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A system dynamics model for analyzing modal shift policies towards decarbonization in freight transportation

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ABSTRACT

The decarbonization of freight transport is currently a big challenge to tackle. One way of decarbonizing the sector is the modal shift towards the least polluting transport modes. This research aims to shed light on modal shift time dynamics in developing economies and considers whether a System Dynamics approach can assist with the policy-making decision about a modal shift towards freight decarbonization. This research explores policies that promote the modal shift of freight transportation for a Brazilian case study, using a System Dynamics model. Policies include fiscal and regulatory measures and infrastructure investments. The findings show that the process of modal shift is slow. However, implementing a combination of stricter policy measures early on, and changes in infrastructure investment strategies, accelerate the shift and this seems to be a robust measure package, capable of promoting a modal shift and decarbonizing the system. The model used highlighted how the system tends to adjust to modal shift measures, which tend to lose efficiency over time, slowing down the pace of decarbonization. Findings also display how modal shift policies alone might not be sufficient to achieve a reduction in CO_2 emission. Addressing the problem with a System Dynamics approach may help decision-makers in economically developing countries to develop more effective policy strategies.

1. Introduction

The transport of goods is essential for economic development. However, freight transport also plays a significant role when it comes to resource consumption, pollution, and climate change. In 2017, road freight transportation accounted for around 7% of the total world energy-related carbon dioxide (CO_2) emissions (Kaack, Vaishnav, Morgan, Azevedo, & Rai, 2018). Freight demand is expected to increase and as this sector relies heavily on fossil fuels, decarbonization in freight transport seems to be a difficult challenge to be tackled.

Shifting freight transportation from road to rail would entail a reduction of CO_2 emissions (Hou & Geerlings, 2016). Nevertheless, what most countries have experienced is a growth in road freight and a shift from rail to road (Kaack et al., 2018). The modal shift can be promoted by having policies targeting certain infrastructure investments (e.g. new infrastructure projects or by improving existing infrastructure), fiscal measures (e.g. fuel pricing or road pricing), and regulatory measures (e.g. truck size and weight limits) (Bickford et al., 2014; Woodburn, Browne, Piotrowska, & Allen, 2007).

Political decisions on new infrastructure projects, as well as fiscal and regulatory measures to promote modal shift, are long-term commitments and involve multiple stakeholders. The implementation of such decisions is time demanding and the impact cannot be measured right away, creating a complex and time-dependent, dynamic problem. Moreover, the time window to apply decarbonization policies is relatively short as many of the political goals to achieve CO_2 emission reductions are expected to be achieved in the coming decades (European Commission, 2011; European Environment Agency, 2019).

Kaack et al. (2018) mentioned the importance of looking into emerging economies and developing countries when looking for ways to replace road transport with rail transportation. Developing countries experience rapid growth in transportation demand, which entails the need for new transportation infrastructure. Brazil's economy relies heavily on exports and the country has an uneven structure when it

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comes to freight transportation, its current modal split consists of 65% via roadways, 15% via railways, and 20% via waterways (ANTF - Associação Nacional dos Transportadores Ferroviários, 2020). The demand for new infrastructure in Brazil is peaking, the country is under an intense private-public partnership (PPP) program as a strategy to overcome the limitations of its infrastructure network, focusing on improving its rail and waterways corridors, which makes Brazil an interesting country to study freight modal shift policies.

To analyze the modal shift impacts in such a system, it is necessary to look beyond isolated events and measures and study the interaction of different parts of the system and how these parts relate through time. System Dynamics (SD) is an approach that allows the study of the impact of different policies in such complex systems (Pruyt, 2013). The dynamics' complexity effect arises from the freight system's multiple feedback loops due to many interconnected components. This research aims to design and apply an SD model that can estimate future CO_2 emission impacts of modal shift policy measures over time, in the Brazilian context. We incorporated infrastructure projects, pricing measures, and stakeholders' decisions in our application to allow decision-makers to understand the complexity of the Brazilian freight system and how it will develop its CO_2 footprint over time using different possible modal shift policy scenarios. Our scientific contribution is that, as far as we know, no study has analyzed the usefulness of a detailed SD model to determine which policy measures could be considered in Brazil to accelerate the modal shift, as well as the lag time the Brazilian freight system needs to adapt to the policies. By using SD, we can estimate the adaption times that are required in the different modal shift policies before CO_2 emission takes off. In the discussion, we also address the extent to which our findings can be generalized for other emerging economies.

We conducted a literature review on SD methodology applications in freight systems to define the basic setup of our model. From the literature, we extracted the elements needed to simulate the freight modal shift process at a national level. In the next step, we conducted interviews with experts, trying to grasp important aspects and factors for our model that were not fully covered in the literature. Using the findings from the literature and the interviews, we developed a causal loop diagram (CLD), illustrating the key relations in the system, followed by the development of the stock and flow diagram. We verified and validated the model using tests as proposed in the SD literature. Finally, we applied the SD model to analyze the behavior of the system when implementing policy measures to study the promotion of a modal shift and the reduction of CO_2 emissions.

The remainder of the paper is organized as follows: Section 2 describes the relevant literature on System Dynamics and its application to transportation problems, focusing on promoting a modal shift towards lower emission mode. Section 3 summarizes the process of the interview with experts. Section 4 presents the SD model developed for this research. Section 5 briefly introduces the validation and verification tests that were performed to ensure that the model was implemented following its specification and that it was an accurate representation of the system. Section 6 presents the experiments carried out and the discussion of the results. Lastly, Section 7 shows the conclusions and recommendations of this research.

2. Literature on freight decarbonization SD modeling: positioning our SD modeling choice

In this section, the state of the art in SD modeling in the research fields of freight transport, mode choice, and modal shift is shown. The approaches presented are investigated in detail and consideration is given regarding whether they are suitable for our research focus. Additionally, we position our choice for SD modeling within the wider freight modeling approaches.

The SD methodology was developed by Forrester (1961) as a basis of explanation to illustrate the effects of decisions in complex, dynamic systems, in which the time functions are emphasized. The specific feature of SD is its non-linear feedback structures. For this reason, the interdependencies between system submodules have to be identified and illustrated in an iterative modeling procedure (Thaller, Clausen, & Kampmann, 2016). Abbas and Bell (1994) discussed and evaluated the strengths and weaknesses of SD concerning its suitability and appropriateness for transportation systems modeling. Shepherd (2014) presented a review of SD studies, categorizing them by area of application in the field of transportation and providing a summary of insights and recommendations for any future application of the SD approach in this field. There are a few studies regarding the mode choice or mode shift aspect.

Piattelli, Cuneo, Bianchi, and Soncin (2002) developed a macrolevel of variable aggregation approach, based on a generalized transportation model, to study the modal shift between roadways, railways, and waterways in Germany. They included three different public interventions in the model, possible investments in infrastructure for each mode, public coverage of operational costs by mode, and additional fuel taxation. Results showed that investments in infrastructure are more effective in promoting a decrease in freight transportation on roadways, compared to regulatory measures, such as fuel taxation. Han and Hayashi (2008) researched CO_2 mitigation scenarios in China's inter-city freight transport using SD modeling. They considered four different transport modes: railway, highway, waterway, and airway. Factors such as freight turnover volume, freight volume, network length, and fuel intensity were included in the model. The authors considered improving the traffic network (railway, highway, waterway, and airway growth rate) and fuel tax regulations as policy measures. Their simulation results showed that investing in the railway network is the most effective measure to reduce CO_2 emissions.

Liu, Mu, and Gong (2017) carried out a study using System Dynamics to evaluate modal shift policies to eliminate overload trucking in China, while promoting more sustainable alternatives such as railways. The authors considered rigid weight regulation and investments in railway infrastructure as policy measures. The results show that stricter weight regulations led to a higher total cumulative cost and did not have a positive impact on sustainability, while building a new railway could lead to an effective modal shift, removing freight from road and achieve better results in terms of sustainability. However, the research does not tackle the stakeholder aspect of the dynamics, and how they could react to certain changes in trend, e.g. if rail transport becomes financially more attractive than road, what would the trucks operators do to try to still keep their market share?

Choi, Park, and Lee (2019) developed a system dynamics model to analyze the impact of policy measures on promoting the modal shift from road to rail, using the steel industry for steel rolled coils transport in South Korea as the case study. In this study, containerization and taxes imposition on road transportation were applied as policy measures. The results show that containerization promoted the modal shift more rapidly than the taxations. The paper was able to provide a model that can support on anticipating the modal shift from road and to shed a light on promoting the modal shift using containerization. However, the rate to implement the policy measures was not provided and some aspects such as warehousing and transshipment costs were left out of the model.

GLADYSTE (Global Scale System Dynamic Simulation Model for Transport Emissions) is a model prototype that enabled the estimation of passenger and freight transport demand and emissions, and it simulates the impact of policy and technological measures in transport-related sectors, covering different transport modes and different regions of the world up to 2050 (Purwanto, González, Vanherle, Fermi, & Fiorello, 2011). The GLADYSTE model defined four main modules to simulate the transportation system and environmental impacts: Demand, Fleet, Environmental, and Welfare. However, the authors did not present any SD diagram and did not provide details in terms of lag time on the decisions' effects. Brito Junior et al. (2011) used an SD approach to study the modal shift of freight transport between road and waterways, as part of the decarbonization policy, using Brazil as a case study. They analyzed the modal shift based on the level of investment in the mode's capabilities and governmental pressure to reduce CO_2 emissions. They created a framework divided into four parts: transport capacity, transport demand, modal shift, and CO_2 emissions. The authors defined five different scenarios to simulate (pessimistic, moderate, moderate CO_2, optimistic and optimistic CO_2) and compared the evolution of the modal shift between these two modes over fifteen years. Their results showed that the inertia for the maturation of the modal shift is long and stricter decarbonization policies could help accelerate the modal shift. However, despite the important results, the paper does not mention the stakeholders' involvement. It does not detail which measures could be considered to accelerate the modal shift, as well as the lag time to adapt to the new policies.

System dynamics is a tool that can also be used to analyze different type of transportation issues. While most of the papers we mentioned focused on inter-urban freight transportation, Astegiano, Fermi, and Martino (2019) built a modal to investigate the impact of electric bikes on modal split in Europe at an urban level and its effect on emission reduction. The simulation shows that e-bikes has a positive effect on reducing car and public transport modal share and contributes to make active modes more attractive.

Ghisolfi, Tavasszy, Correia, Chaves, and Ribeiro (2022) reviewed system dynamics models addressing different strategies for freight transport decarbonization, including the modal shift from road to alternative modes. They reviewed a total of 50 studies and highlighted the lack of transparency concerning how the time-dependent behavior is determined, especially on the time-leg and delay assumptions for each decision to achieve the results in some defined terms. In other words, these studies do not provide an understanding of how the system's interactions and processes can entail the time-lag needed for companies and the government to adapt and change to other transport modes as part of the decarbonization policy.

