers of transformations, as expressed in the storyline, which requires some specific data disaggregation.

For example, exploring the transition of the production and consumption system towards the reducing, reusing and recycling of products requires going beyond an aggregated tonne-kilometres description of the transport demand. Indeed, it requires distinguishing between the demand for transport, expressed in tonnes transported, from the geographical structure of supply chains, expressed in kilometres. Finally, this cross-country set of indicators should be common to all countries, and at the same time, be a database to recalculate and extract key quantitative indicators relevant to informing national debates. It should therefore provide a systematic categorization enabling different quantitative recombinations.

3.3. Ensuring consistency through iterative backcasting

The third step involves iterative backcasting. The *dashboard* contains the main quantitative objectives, which often combine the effects of various actions, facilitating a scenario-wide analysis of consistency. While initial consistency checks are implemented at the level of each storyline category and quantification step, this consistency check involves verifying that the combination of all chapters of the *storyline* reach both the decarbonization objective and the main socio-economic goals. This overallconsistency check takes place in a feedback loop where the storyline and quantification steps are dealt with iteratively until all parts are consistent with each other. Furthermore, the dashboard also serves as a means to ensure that each part of the narrative plays a role in the decarbonization effort.

Annex 2 provides an overview of the modelling architectures used by the research teams in Brazil, India and South Africa to quantify the *storyline* and populate the *dashboard*. It also provides an analysis of some of the challenges faced during the implementation of the framework. Annex 3 provides additional elements on the data disaggregation options of the transport demand.

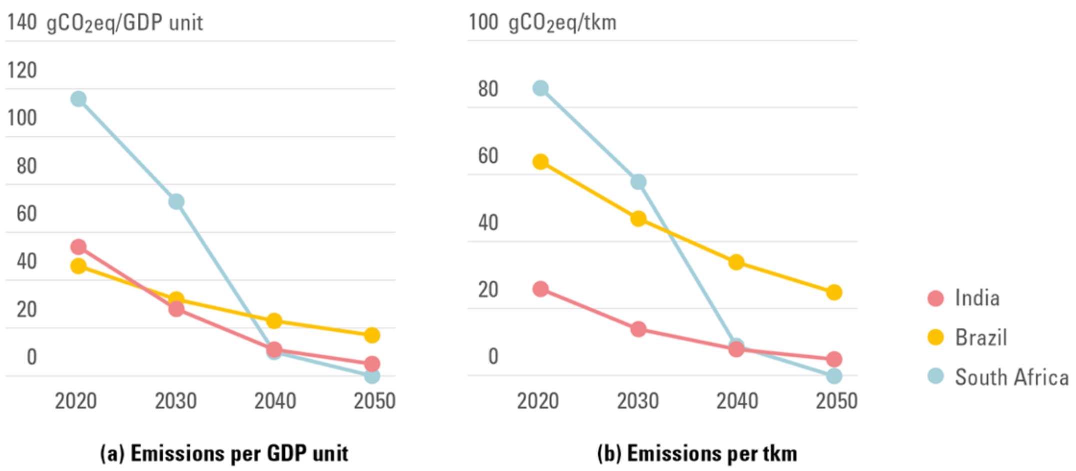
4. Building and comparing systemic and policy-relevant long-term deep decarbonization pathways

In this section we present a country comparison of the required long-term transformations in key areas – mobility needs, modal and logistics choices, road logistics organization, low-carbon vehicle and fuel technology deployment. This comparison uses information reported in the national *storyline* and *dashboard* framework.

4.1. Overall country comparison of freight transport transitions

In Brazil, India and South Africa, freight transport emissions accounted for, respectively, 6.5%, 4% and 5% of national GHG emissions in 2019. While all these countries have fast-growing economies, current analyses illustrate possible decarbonization pathways for freight transportation that are consistent with a national carbon neutrality goal. On a per GDP unit basis, freight transport emissions could be reduced by 63% to almost 100% between 2020 and 2050, reaching less than 5 gCO_2eq/GDP unit in India and South Africa and around 20 gCO_2eq/GDP unit in Brazil (Figure 1). On a per tonne kilometre travelled (tkm) basis, emissions are reduced by 60% to almost 100% in 2050 relative to 2020, reaching less than 5 gCO_2eq/tkm in India and South Africa and around 25 gCO_2eq/tkm in Brazil (Figure 1). This corresponds to absolute emission reductions of 29% for Brazil, 47% for India and 99% for South Africa in 2050 relative to 2020 (See Kaya identities in Annex 4).