Ghisolfi et al. (2022) also shows how many of the SD papers focused on the decarbonization of freight transportation lack when it comes to presenting their model. Out of the 50 studies reviewed, only 19 presented both qualitative (causal loop diagram) and quantitative (Stock and Flow diagram) models, while 14 papers did not present any model. This creates a scientific gap as it makes it harder for new research to be built from what was done before. The paper brings to attention the lack of transparency when it comes to the source of some of the information used on these models and it touches on the lack of stakeholder involvement during the study, except for papers such as Seitz (2014).

Despite this gap, the brief overview presented above also shows how versatile this method can be. Through different research it was possible to tackle the same problem while considering different points, from modes contemplated to policy measures, using different assumptions, simulation timeframes, and countries as their case study, showing how wide the range of applicability such a tool has. What is especially unique in this study compared to other freight transport SD studies is that we expand the use of SD to tackle transportation problems by not only looking into new lag-time aspects of freight but also by evaluating different combinations of policy measures, intensity, and implementation time.

One of the advantages to use SD is also the lack of existing numerical data in the Brazilian context. Based on assumptions, interview results, and rough data, by using SD we can gain policy insights into what is an incomplete situation, data-wise. Other modelling approaches can use hypothetical data and rough assumptions, however, SD is considered adequate in structuring messy and wicked problems through ‘group model building’ approach (see Saryazdi, Ghatarim, Mashayekhi, & Hassanzadeh, 2020 for a large review on group model building). Saryazdi et al. (2020) shows that group model building is widely used to extract ‘data’ and insights from experts to build causal loop diagrams and quantitative stock and flow diagrams, also in the field of transportation (i.e., Elias, Cavana, & Jackson, 2004).

Jonkeren, Francke, and Visser (2019) give an overview of methods for analyzing the modal shift in freight transport and its CO_2 gains. Discrete choice models, Life-Cycle approaches, simulation models (macro and micro), and even qualitative approaches are applied in this field. Based on their analysis, a possible alternative modeling route for us could have been discrete choice modeling in combination with some kind of network simulation modeling, for example. First, to understand the choices of Brazilian shippers (e.g. their mode choice) and the choices of Brazilian carriers (e.g. their route or vehicle choice), discrete choice modeling, in the context of new climate policies, could have been applied. Subsequently, the outcomes of these choice models could have flown in network simulation models, agent-based models, or even in the more classic four-stage transport models, among others, for analyzing potential feedback loops. For example, if the choice model shows that in the context of some modal shift policy more Brazilian shippers choose inland shipping but the waterway capacity lags behind, the simulation models would show longer transport times due to waterway congestion which in turn would influence the shippers' choices. Although combining these numerical modeling approaches would potentially be more accurate compared to our more assumption-based SD approach, the combination is also very time-consuming and data-intensive (and whether all the data required can be estimated with a sufficient amount of reliability is highly uncertain).

So, for this study, SD seems fit for purpose, but it should be noted that assumptions and rough insights play an important role in our SD outcomes, which means that the final results should be interpreted with some caution.

3. Interviews with experts

The literature review helped to build an initial understanding of the complexity of decarbonization policies applied to freight transport. However, there was still a need to understand some peculiarities not presented in scientific papers, such as the considerations made by infrastructure users regarding mode choice, how the different perspectives of the stakeholders involved in the policy-making process could impact the promotion of this modal shift, and how this could be presented time-wise.

We interviewed experts to better understand the dynamics between the actors involved in the freight transport policy-making process (specifically the carriers) and the governmental decisions about which projects to prioritize and invest in. We used an unstructured format (Figgou & Pavlopoulos, 2015), allowing experts to provide their opinion on the topic without the author's interference and thereby collecting data based on the expert's perspective and experiences (Nepveu, 2020). For this research, we selected six different Brazilians experts to talk to, from policy makers to port directors and exports/concessions experts, to have an overview of the topic. The experts interviewed can be seen in Table 1.

The experts provided insights on important variables included in the model and the “gaps” between decision-making and its effective implementation. Providing the necessary infrastructure on its own does not guarantee that a modal shift will take place; there is a need to dig deeper into the infrastructure user's perspective, comprehend what they consider necessary when choosing which infrastructure to use, know how they will include a modal shift into their strategic planning, and know how willing they are to shift from one mode to another.

In Table 2, a summary of all the time aspects/lag-time/delays questions we selected for our research is presented. We divided the table into two groups (1) Infrastructure Implementation and (2) Infrastructure Usage. Besides the identified time aspects/lag-time/delays, the table also presents which actors are involved in each one of them.

After the interviews, we organized the main findings into external and internal aspects of freight dynamics used as variables or as parameter values in the model. We highlight here the aspects related to the

Table 1
Interviewees overview.

Expert number	Role	Field of expertise
1	Director of Operations in a Brazilian port	Port operation
2	Project Manager working for the Brazilian government	Government strategic planning
3	Manager of Market Intelligence in a Brazilian railway company	Concession planning; new infrastructure projects; demand analysis
4	Executive Program Manager in a Brazilian railway company	New infrastructure planning; demand analysis
5	Senior Policy Specialist at a not-for-profit organization	Implementation of regulations; formulating the public policy for infrastructure projects
6	Logistics and Operations Manager in a commodity exports company	Export of agricultural commodities

Table 2
Summary of the time aspects/lag-time/delays.

Groups	Identified time aspects/lag-time/delays	Actors Involved
Infrastructure Implementation	How long does it take to elaborate the concession plan for a specific infrastructure project?	Government
	How long after the pre-project phase does it take to choose an infrastructure project to implement?	Government Carriers Shippers
	What are the bureaucratic aspects involved in such projects and how can they delay their implementation?	Government Carriers Shippers
	Once the company has been chosen, how long does it normally take for the project to be implemented?	Government Carriers
	How is delay considered when planning the execution of an infrastructure project?	Government
	How long does it take to elaborate a project fund provided by the public sector?	Government
Infrastructure Usage	How long does it take to reach an equilibrium between carriers and shippers (supply and demand) on a new network?	Carriers Shippers
	Once the new infrastructure is available, how long does it take for shippers to shift from one mode to the other?	Carriers Shippers
	What are the aspects that might delay the migration from one mode to the other?	Carriers Shippers

implementation time and ramp-up time, shown in Table 3, and the parameter values shown in Table 4.

Finally, using the insights provided by the interviews, we were also able to estimate how the differences between stakeholders' interests could entail delays in the implementation process of the new infrastructure project and the modal shift. Fig. 1 shows three different perspectives (optimistic, realistic, pessimistic) for the planning and implementation of a new infrastructure project, using the data gained from the interviews, to show how the accumulation of different delays could entail a large difference in the time the modal shift can take place.

4. Model development

The model was built using the information retrieved from the literature review and interviews with experts. When describing the model in this chapter, we will refer to the literature sources and the interviewee results used to underpin the specific model choices.

Table 3
Implementation time and ramp-up time.

Expert 1	The slow maturation process of railways: licensing, concession, and construction takes around 10 years; The slow process allows companies to adapt to change their operation in the meantime; There are examples of infrastructure projects where the study was completed at least five years ago and the project has not yet started.
Expert 2	The structuring time for an infrastructure concession project in Brazil takes around 730 days; Projects carried out by the government tend to be more time-consuming due to the time required to contract studies and works; There is no distinction between private and public investments when it comes to implantation reliability.
Expert 3	When an idea for a project comes from outside the projects already included in the government plan, usually, it is first presented (sold) to the government and this step takes years; The regulatory/environmental aspect of the project is the most bureaucratic part. It takes one year or more to get environmental licences and expropriation; Delays might occur during the implementation of the project. Usually, the delay in the start of the implementation of a project is greater than the delay in the implementation itself.
Expert 4	In strategic planning, the delay is considered. Depending on the project, it can take three years of engineering planning only; Regarding the ramp-up time, each market is different. For commodities, it goes fast as there are fewer decision-makers; This evolution can be fractioned too, starting with 30% of the load, then it goes to 80% then 100%.
Expert 5	One of the advantages of public-private projects is that companies start to charge the user from the moment they deliver the infrastructure, an extra incentive to deliver the project on time; For the pre-project phase, public works have a lean stage, leading to greater chances of delays during the implementation due to project inconsistencies; The ramp-up time depends on the project. This is something specific to each project, not a systematic issue.
Expert 6	Almost 100% of the grains transported by roads in Brazil have an "on-spot" set-up with truckers; For waterways and railways, some traders do not have a contract for their transport because the logistic operating companies are subsidiaries of the trading companies themselves; Because there are more alternatives for shipping cargo, traders do not feel comfortable with a long-term contract. A seasonal contract is more attractive.

4.1. Causal loop diagram

A complete visual representation of all cause-and-effect relations between the variables and feedback loops can be found in the Causal Loop Diagram (CLD), given in Fig. 2.

Decisions on new infrastructure investments rely on the available funds allocated for such projects (top right, Fig. 2). The amount of funding allocated is affected by both private and public sector investments. According to Diaz, Behr, and Ng (2016), investments in infrastructure are essential to the economy of a country, explaining the connection between investments and the country's GDP. The GDP is then linked to the volume of investments made, which is linked again to public sector investment, leading to a reinforcement loop and the government's concession agenda, which is then connected to the private sector investment reinforcement loop. Profitability expectation is an external variable that influences the private sector's decision to invest in infrastructure projects. The new infrastructure projects rely on the funds available for infrastructure-related investments in an inversely proportional relationship, as the more investment made, the less money is available in the fund, and vice versa. New infrastructure investments are also affected by geographical restrictions (such as river trafficability and environmentally protected areas) and the innovation penetration rate.

Innovation can impact possible new infrastructure investments, and therefore it should be considered when simulating the evolution of freight transportation over the up-coming decades (van Binsbergen, Konings, Tavasszy, & van Duin, 2014). In this diagram, innovations

Table 4
Parameter values retrieved from expert interviews.

Parameter	Value	Units	Source
Railway infrastructure project	10	Years	Expert 1
Ramp-up time	Instant	–	Expert 1
The possible delay between the end of the pre-project phase and the start of the implementation	5	Years	Expert 1
Structuring time for concession projects	730	Days	Expert 2
Strategic planning	15	Years	Expert 2
Environmental license and expropriation	1	Year	Expert 3
Possible delay in obtaining environmental license and expropriation	1	Year	Expert 3
Possible delay in the project implementation	5 to 8	Months	Expert 3
Trader x Operator maximum contract length	1	Year	Expert 3
Possible delay in government authorization	3 to 4	Years	Expert 4
Structure time of engineering project	2 to 3	Years	Expert 4
Increase in volume transported per year after the new infrastructure is available	30% then 80% then 100%	Tons/Year	Expert 4
Ramp-up time	3 to 5	Years	Expert 5
Material loss per transshipment	0.25%	Tons	Expert 6
Trader x Operator contract length Railway/Waterways	6	Months	Expert 6
Trader x Operator contract length Road	1	Per shipment	Expert 6
Time to reach maximum capacity	3	Years	Expert 6
Possible delay in reaching maximum capacity	2	Years	Expert 6

were aggregated into possible benefits and drawbacks that might impact the model and are represented by the green-colored variables. The innovation penetration rate is affected by both the stakeholder commitment (+) needed when researching innovation and the high implementation cost (–) required.

Infrastructure projects are split in the CLD into three main factors: infrastructure maintenance projects, increase in the network's density, and modal integration (access-point density and transshipment-related projects), all three of which influence network capacity. There are delays between new infrastructure investments and capacity because of the project's implementation time. The capacity of a certain mode further impacts the mode attractiveness, creating reinforcement loops between new infrastructure investments and mode attractiveness (Brito Junior et al., 2011; Han & Hayashi, 2008; Piattelli et al., 2002). Mode attractiveness is also influenced by generalized transport costs, which include freight tariffs, distances, travel time, and reliability. There is a balancing loop between generalized costs and freight volume, as the costs have an inversely proportional relationship with the freight volume transported.

Our CLD includes regulations to reduce CO_2 emissions that impact generalized costs, such as economic instruments, knowledge-based instruments, and new vehicle technology policies (Stelling, 2014). The implementation process of these measures is time demanding and could be affected by possible conflicts among stakeholders. After the policy measure has been chosen, it is slowly inserted into the system. These connections were made, based on the work of Gössling, Cohen, and Hares (2016).

Another key relationship in the model is between modal share, fuel consumption, CO_2 emissions, and the need for regulations (bottom of Fig. 2). Modal share is mainly affected by mode attractiveness; the modal share is connected to the number of freights transported by each mode, which directly relates to fuel consumption. Fossil fuel consumption is proportionally linked to the amount of CO_2 emissions, which subsequently directly relates to the need to regulate these emissions. These regulations impact the generalized costs and further affect mode attractiveness in a balance feedback loop. These relationships were mainly based on Han and Hayashi's findings Han and Hayashi (2008).

4.2. SD model

Based on the CLD, we developed the stock and flow diagram, providing more detail. The main goal of the model is to analyze the modal shift over time, driven by investments made in different modes and the implementation of policy measures to reduce CO_{2e} emissions. We divided the SD model into eight modules:

- Economic-related variables;
- Freight volume generation;
- Multimodal network;
- Road saturation;
- Fiscal and regulatory policy measures;
- Vehicle-related technological innovation;
- Modal split;
- CO_{2e} emissions.

Fig. 3 presents a visual representation of all the modules that constitute the model and how they are interconnected. It also presents the main actors involved in some of them.

4.2.1. Economic-related variables

The first part of the model is the economic-related variables. In this module, we show the relationship between GDP and the volume of investment, as described in the work done by Diaz et al. (2016). The link between GDP's increase and the amount of freight transported in the network is also presented and shown in Fig. 4.

There are essential time steps between allocating funds for transport-related investments and starting to implement the projects. These steps are part of the government's strategic planning and involve multiple aspects and stakeholders, as seen in the interviews. For this model, we aggregated the steps into three parts: (i) the pre-concession/pre-project phase, (ii) the time needed to choose which projects to implement, and (iii) the time required to obtain the environmental license and to perform land expropriation.

From Fig. 4 it can be observed that the change in GDP leads to a change in the volume of investment that both private and public sector companies can make in the network infrastructure. Therefore, the change in GDP plays a role when allocating infrastructure funds. Once the funds are allocated, it impacts each mode's capacity, as presented in the Multimodal network module.

4.2.2. Freight volume generation

The second module refers to the generation of the volume transported per mode per year. In the model, shown in figure 5, the network's freight volume is multiplied by the percentage of the modal split. By doing this, we can estimate the expected volume of freight to be transported per mode. The stocks - “Value of road volume”, “Value of rail volume”, and “Value of waterway volume” - accumulate the freight volume values over time. The inflow variables represent changes in the volume for each mode, which depend on the previous year's total freight volume and the current year's freight volume growth rate. The change in the value of roads, rails, and waterways' volume represents the increase/decrease compared to the previous year's volume.

4.2.3. Multimodal network

The multimodal network module was initially based on Brito Junior

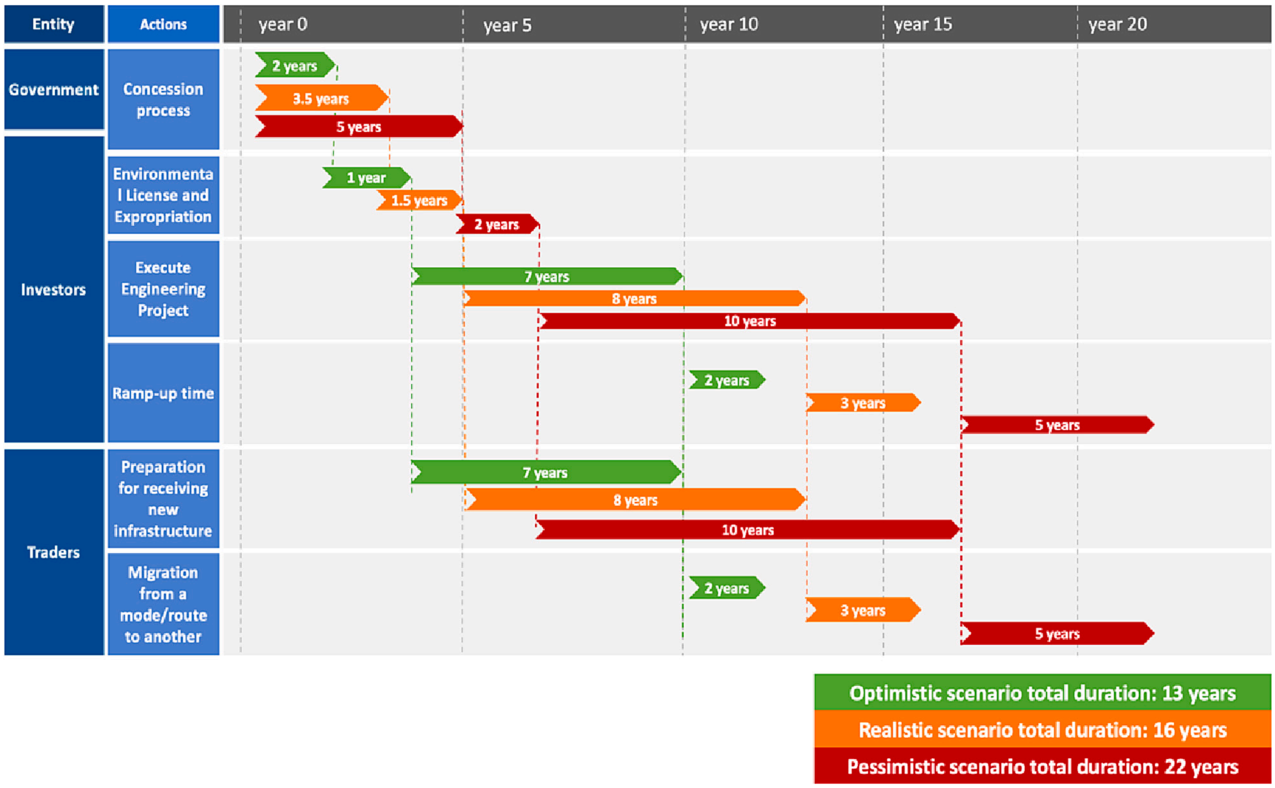

Fig. 1. New infrastructure project: implementation and mode shift timeline.

et al. (2011) and further adapted to the purpose of this research and the specifications of each of the available modes. For the road network (Fig. 6), the sum of funds allocated from the private and public sectors might lead to a change in road infrastructure capacity in two different ways: either by extending roads in the current network (e.g. from two lanes to four lanes) or by constructing an entirely new highway. Here, we introduce another time-related aspect to the model, as implementing a highway project takes time. Moreover, the inauguration can be done in parts, increasing the kilometers available as the construction occurs. In this model, we represent this aspect by the stocks "Amount of Km implemented" and "Amount of Km extended", which are followed by the outflows "Partially inaugurating new highway" and "Partially inaugurating extended highway", respectively. We then use these variables as inflows for "Single-lane highway network length" and "Double-lane highway network length". The passage of time and use of the infrastructure entails capacity erosion of the network, as indicated by Brito Junior et al. (2011).

With the information gathered, we can calculate the total amount of the highway network length. This critical information is used to calculate the vehicle/capacity ratio (saturation) of the road network as shown in the Road Saturation module.

For the rail network, we measure the infrastructure capacity in tons and it is influenced by the funds allocated and the infrastructure projects considered for this mode. Similar to highways, this network also loses its capacity as it is used. However, unlike the road network, rail freight in Brazil does not share its infrastructure with passenger rail. Therefore, we calculate rail transport saturation differently. On the one hand, the number of tons the network supports are converted to the maximum number of trains on the network, based on the rolling stock capacity. On the other hand, we use the rail transport demand, which is an output of the freight volume and modal split, to calculate the network's train flow. Under rail saturation, the network's installed capacity is also considered. A visual representation of the rail network and all the connections mentioned is presented in Fig. 7. The structure of the waterways network resembles the railway one. Hence, the diagram for the network is not depicted in this paper.

Converting the annual freight demand into the number of trains per day allows the establishment of a future comparison with the railway's installed capacity, which indicates the degree of saturation of the network. Once we have found the number of tons per train, it is possible to calculate the number of annual trips made by train. Because we are working on a national level, we assumed that all the trains in the network had the same characteristics. To find the number of pairs, Eq. (1) is used.

$$Daily\ number\ of\ trains = (Tons/(Train\ capacity))/(365/(Seasonality\ index)) \quad (1)$$

To simulate the most critical scenario, in which product distribution throughout the year is not homogeneous, a seasonality index of 1.21 was used to represent the impact in the distribution due to the change of seasons, defined as the relation between 365 days within a year and the operational days of the freight (ANTT - Associação Nacional de Transportes Terrestres, 2020b). The installed capacity is defined by Eq. (2).

$$Installed\ capacity\ in\ number\ of\ trains = (1,440\ x\ k)/(t_{cg} + \theta) \quad (2)$$

where:

- The railway efficiency index linked to the maintenance of the permanent rail expressed by $k = k1\ x\ k2$;
- 1440 = number of minutes in a day (24 h × 60 min);
- $k1$ = (1,440 − *maintenance time*)/1,440;
- $k2$ is the efficiency index linked to the management of operational resources;
- t_{cg} is the round-trip train time (minutes);
- θ is the licensing time (minutes).