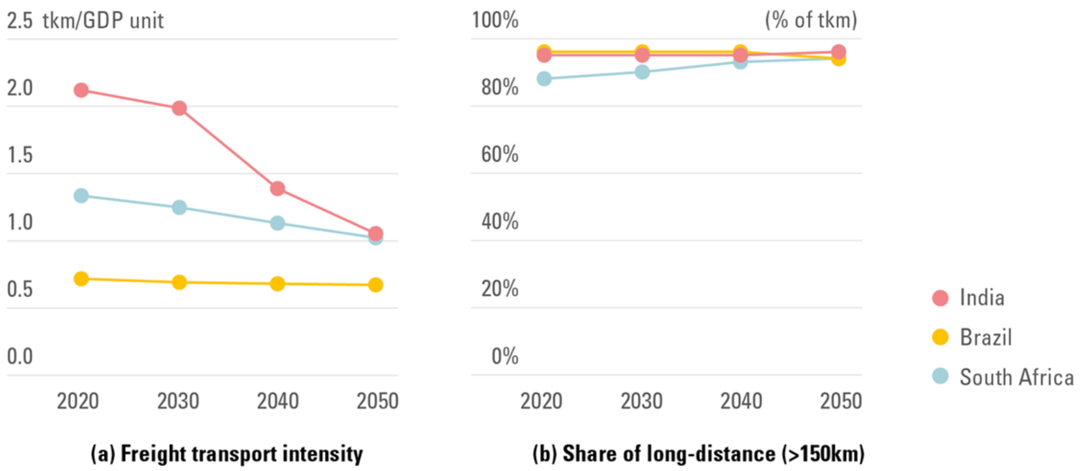
Figure 1. CO_2eq emissions from freight transport (a) per GDP unit and (b) per tkm, 2020-2050



4.2. Mobility needs

While the domestic transport of goods depends on structural economic factors linked to national production and the consumption of goods or the significance of the country's production in international trade, other factors such as the nature of goods transported or the industrial and spatial organization of supply chains play a role in impacting future tonne-kilometres. In Figure 2 we therefore look at two different indicators: freight transport intensity (tkm/GDP unit) to understand the role and structure of the economy, and the share of long-distance transport demand (% tkm) to analyse the role and structure of the spatial organization of production and supply chains.

Figure 2. Freight transport intensity (a) and share of long-distance (>150km) transport demand (b), 2020-2050



Note: Long-distance is defined in this work by traffic above 150 km.

Economic structure and freight transport is quite different in 2020 in the three countries, with the Indian economy generating three times more tkm for one average GDP unit compared to the Brazilian economy. However, this ratio is expected to decrease in India and South Africa and converge at around 1 by 2050, while remaining stable at 0.7 over this period for Brazil (Figure 2.a). This is mainly due to the transition towards a more service-oriented economy and the development of more efficient freight services. Nevertheless, in Brazil, India and South Africa, GDP is expected to grow by a factor of 1.9, 5.7 and 2.2, respectively, by 2050 compared to 2020, which will lead to an overall increase in total freight transport demand (in tkm) that is projected to reach, respectively, 1.8, 2.8 and 1.7 times that of the 2020-level by 2050.

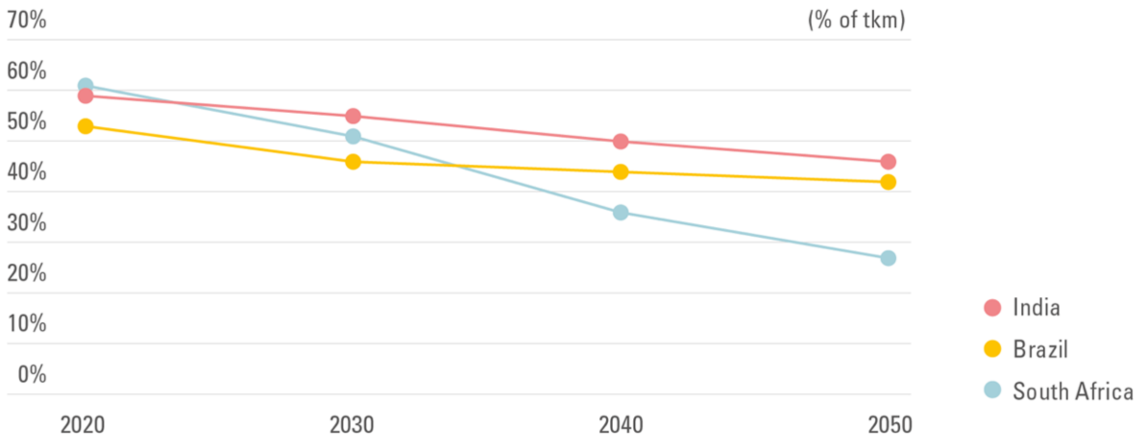
For the three countries, demand has been analysed in relation to regional (<150km) and long-distance (>150km) transport (Figure 2.b). All countries currently have a very high proportion of long-distance transport demand and this dominant role will remain until 2050. It will play an even bigger role in South Africa, increasing from 88% to 94% by 2050. South Africa has a large geographic spread, with long distances between the metropolitan areas where most economic activity takes place and a history of industrial and economic development far from seaports (J. H. Havenga et al., 2016). The economic centre is in the Gauteng province, 600 km from the nearest seaport, which makes up approximately a third of South African GDP (RSA, 2022). There is a dependence on imported consumer goods, the export of bulk commodities, and the distribution of manufactured and agricultural goods produce over long distances (J. H. Havenga et al., 2016; World Bank, 2021). In Brazil, the slight downward trend, about 2%, is mostly due to an increase in last mile deliveries (food and parcels), reflecting the ongoing internet revolution and associated digital activities (CGEE, 2022). In India, long-distance freight transport will continue to represent a very high share of the total due to the development of national rail and road networks that connect most of the industrial and agricultural centres across India (Ministry of Information & Broadcasting, 2023). In all cases, these transformations only reflect current policies and trends in economic structure and supply chain organization.