We needed to make generalized assumptions to be able to apply this at a national level. Typically, we do this calculation for each railway yard, terminal, or both. However, we decided to use an average distance

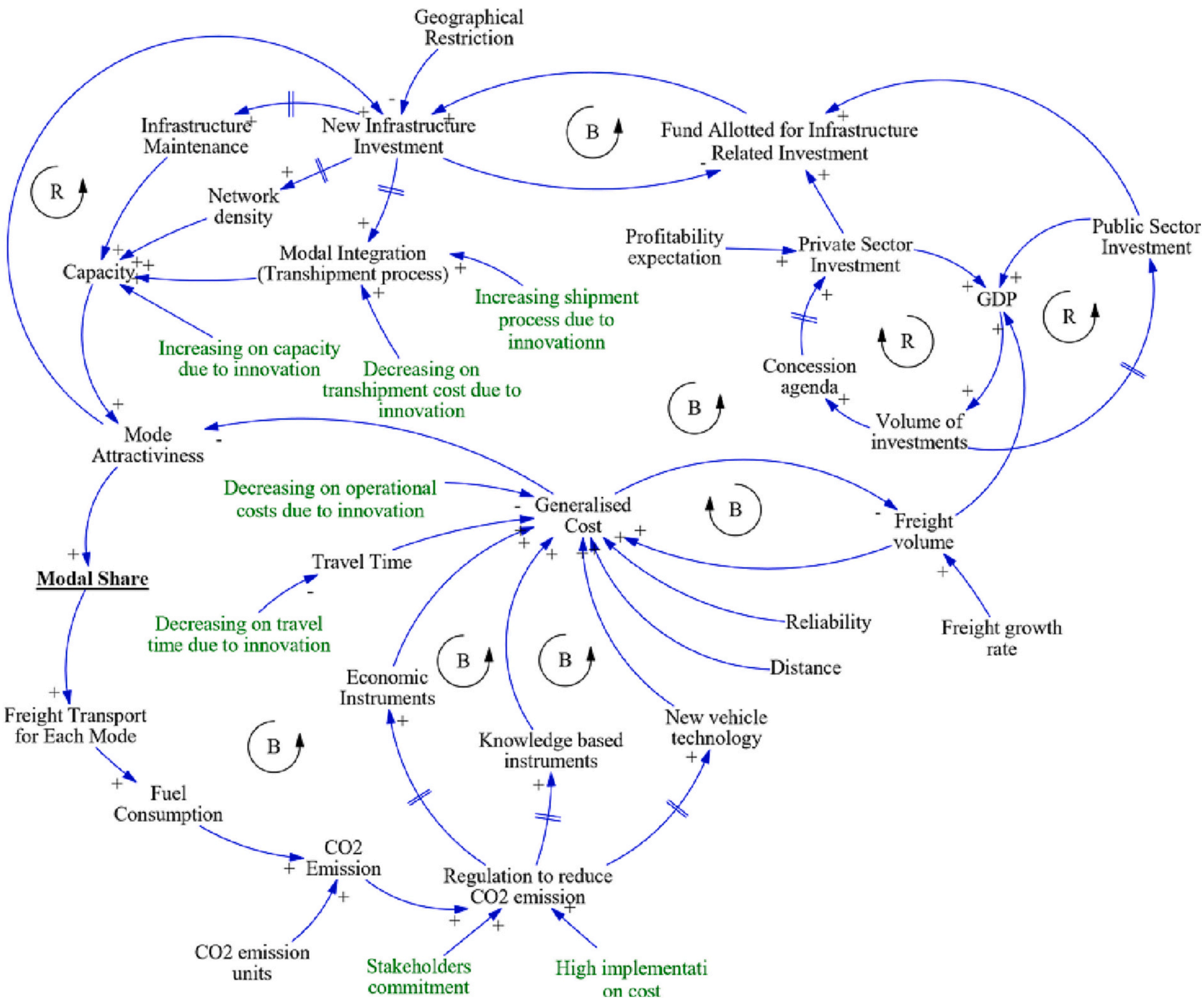

Fig. 2. Causal loop diagram.

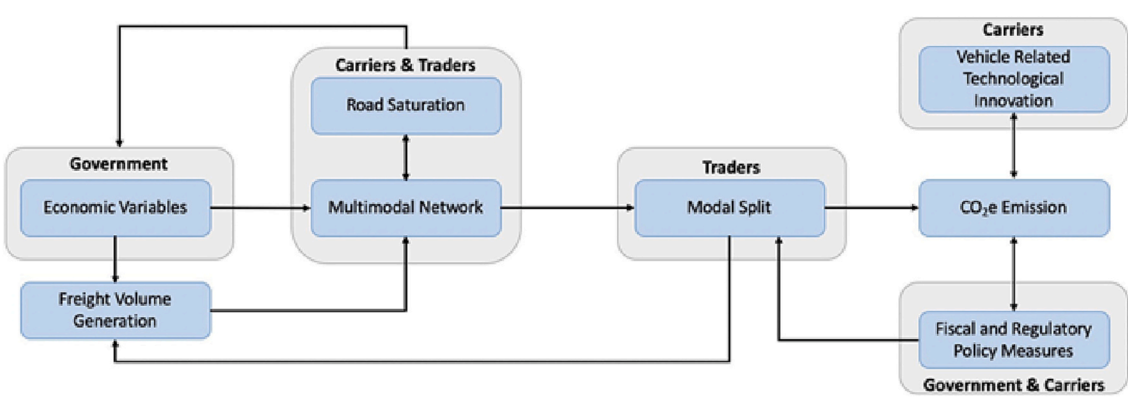

Fig. 3. Modules included in the SD model and main actors involved.

between these points instead. We considered that the parameter values would be the same as the ones used by the government in ANTT - Associação Nacional de Transportes Terrestres (2020b), being:

- $k1 = 0.9208$;
- $k2 = 0.8$;
- $\theta = 5$ min;

The only parameter that needed to be estimated was the round-trip time (min). For this, we used the distance value of 15.85 km between each rail yard/terminal and a travel speed of 36.73 km/h (ANTT - Associação Nacional de Transportes Terrestres, 2020b).

Once we obtained the values of both the daily number of trains and installed capacity in the number of trains, the total saturation in percentage can be found using Eq. (3).

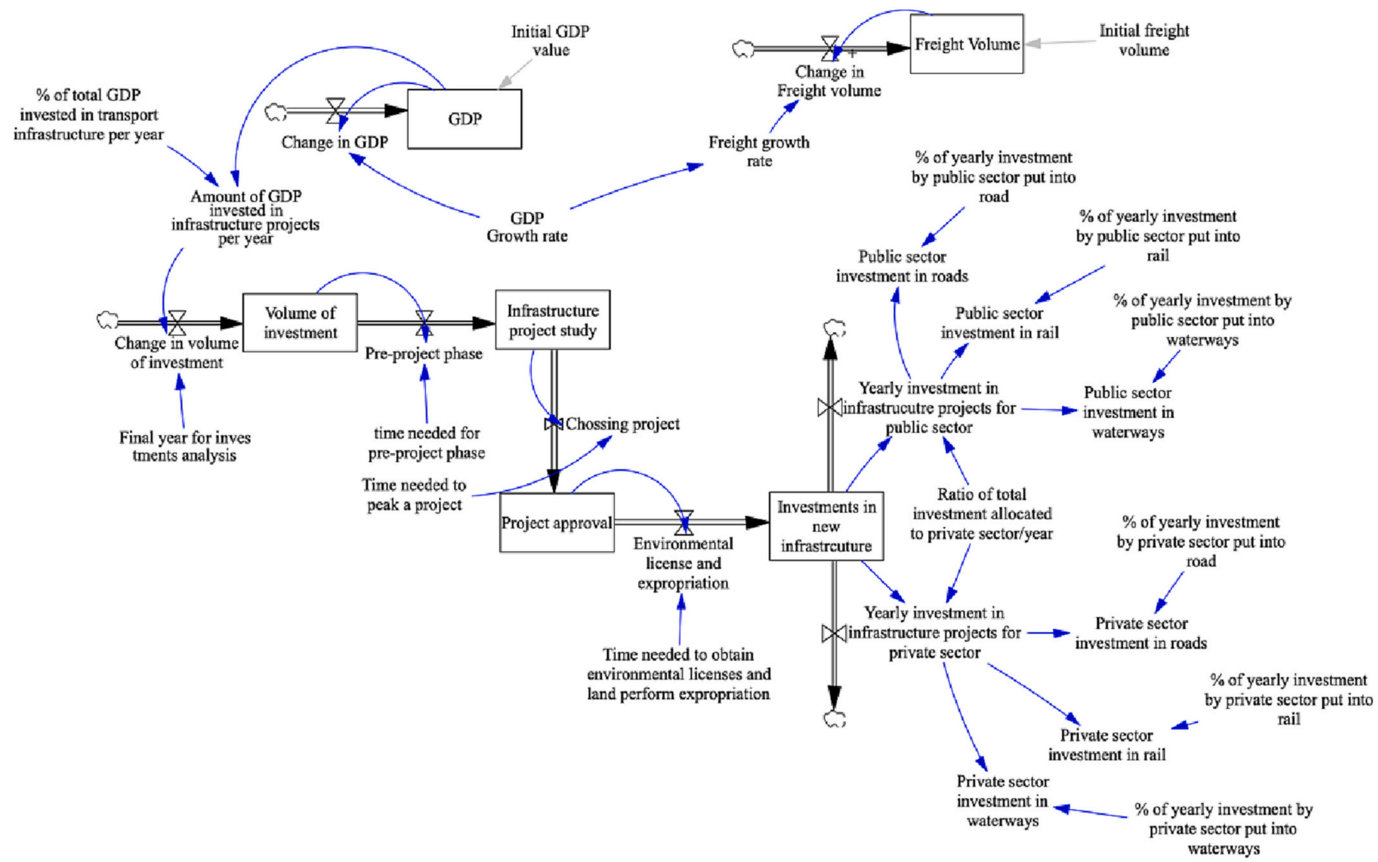

Fig. 4. Economic related variables.

$$Saturation\ (\%) = (daily\ number\ of\ trains)/(installed\ capacity\ in\ number\ of\ trains) \quad (3)$$

For waterways, a similar calculation was made to obtain the necessary number of trips made by vessels to transport the demand for inland shipping. We assumed that ships could carry up to 18,000 tons each. We obtain the daily number of Vessels using Eq. (4).

$$Daily\ number\ of\ vessels = (Tons/(Vessel\ capacity))/365 \quad (4)$$

Because there is no installed capacity in the waterway network, its saturation is measured by the ratio between the daily number of vessels and the total amount of vessels available.

4.2.4. Road saturation

As previously mentioned, road freight shares the network with passenger vehicles. We need to consider this when modeling the network's capacity, as it influences road travel time and vehicle/capacity ratio. We developed this module so that the model included this specificity, as based on Ghisolfi et al. (2019).

The first step is to add the number of road freight vehicles circulating in the network to the other vehicle categories that also use the infrastructure. The top-left part of the diagram in Fig. 8 presents steps to calculate the number of heavy vehicles. We use the freight volume and modal split to calculate the demand and divide it per vehicle capacity to find the number of heavy vehicles required to ship all the necessary goods. The bottom-left part of the diagram shows light vehicle traffic.

The steps and equations used to calculate the number of heavy and light vehicles in the network are quite similar. The main difference is that, while we calculate the heavy vehicle traffic volume using the demand and modal split percentage, we find the light vehicle traffic volume using a light-duty vehicle (LDV) growth rate that multiplies the stock variable throughout the simulation times. We assumed a constant growth of 3% per year (DNIT - Departamento Nacional de Infraestrutura de Transportes (National Department of Transportation Infrastructure), 2006).

Given the total highway traffic, it is necessary to convert it into a unit of passenger car equivalent (PCE), as defined by the Highway Capacity Manual – HCM (TRB - Transportation Research Board, 2010). To calculate road capacity, the HCM also provides the adjustment factors, due to the presence of heavy vehicles, which reduces the traffic speed of the highway. After finding out the load of the whole network, an analysis is carried out aiming to determine the relationship between equivalent traffic volume and the average capacity of the link (V/C). With the V/C ratio value, it is possible to calculate the highway travel time, using Eq. (5), provided by the Bureau of Public Roads (BPR - Bureau of Public Roads, 1964).

$$t = t_0\left(1 + \alpha\left(\frac{V}{C}\right)^{\beta}\right) \quad (5)$$

where:

- t = average travel time;

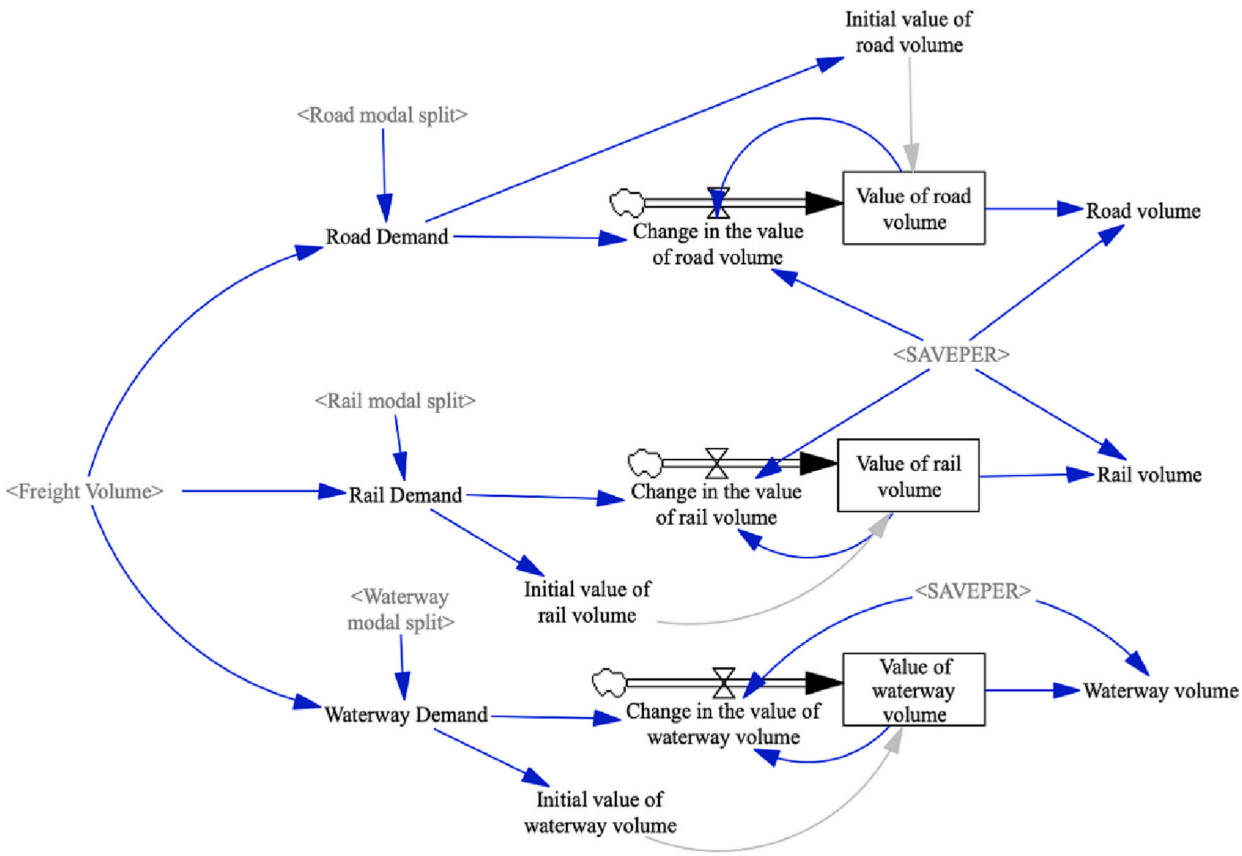

Fig. 5. Freight volume generation.

- t_0 = free flow travel time (obtained by dividing distance by free-flow speed);
- α = calibration parameter, normally 0.15;
- β = calibration parameter, normally 4.

Because we developed this model for a national level, we needed to estimate an average stretch distance to analyze the capacity. Furthermore, it was necessary to assess the annual average daily traffic (AADT). We also used the double-lane highway ratio in the whole highway network to assign the amount of traffic using double-lane and single-lane highways. Once we did all of these steps, we used a weighted average to find the national V/C ratio.

4.2.5. Fiscal and regulatory policy measures

Besides deciding where to allocate funds for investments, we also included other policies to promote modal shifts, such as fiscal and regulatory measures (Stelling, 2014). The measures considered include (i) fossil fuel taxation, (ii) infrastructure fee, (iii) marginal tax on CO_2, and (iv) emission trading systems (ETS). These measures can have different implementation time frames, costs, and adaptation times. We must understand the differences in the policy-making decision process and include possible delays due to stakeholders' conflicts. In the end, all these policy instruments will be converted into cost per ton and added to the generalized cost to measure the impact in the modal split. Because all the different modes have the same structure for the fiscal and regulatory measures, only the road diagram is depicted in Fig. 9.

4.2.6. Vehicle-related technological innovation

This module presents the technological innovation related to new types of vehicles. To simulate the increase in the number of new types of vehicles in the model, we needed to estimate these vehicles' penetration rate for each of the modes considered. For this model, we assumed that if the intensity of policy measures increases, so does the penetration rate of sustainable vehicles in the network, as shown in figure 10. A higher number of new vehicles in the network will have a direct impact on the amount of CO_2 produced.

4.2.7. Modal split

As initially mentioned, the generalized cost will be the main factor influencing mode choice. In this module, we applied the logit function (Ortúzar & Willumsen, 2001) to estimate the proportion of freight volume transported by each mode, considering their utility function and generalized cost. The generalized cost includes all the variables that impact the resistance to choose a mode. Such resistance is influenced by the shipment costs, the travel distance, the penalty assigned to the network because of its saturation, and the fiscal and regulatory policy measures. Moreover, for railways and waterways, the transshipment process, which includes the access/egress trip and the transshipment itself, also impacts the general cost. Eq. (6) shows how we calculated the generalized cost for roads, while Eq. (7) presents the cost calculation for rail, which is similar to the waterways cost calculation.

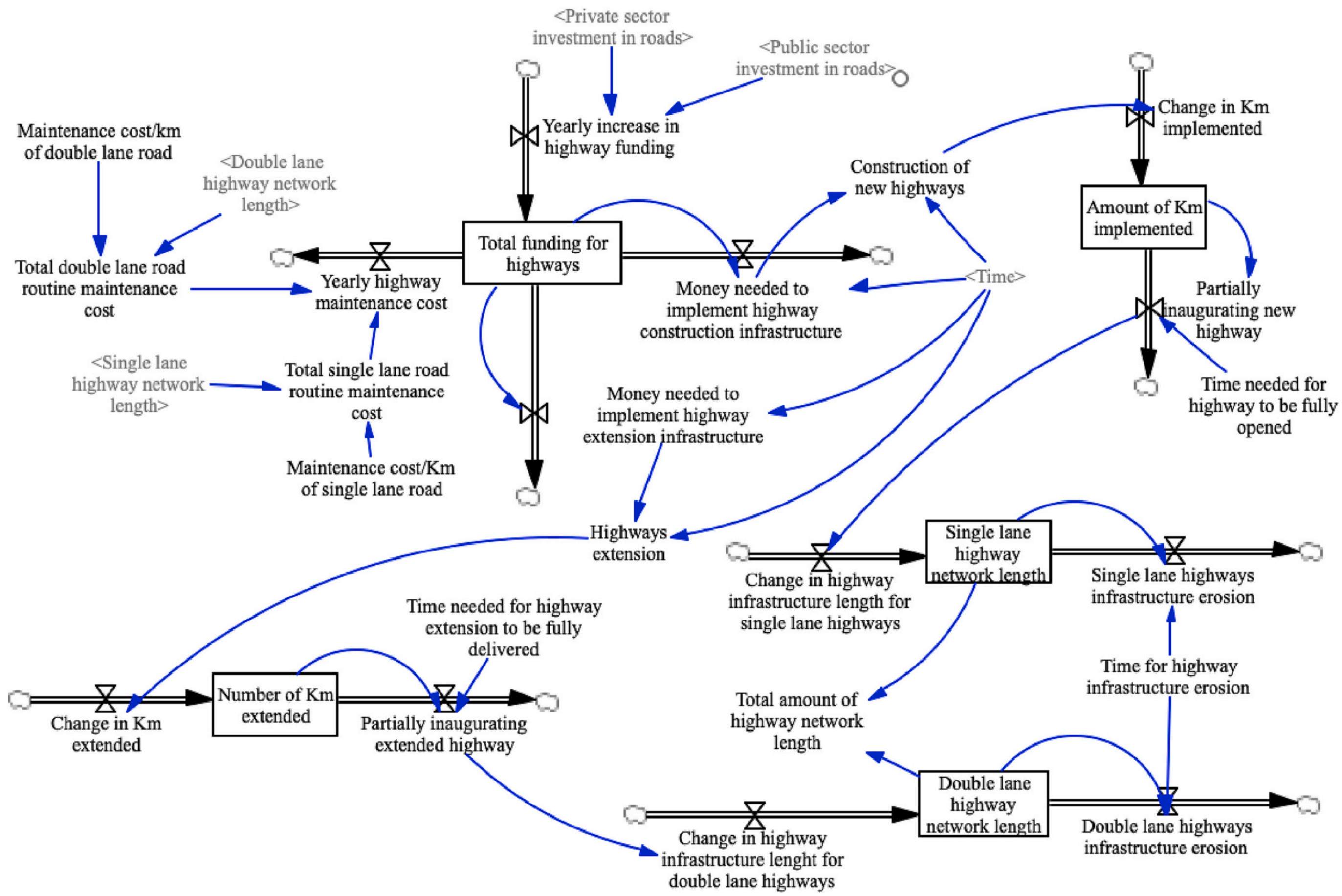

Fig. 6. Road network capacity.

$$\textit{Road freight transport cost} = (\textit{Saturation of road network cost} + \textit{Total road distance cost (shipment cost)} + \textit{Road economic instrument costs}) \tag{6}$$

$$\begin{aligned}\textit{Rail freight transport cost} = {} & (\textit{Saturation of rail network cost} + \textit{Total rail distance cost (shipment cost)} + \textit{Rail economic instrument costs} \\ & + \textit{Railway transhipment cost} + \textit{Total road transport cost to access})/\textit{egress transhipment point for railway}\end{aligned} \tag{7}$$

After calculating the modal split, the respective freight values for road, rail, and waterways feed back into the freight volume generation. We provide a visual representation of the cost calculation for roads in Fig. 11 and rail in Fig. 12. Due to its similarity to the rail cost calculation, the waterway's cost structure is not displayed.

From the shipper's perspective, it is important to look into the difference in the total costs of the modes available, based on the travel distance. Comparing the shipment costs between origin and destination allows them to choose the best alternative in terms of price. This part of the research was based on the Transport Costs Methodology, developed by the Brazilian government (EPL – Empresa de Planejamento e Logística, 2020). They estimated the transport cost for highways, railways, and waterways, considering both the fixed and variable costs. Their work also enables the estimation of each of these costs for five different commodity groups, namely: agricultural dry bulk, non-agricultural dry bulk, general freight, containerized goods, and liquid bulk. Moreover, the transshipment cost was also obtained for each of these commodity groups.