Research teams have also started to explore the future of transport demand based on commodity analysis, as a means of better understanding and assessing the transformation of industries, and to consider modal and logistics choices from a value chain perspective. An initial aggregated analysis has shown that the average trip distance (km/ton) will remain stable over time in Brazil and South Africa, respectively around 350 km and 200 km, while it will increase in India from about 800 km to 1000 km by 2050 (Annex 3).

4.3 Modal choices

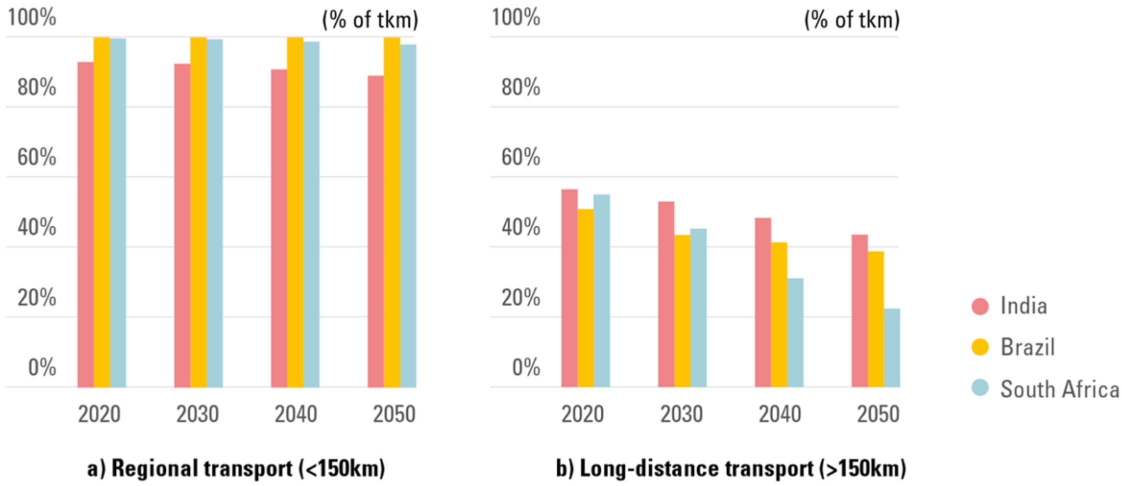
A structural decarbonization strategy is the modal shift from road transport to bulk modes of transport, e.g. rail and inland waterways and coastal (IWW&C) transport. In all countries, the share of road transport in total freight mobility started from similar levels in 2020, of between 53% and 61%, and is expected to decrease to between 27% and 46% (Figure 3), but at different rates and with different roles played by the alternative modes of rail and IWW&C transport. In South Africa, road transport shows the greatest decrease and rail services are the only alternative, which represent the rest of the country's freight transport. In Brazil and India, road transport decreases by around 11 to 13 percentage points (pp) between 2020 and 2050, while rail services increase respectively by 9 and 11 pp, and IWW&C transport by 2 pp in both countries. While in India the dominant alternative mode by far is rail, with IWW&C transport representing about 1% in 2020 and 5% of the modal share by 2050, the Brazilian situation is, however, more balanced. In Brazil, the modal share of rail represents about 27% in 2020, increasing to 36% in 2050, while the IWW&C transport modal share represents about 18% in 2020 and 22% in 2050. In Brazil, this mostly comes from the fact that coastal shipping is heavily developed.

Figure 3. Share of road transport in total mobility (%tkm), 2020-2050



Most variation comes from changes in the modal structure of long-distance transport, which relates to trips above 150 km (Figure 4). Indeed, for regional transport, which involves trips under 150 km, road transport remains predominant at around 89-93% in India, 98-100% in South Africa, and 100% in Brazil for the period 2020-2050. In addition, as previously mentioned, long-distance transport represents more than 90% of all transport demand in tkm in all countries.