Regarding the network's saturation, we assumed that if the saturation level is below 1, the higher the saturation, the better. It allows the network to increase the trip's frequency (e.g. the number of train trips/day), decreasing the costs needed to store commodities and the waiting time to load/unload the vehicles. The saturation only starts to become a problem once it goes above one, representing that the network is no longer able to support its demand; this leads to congestion on the roads, for example. Hence, in these cases, a penalty is added.

Another relationship that is important to highlight is the network's density. For this research, we assumed that as the infrastructure network increases, so does its density, impacting the distances needed to access a transshipment terminal. For example, after implementing new roads, the distance needed to access a barge terminal to perform the transshipment process from road to waterways might decrease. Similarly, as the rail network gets denser, the distance the trucks need to access/egress a transshipment terminal also tends to decrease. This relationship slowly decreases the road distance, and therefore the costs to access/egress such a terminal, making railways and waterways more attractive. To simplify the model, we assume that all the transhipments made in the network are road-rail-road and road-waterway-road.

4.2.8. CO_{2e} emission

CO_{2e} Emission is the final module to be introduced. Here, we can estimate the yearly amount of CO_{2e} emission generated by freight

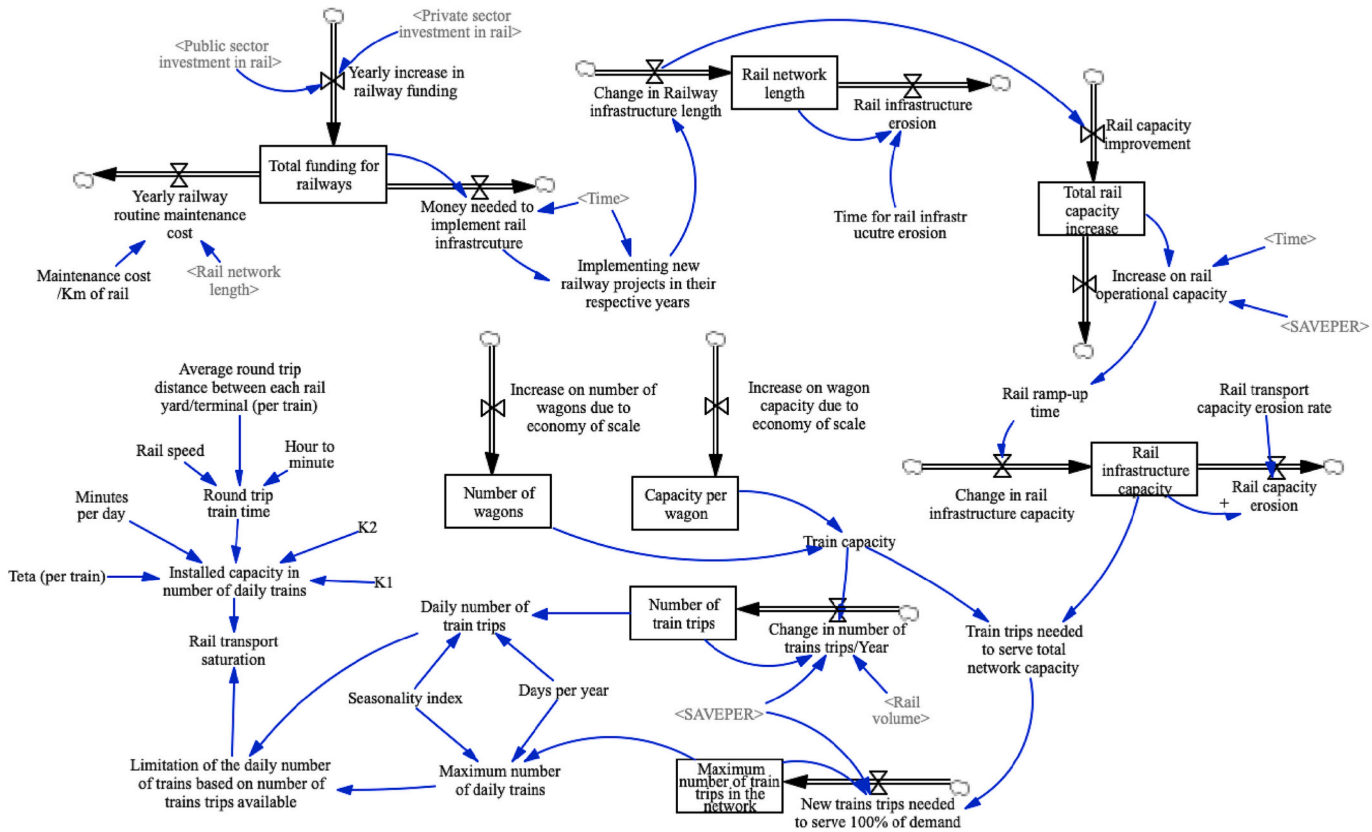

Fig. 7. Rail network capacity.

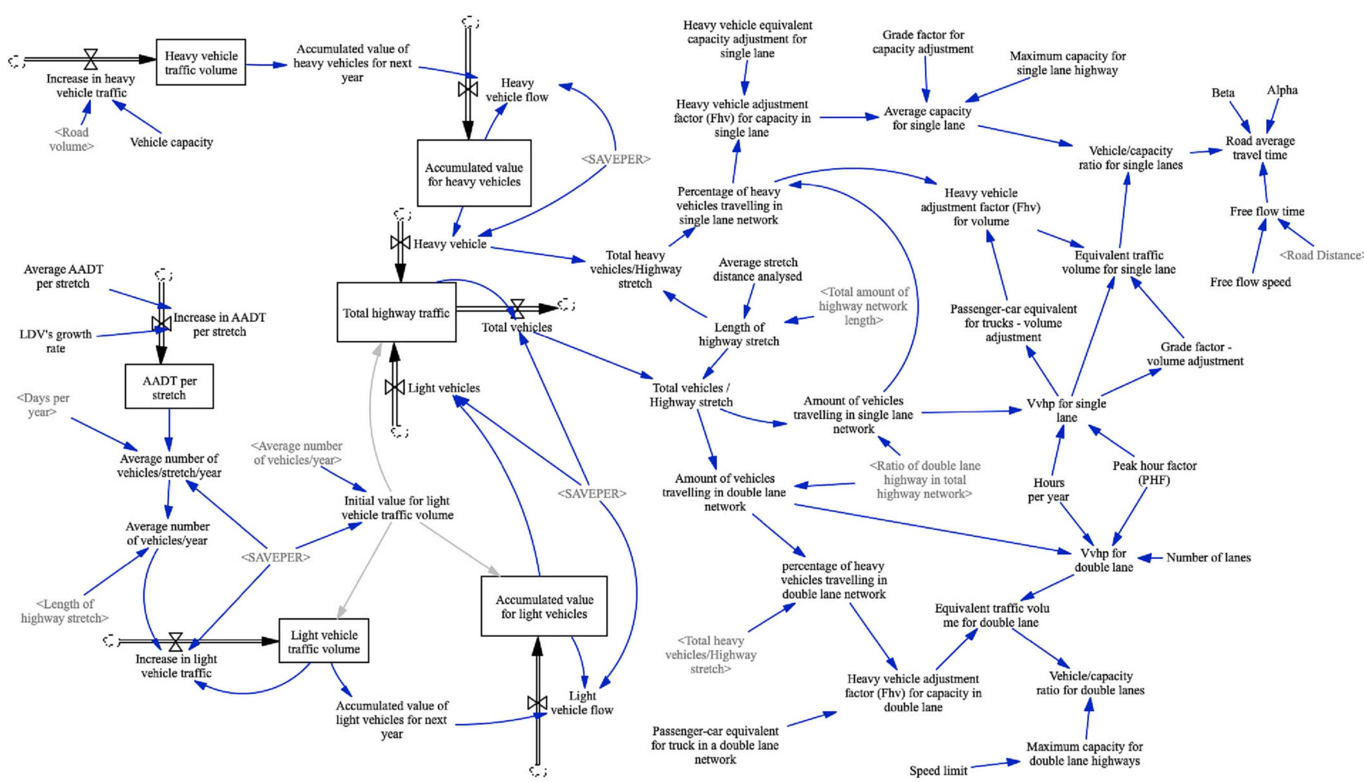

Fig. 8. Road saturation.

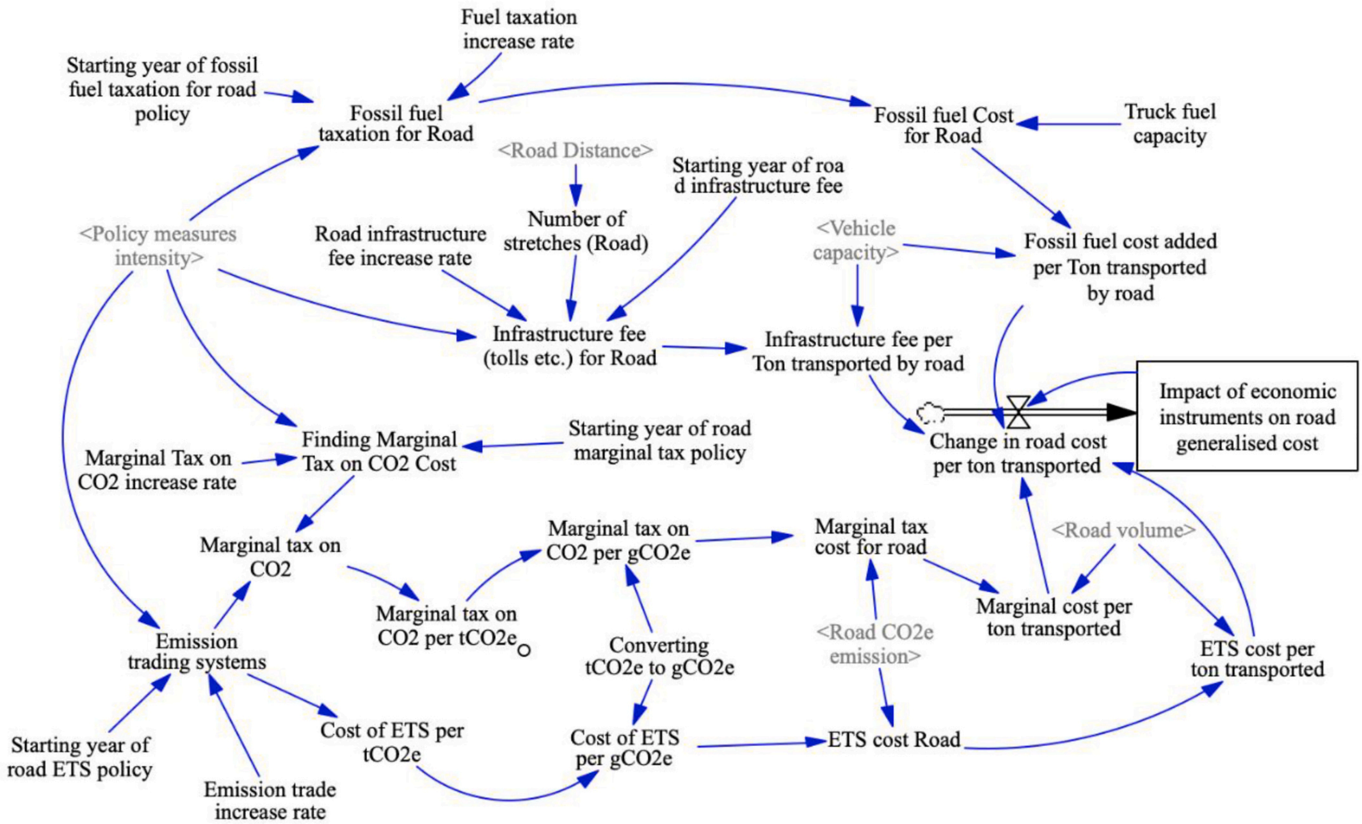

Fig. 9. Economic instruments policy.