Figure 4. Share of road transport in: a) regional transport and b) long-distance transport, 2020-2050



These results come from investment in multimodal and linear infrastructure associated with new regulatory and institutional reforms for the rail and IWW&C transport sector, which targets specific industries and economic regions to offer credible alternatives to "road-only" transport services.

In India for example, the fastest decrease in the modal share of road from 2030 will be driven by the Gati Shakti National Master Plan (Ministry of Road Transport & Highways, 2022) and the Bharatmala project, which focus on improving multimodal and last mile connectivity, by the Sagarmala project that promotes port-led development, and the development of dedicated rail freight corridors (Department of Economic Affairs, 2021). In Brazil, the future decrease in the modal share of road transport stems from high-capacity infrastructure that was planned in the 2011 National Plan for Logistics and Transport, which is due to be completed by 2030 (EPL, 2018). It is also assumed that over the next decade the Brazilian government will invest in intermodality, with specific multimodal transshipment infrastructure at the main strategic freight interconnections and ports to ensure that maritime cabotage and rail are gradually preferred for long distances (EPL, 2021). South Africa has officially recognized the under-utilization of the current public Transnet infrastructure, which is due to the ageing of the network, poor operational service performance, insufficient intermodal facilities and too many access barriers for private freight operators (DoT, 2022; J. H. Havenga et al., 2021; NPC, 2020). This work assumes that structural reform will take place during the next decade, with significant investment to upgrade the infrastructure and to change the market structure.

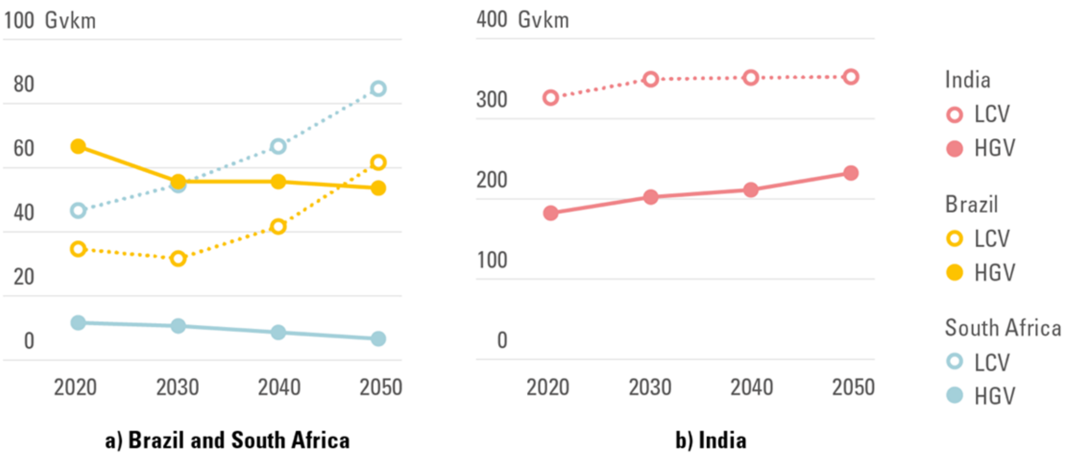
In all cases, the reinforcement of rail and IWW&C transport requires changes and regulations to support shippers and cargo owners to change their behaviour and to enable a competitive service in terms of costs, transit time, delays, and safety. Such regulations aim, for example, to reduce bureaucracy or facilitate access to infrastructure in some cases, such as in Brazil, through federal laws No. 14,273/2021 and No. 14,301/2022, which create economic and operational incentives for increasing the use of railways and cabotage. In South Africa, an independent transport economic regulator could be created to facilitate non-discriminatory access to the network and encourage external private operators, services, and innovations (DoT, 2022). In India, in 2022, the Prime Minister launched the first National Logistics Policy (India, 2022) to reduce the very high cost of Indian logistics and improve business efficiency with, for example, the implementation of the first national Unified Logistics Interface Platform to simplify logistics processes.

4.4. Road logistics organization

The improvement of road logistics, e.g. the choice of the most efficient road vehicles, the optimization of shipments in terms of size and load, and the reduction of empty running, is another key strategy. While the modal share of road will decrease on average in all countries as described above, it will not be enough to decrease the total tkm made by road in Brazil and India over the period 2020-2050, but it will in South Africa, which has the highest modal shift towards rail, where the road tkm will decrease by 25%. In Brazil and India, the total tkm made by road will continue to grow by 45% and 120%, respectively, mostly driven by the overall increase in freight demand.

Nevertheless, in all countries, road vehicle traffic will increase, but the circumstances will be very different (Figure 5). In Brazil and South Africa, Heavy Goods Vehicle (HGV) traffic will decrease while Light Commercial Vehicle (LCV) traffic will increase. In India, both LCV and HGV traffic will increase. In South Africa, while road transport demand (tkm) will decrease, the share of LCVs in regional road traffic will remain very high (above 90%) and is increasing from 50% to 75% of long-distance road traffic. In India and Brazil, while the road regional transport demand (tkm) will multiply by a factor of 1.2-1.6 over the period (compared to 0.3-1.2 for road long-distance transport demand), the share of LCV traffic will decrease in regional transport but will remain dominant (above 90%) and will increase in long-distance transport while remaining in the minority (below 15%). This represents an increase in operational efficiency for regional transport with better HGV utilization, and also reflects the increasing trend for short distance and fast road transport and commercial services, which will penetrate into the long-distance transport delivery sector (EPL, 2021; J. Havenga et al., 2018; TCI, 2015; TransNet, 2015).

Figure 5. Total road traffic (Gvkm, e.g. Billions of vkm): in Brazil and South Africa (a), and in India (b) with Light commercial vehicles - LCV (dashed line) and Heavy Goods Vehicles - HGV traffics (Solid line)

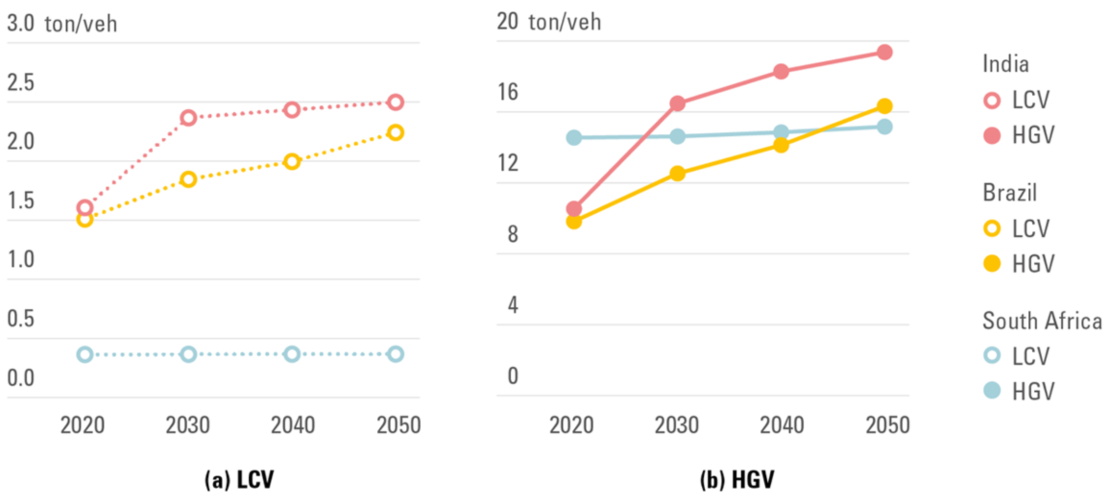


Notes: Heavy Goods Vehicles covers all commercial trucks with a gross vehicle weight (GVW) of over 3.5 tonnes. Light Commercial Vehicles covers all commercial vehicles with a GVW of under 3.5 tonnes.

In addition, the average load factor, which includes empty running, plays a different role in the three countries (Figure 6). In Brazil, it is assumed that the LCV and HGV average load factors will increase over time, reaching more than 2 for LCVs and 16 for HGVs in 2050.

Currently, empty running accounts for about 40% of truck trips, a figure that is expected to be reduced through collective programmes such as the *Programa de Logística Verde Brasil* (*PLVB*) and the development of digital freight exchanges between logistics operators, which will increase operational efficiency (Goncalves et al., 2020). In South Africa, no specific actions or changes have been considered to improve the situation, and the average load factor is projected to remain stable over the period. In India, it is assumed that the combination of new policies like the governmental policy to increase the axle load limit by 25% (MoRTH, 2018) or the National Logistics Policy (India PM, 2022), with the development of digitalization in the freight sector, scheduling and dispatching will contribute to bring improvements to the average load factor and reduce empty running.