transportation and the accumulated value over the years. To do so, we use the volume (in Tons) and the distance assigned for each mode to assess the number of Tons per mode (TKU). The calculator, provided by EPL (ONTL - Observatório Nacional de Transporte e Logística, 2021b), was used to give the value of one g CO_{2e} emitted per TKU for each mode. This module also dealt with the differentiation between emissions from sustainable vehicles and regular vehicles. It was assumed that a sustainable vehicle emits 25% less g CO_{2e}/TKU compared to standard vehicles. The ratio of each type of sustainable vehicle in the network was calculated, as shown in Fig. 13, and fed into the CO_{2e} calculation.

Fig. 14 also shows how the intensity of the policy measures is analyzed. We set up a reduction goal for CO_{2e} generated per year. If the result aligns with the goal, the policy measures do not have to be too strict. However, the higher this difference, the stricter the measures become.

Lastly, the "Accumulated CO_{2e} Emission from inter-urban freight" stock presents the accumulated volume of CO_{2e} emission during the simulation range time, as presented in Fig. 15. By having these two different stocks in the model, we can analyze how the emissions evolve yearly and how they are accumulated over time, increasing the possibility of analyzing the impact of the policy measures.

5. Verification and validation

The proposed model was verified and validated by following the SD model validation process as suggested by Forrester and Senge (1980) and Sterman (2000). The verification tests included: (i) Dimensional consistency, (ii) Time horizon, (iii) Structure verification, (iv) Extreme conditions, and (v) Integration error. The tests showed that the model was implemented accordingly to specifications. Hence, it can be compared with the structure of the system (conceptual model). The model showed consistent dimensions behaved according to the basic physical realities. The model also behaved as expected when simulated for an 80-year long time window and also responded realistically when subjected to extreme conditions. Moreover, the model was validated by the following tests: (i) Behavior prediction, (ii) Behavior anomaly, and (iii) Behavior sensitivity, which ensured that the model is a good representation of the real system. However, it should be mentioned that assumptions were made to represent the freight environment in a closed system, meaning that this model can only be used within its boundaries.

To perform the Behavior prediction tests, a combination of three different simulations was executed. The first one is the base case scenario, where no policy measures were inserted to promote modal shifts. As an outcome, little change in the modal shift was seen, and no significant change in the volume of CO_{2e} emission per year was obtained, which is in line with the expected behavior. In the second test, the infrastructure projects were implemented in the networks, showing that the network's implementation will already entail a higher modal shift from the road to the other modes, as predicted. This also led to a decrease in the amount of CO_{2e} emission per year. In the third test, an infrastructure fee was applied to the road network on top of the implementation of new infrastructure projects, promoting an even higher modal shift and accelerating the decrease of the yearly value of CO_{2e} emission.

The Behavior anomaly test was done continuously during the development of the model. Moreover, a freight expert was involved in the final steps of the model development, checking the assumptions and validating the corresponding model behavior. Throughout the process, his remarks were evaluated and implemented, if possible. Finally, in the behavior sensitivity test, all values of the parameters that are not known were individually changed to between ±10% of their initial value with a random-uniform distribution. To study the results, we defined key performance indicators (KPIs) to evaluate the overall performance of the model, which are (i) the value of CO_{2e} (yearly and accumulated), (ii) the modal split, and (iii) the amount of freight volume assigned for each of the modes. For every combination of KPIs and parameters, the outcome

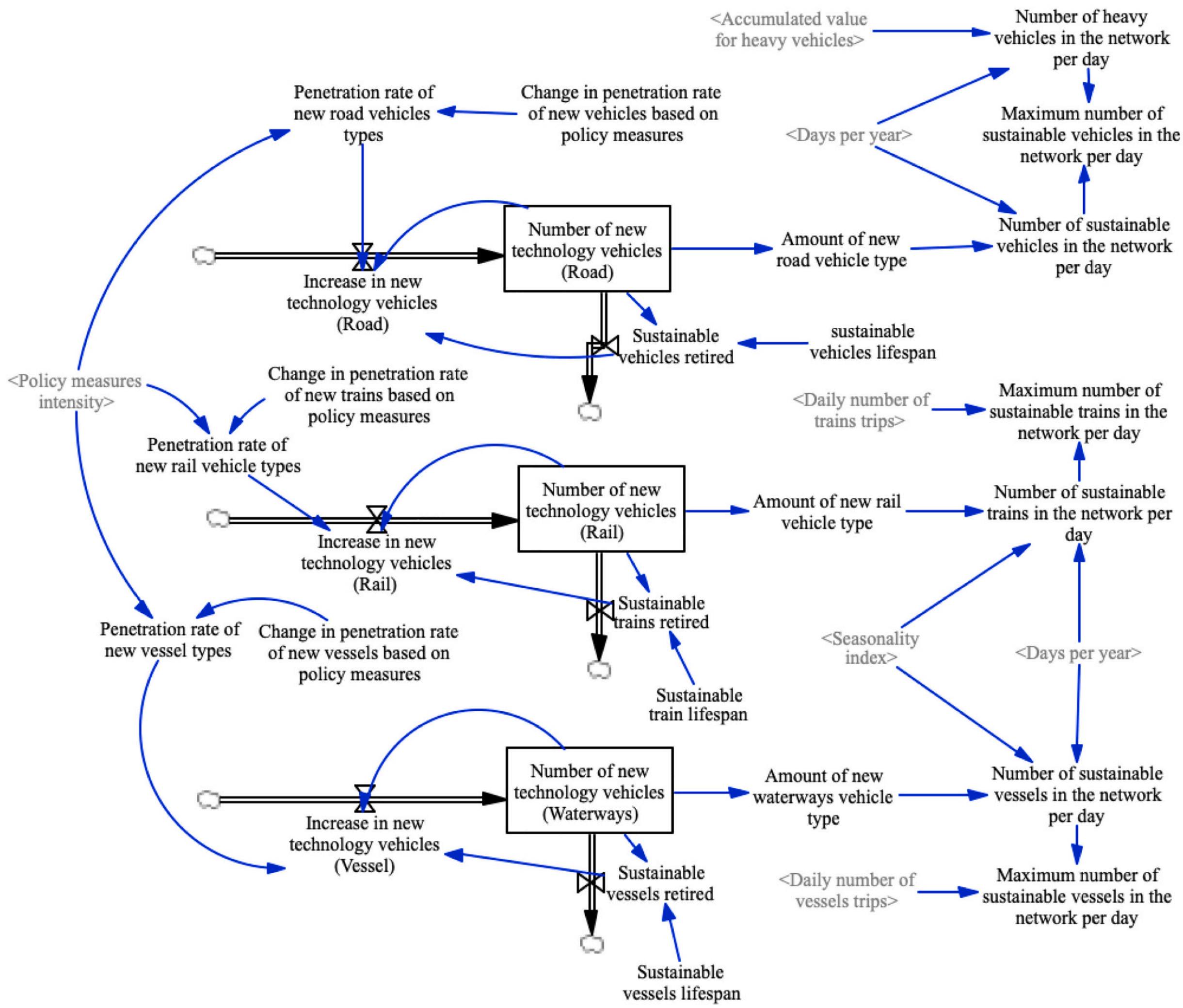

Fig. 10. New vehicle technology module.

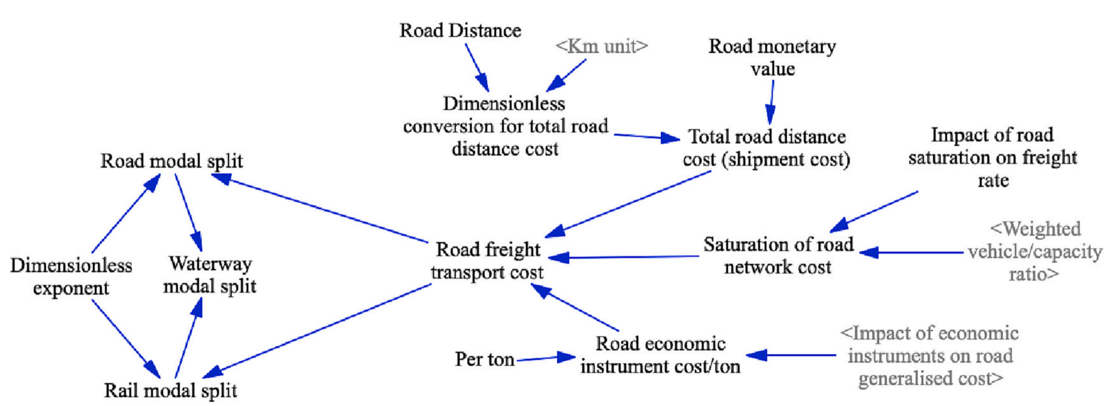

Fig. 11. Road cost.

was analyzed. The influence of the parameter on the KPI should be comparable with its effect in the real system (Heinen, 2021). As expected, the sensitivity analysis showed that the indicators of the model are very sensitive to the value of distance and the distance needed to access/egress the transshipment point for railways and waterways.

6. Applying the model - Brazilian case study

We applied the verified and validated model in the context of Brazilian freight transport. We simulated the model for 30 years, considering agricultural bulk as the commodity type because it is one of Brazil's most relevant commodities. It is also not tied to a specific mode, hence, there is competition between carriers.