Figure 6. Average load factor (including empty running): of LCV (a) and HGV (b)

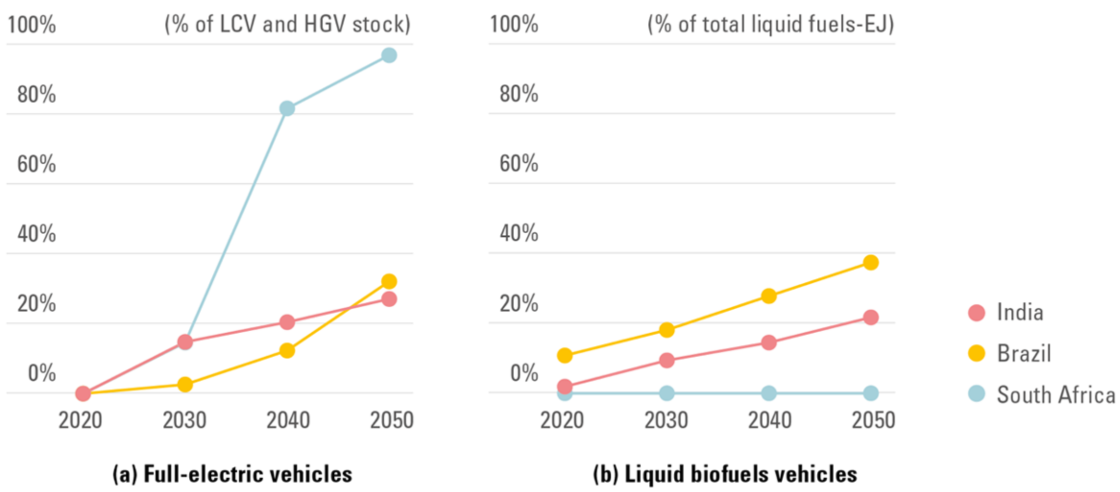


All transformations expressed in the storyline categories relating to production, consumption and trading systems, to the development and management of infrastructure, and to logistics operations, have a systemic effect on the total freight transport demand, on spatial flow distributions and related logistics choices (mode and vehicle choices, routing, loading…). Together, this contributes to lower energy demand and facilitates the shift towards low-carbon fuels. For example, shifting long-distance transport to electric rail, when long-haul low-carbon truck technologies are still immature, will contribute to the acceleration of national decarbonization in all scenarios.

4.5. Low-carbon vehicle and fuel technology deployment

All deep decarbonization pathways account for a shift from liquid fossil fuels towards low-carbon electricity, agro-biofuels or low-carbon hydrogen. In all scenarios, the share of non-fossil fuel energies in the total final energy consumption of freight increases in Brazil, India, and South Africa, respectively, from 11%, 7% and 2% in 2020, to 39%, 64% and 98% by 2050. This is mostly due to the development of road electric vehicles and liquid biofuels (Figure 7).

Figure 7. Share of full-electric road freight vehicles stock (a) and liquid biofuels vehicles (b)



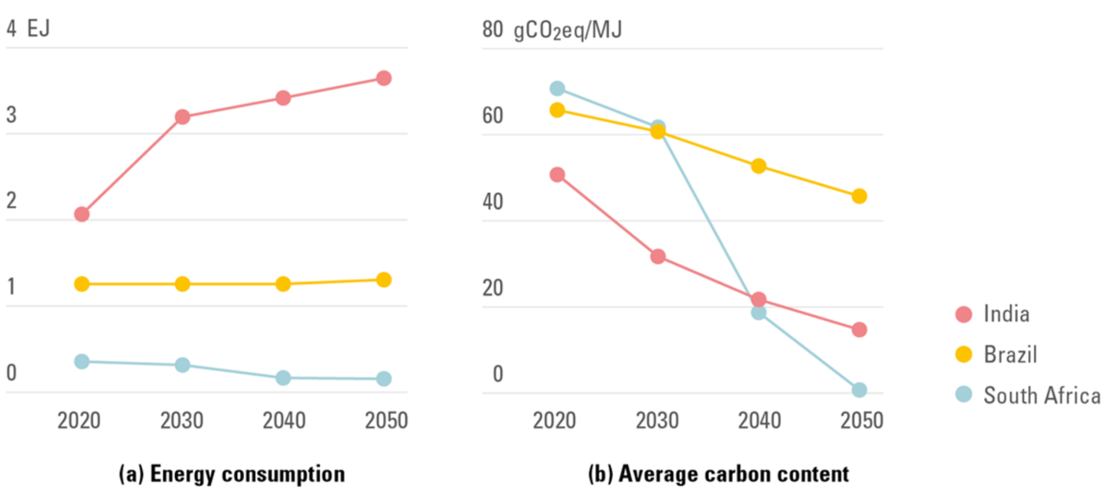
Road emissions due to the combustion of liquid fuels represented more than 90% of all freight emissions in 2020 in all countries. The market penetration of battery electric vehicles (BEV) will start during this decade, representing about 2% to 15% of the road vehicle fleet by 2030 and up to 27%, 32% and 97% by 2050, respectively, in India, Brazil and South Africa (Figure 7.a). In all countries, the development of BEVs will be more significant in LCV rather than HGV fleets, with increases of, respectively, 41% and 7% in Brazil, 28% and 26% in India, and 100% and 70% in South Africa. This is mainly explained by the fact that battery capacities are better suited for LCV use than for HGVs, and also for short-distance and urban trips. In South Africa, one of the main reasons for the EV boom is that LCV purchase parity with internal combustion engine (ICE) equivalents will be reached by 2030 (Greencape, 2023). In Brazil and India, this purchase parity is expected to be reached later, by around 2035-2040. Nevertheless, in Brazil and India, it is assumed that new regulations will create a favourable environment for EV markets: new credit offers and financial support, new and additional domestic manufacturers of vehicles, components and batteries (EPE, 2023; NITI Aayog & RMI, 2022). From 2040 onwards in Brazil, for example, the most intensively used vehicles (LCVs and light-medium trucks) will represent 100% of sales in metropolitan areas. In India, the investment cost of the charging infrastructure, as well as vehicle purchase price will remain major barriers for rapid EV development, which explains the less optimistic scenario for EVs (NITI Aayog & RMI, 2022). Regarding the future of ICE vehicles, an almost complete phase-out by 2050 was forecast for South Africa, with no liquid biofuel development considered. In India and Brazil, ICE vehicles may continue to represent more than 60% of road vehicle fleets with, respectively for these countries, up to 72% (including 26% Plug-in hybrid electric vehicles (PHEVs)) and 90% of the HGV stock in 2050, due to the potential development of biofuels for road mobility by 2050. Brazil has a very well-established biofuel industry and liquid biofuels production could therefore deliver about 0.5 Exajoule (EJ) for freight transport vehicles by 2050, compared to about 0.15 EJ in 2020. Indeed, the government is continuing to provide support for biofuel production and distribution through the RenovaBio programme, as well as the introduction of the Rota 2050 programme, which should replace the current Rota 2030 at the end of the decade (CentroClima, 2023). In India, liquid biofuels will represent about 0.3 EJ by 2050 compared to 0.03 EJ in 2020. On average, in India and Brazil, respectively, the share of liquid biofuel in total liquid freight fuels will increase from 2% and 11% in 2020 to 22% and 37% (Figure 7.b). In India, independence from oil imports is a key priority of the national biofuel

policy, and with the role of agriculture in the country, biofuel production is seen as a major contributing lever to improve the incomes of farmers, to achieve higher employment levels in agriculture and to contribute to decarbonization (MoPNG, 2019). However, its development could be limited due to several challenges, such as land-use competition (Ravindranath et al., 2011), biodiversity conservation (IPBES, 2019; Santangeli et al., 2016) and water use (Jewitt & Kunz, 2011). It should be noted that biogas has not been considered as an economically relevant option in any country.
Annex 5 provides additional elements on the future of plug-in hybrid electric vehicles (PHEV) and fuel-cell electric vehicles (FCEV) in these countries, showing the very specific nationally driven storyline for FCEV development in South Africa.

These transformations lead to a decrease in the carbon content of energy used from around 70gCO_2/MJ in 2020 down to almost 0, 17 and 46 gCO_2/MJ, respectively, in South Africa, India and Brazil (Figure 8.b).

Ultimately, beyond the reduction of carbon content, all transformations to increase bulk modes of transport, to increase road logistics efficiency, and to increase electrification, also contribute to the management of the sector's final energy consumption (Figure 8.a). This total is reduced by around 50% in South Africa and stabilizes at around 1.3 EJ in Brazil, while the overall national freight demand increases. These transformations have also played a role in India, limiting the increase in energy consumption.

Figure 8. Freight total final energy consumption (a) and Average carbon content (b)



5. Discussion and conclusions

5.1. A comprehensive framework integrating all drivers and systemic changes

The DDP pathway design framework for freight has successfully provided a structure for the design of comprehensive sectoral and national deep decarbonization pathways, integrating systemic changes relating to demand, supply chain structure, as well as modal choices and technological changes. Implementation of this framework in Brazil, India and South Africa has enabled the development of freight transport sectoral pathways up to 2050 that are consistent with national climate and development priorities.

However, while it is necessary to consider these systemic changes to reinforce the robustness and ambition of national deep decarbonization pathways, the challenge lies in how they are taken into account within the context of other transformations. To better include these systemic changes, the research teams have been invited to build related qualitative analyses in the storyline and quantitative analyses in the dashboard. If we first consider the quantitative aspect, in this implementation, research teams have used a national transport energy model (NTEM) in combination with national integrated assessment modelling (IAM) to better define the transport sector, including the transport demand structure. However, the granularity and detail of NTEMs regarding the transport demand structure and related drivers has remained low, often represented by an average total tkm and average modal shares. Therefore, the analysis of the tonnes transported and transport distances by type of goods, as well as the analysis of modal shares for intra-regional versus inter-regional transport services, as proposed in the framework to better analyse the systemic changes of demand, required additional data analysis and soft-coupling within the existing modelling architecture. Unfortunately, due to a lack of existing analyses and databases on goods production and consumption, this work has not been fully achieved. Further work could be done to improve the granularity of NTEMs to take a supply chain approach through certain categories of goods, and to add variables to drive the projections of tonnes transported and transport distances. Regarding the qualitative aspect, the framework triggered new qualitative research regarding the drivers of change of transport demand and the development of spatially detailed narratives between intra-regional and inter-regional supply chains and transport. It facilitated the identification of potential opportunities for modal shift and the market penetration of low-carbon fuels in the road freight industry, among others. It also created a space to discuss possible changes in production and consumption patterns, although research teams did not consider disruptive or alternative narratives and assumed a continuity in industrialization patterns in this first implementation.

Finally, this implementation revealed the need to reinforce the national level analytical capacity to explore in more depth the context and future of industrial, consumption and trading systems, and their relationship with mobility. The linking of international and national freight transitions was not studied in this work. In a previous experiment in France (Briand et al., 2019), the implementation of the framework with a better access to national data and analysis on these elements enabled the better integration of industrial and consumption policies to foster less resource-intensive production and consumption, which are more localized for certain types of goods.

5.2. An accountability and comparison framework to structure dialogues

The DDP pathway design framework for freight also provides a transparency framework to compare and discuss national transitions, long-term and short-term ambitions, and policy actions over time. The common structure of the storyline and dashboard therefore facilitate comparability between scenarios, beyond the heterogeneity of modelling tools and national contexts. While the dashboard quantitatively describes the main transformations to reduce emissions, the storyline provides a detailed description of the underlying drivers of these transformations. This combined qualitative and quantitative approach described the transition with information relevant for the decisions of various stakeholders involved in national climate processes such as the revision of NDCs and LTSs.

This implementation has facilitated a cross-country knowledge exchange and triggered discussions among national research teams on common and differentiated paths, barriers and solutions, such as for the market penetration of EV LCVs in intra-regional and inter-regional transport. The use of the storyline structure facilitated the identification of discussions needed with key transformational actors, for example with shippers about their logistics organization and constraints. However, to accelerate decisions, further dialogues between research and policy actors should be structured around all storyline elements to discuss stakeholder-specific barriers and facilitators of decarbonization transformations.

In this existing framework, two limitations have been noted and could be addressed in future. First, individual national transitions are not fully independent and changes in the global context influence national transitions, for example: the future of international maritime transport and the impacts on national ports and IWW&C transport transition; the future market for second-hand vehicles and its impacts on the market penetration of alternative fuels; the future of international finance mechanisms and impacts on the cost of the transition; the future of international trade regulations and impacts on import and export-related transport demand, etc. Second, the freight transport framework does not offer an accountability framework for emissions relating to the building of infrastructure or vehicle manufacturing, as these emissions are accounted for in the industrial sector. However, as this could provide additional insights on indirect emissions and co-impacts of the sectoral transition (Awaworyi Churchill et al., 2021; Qian et al., 2022), such elements could be included in future in the storyline structure of the framework. In addition, further analysis could be provided by specific environmental impact assessment tools (Coutinho et al., 2019; Mateichyk et al., 2021; Shah et al., 2010).

5.3. Remaining challenges for deeper emissions reductions in the freight sector

This work illustrates how freight transport emissions could be reduced by 29% for Brazil, 47% for India and 99% for South Africa in 2050 relative to 2020, while enabling national development and carbon neutrality objectives to be reached. Brazilian and Indian research experts faced different challenges in providing pathways to reach close to zero emissions for freight transportation. In the case of Brazil, the level of ambition presented in this scenario is mostly explained by the fact that the Brazilian cross-sectoral analysis revealed more cost-effective actions in sectors other than freight, such as agriculture, forestry and the land-use system, enabling Brazilian carbon neutrality to be reached by 2050. This therefore explains the rather low ambition for freight in this study, however other national studies have shown greater potential (Camargo et al., 2023). Regarding India, the analysis of intensity indicators has ascertained that the main driver of emissions is the booming socio-economic development of the country. Indian energy consumption per tkm is the smallest in 2020 and will continue to reduce to become the same as South Africa by 2050, while the electrification of road vehicles will increase, but not at such a high level as considered possible in South Africa. At the same time, Indian experts are considering the strongest decoupling effect between transport demand and GDP, while starting from the highest intensity in 2020. In all countries, additional measures to transform the organization of industry could reinforce this decoupling between development and transport demand, while at the same time reducing the pressure on the energy system transition. Further research in this area is required.

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7. Disclosure statement

No potential conflict of interest was reported by the authors.

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