In 2020, the amount of freight volume in Brazil was 1288.5 million

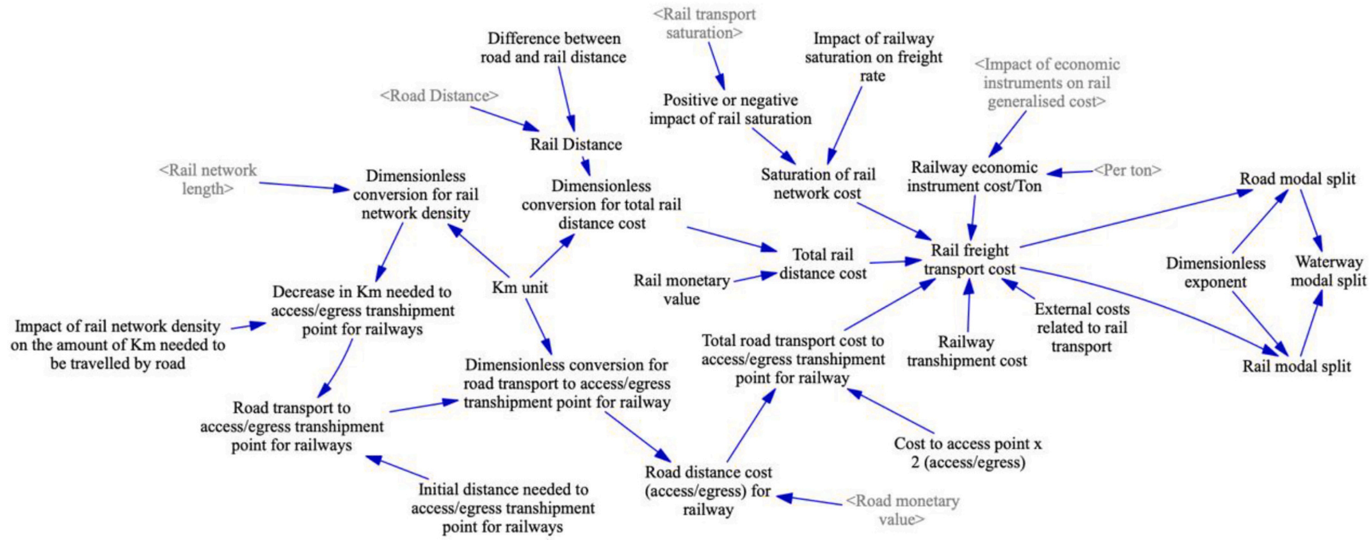

Fig. 12. Rail cost.

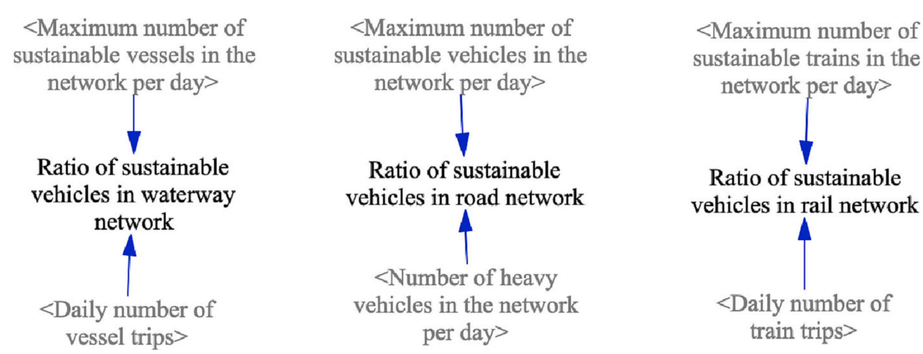

Fig. 13. Ratio of sustainable vehicles in the network.

tons (ONTL - Observatório Nacional de Transporte e Logística, 2021a). Moreover, its Gross Domestic Product (GDP) was worth 1839.76 billion US dollars in 2019, according to official data from the World Bank and projections from Trading Economics (Trading Economics, 2021); this is approximately 10,056.86 billion reais (R$). This source also provided an overview of the GDP growth rate in Brazil over the last 25 years. The historical data enabled us to analyze the country's economic stability. The lowest value achieved was −9.9% in the second quarter of 2020, and the highest was 7.7% in the following quarter. From the data, it could also be seen that the mean is approximately 0.5 and the variance is around 2. This information also enabled us to create a random distribution with the expected variation of the GDP and freight volume variation. For the base case, it was assumed that freight volume variation is directly linked to the variation of the GDP.

Other critical information is the amount of investment in infrastructure as a share of GDP. Since 2016, Brazil's investment in infrastructure has accounted for <2% of the country's GDP, having remained below 2.5% since the beginning of the decade. In 2019, almost two-thirds of the total investment was made by private companies, enabling us to do a forecast with possible variations on the share of GDP invested in infrastructure projects. Furthermore, it is essential to consider that transport infrastructure is not the only type of infrastructure project in the country. So, it is also necessary to assume a percentage of the total share of infrastructure investments allocated for transport-related projects.

For the base case, we assumed that 70% of the investment in infrastructure comes from the private sector and 30% from the public sector. Moreover, within the private sector, 70% is allocated to railway projects and 30% to highway projects. While within the public sector, 80% goes to highway projects, and 20% goes to the maintenance of the waterway infrastructure.

There are essential time steps between the allocation of funds for transport-related investments and the start of the implementation of the projects. These steps are part of the government's strategic planning and involve multiple aspects and stakeholders. This process leads to an accumulation of delays. Hence, including them in the case study is crucial to understand the modal shift process due to new investments.

Other network characteristics used in the model include the value of the capacity of the trains (175,000 Tons/Train), the capacity of the vessels (18,000 Tons/Vessel), and the capacity of the trucks (57 Tons/Vehicle). The total number of trips in the network is determined by dividing the yearly volume transported per mode by their respective capacity. Lastly, the value for the average travel distance was 630.45 km. The assumed access/egress distance from the origin to the transshipment terminal and from the transshipment terminal to the destination was 67.6 km for the railway and 113 km for the waterways.

As the research aims to analyze the promotion of modal shift as part of the decarbonization process of freight, the results assessed include the modal split and the sum of CO_{2e} emitted per mode per year. Table 5 summarizes all the scenarios analyzed in the case study.

Firstly, we propose the policy measures to be considered and apply these measures to a base case scenario to evaluate the impact they have on the system. Afterward, we introduce other four scenarios used to understand how external events might impact the system's behavior and expand the robustness of the policy measures.

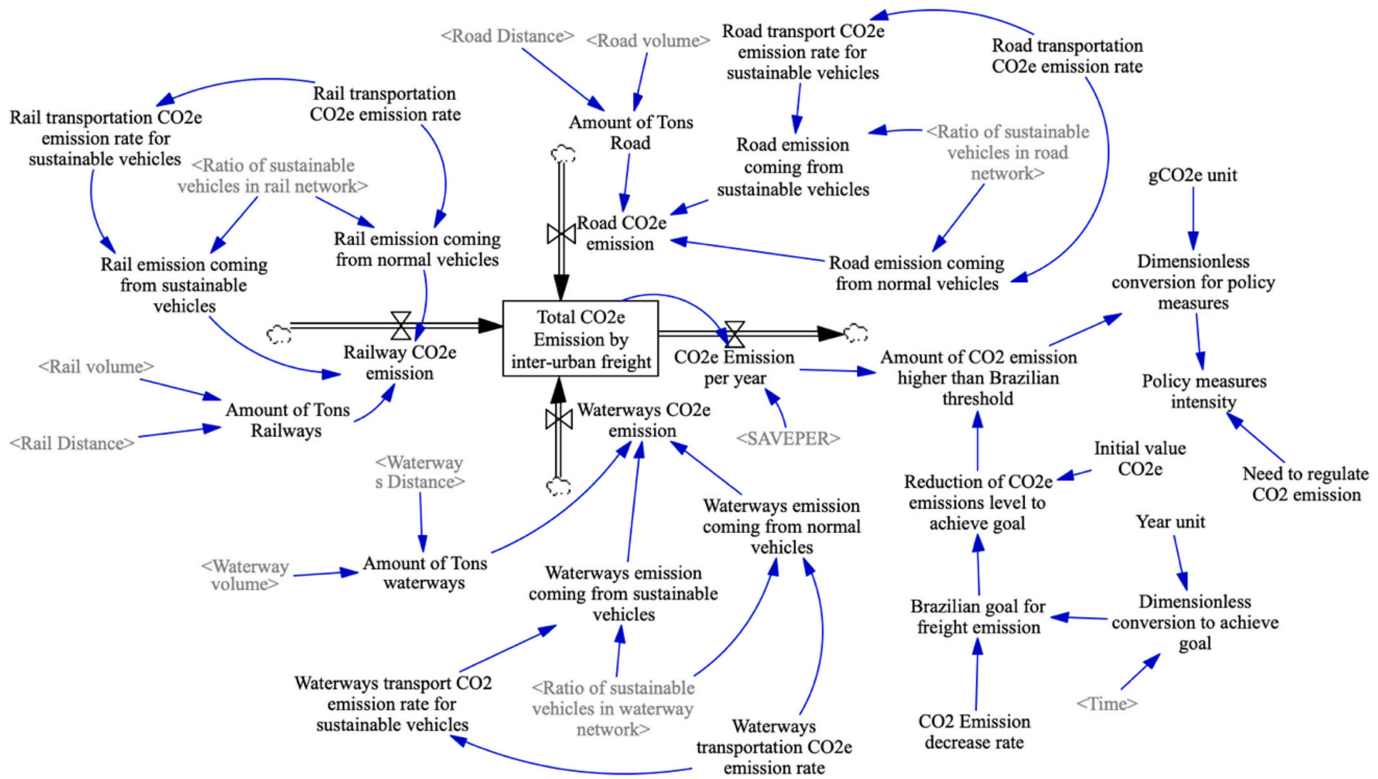

Fig. 14. CO_{2e} (GHG) emissions.

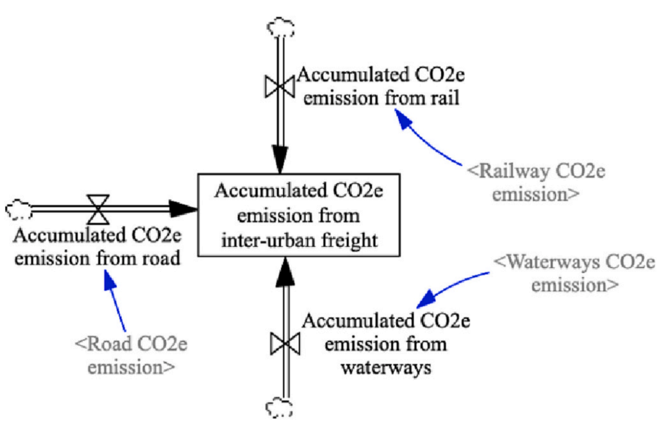

Fig. 15. Accumulated CO_{2e} (GHG) emissions.

Table 5
Summary of scenarios analyzed in the case study.

Base case	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Infrastructure investments; Fiscal and regulatory measures; Combination of both	Constant GDP growth	A higher increase in freight volume	Economic crisis	External pressure to reduce CO_2 emissions

6.1. Base case scenario

Because we are simulating for an extended period, various projects are expected to be added to the network during the time window. The Brazilian government's plan (ANTT - Associação Nacional de Transportes Terrestres, 2020a) for the country's infrastructure was split into four blocks, the current infrastructure, the new infrastructure added by 2030, then 2035 and 2045, as shown in Table 6 and Fig. 16.

Table 6
Summary of infrastructure projects in Brazil, categorized in blocks.

2030 infrastructure block	
Activity	Km added
Highway Extension	4201.63
Highway Construction	3839.67
Railway	3007.00
2035 infrastructure block	
Activity	Km added
Highway	5471.90
Railway	4220.00
2045 infrastructure block	
Activity	Km added
Railway	3801.00

Source: Based on ANTT - Associação Nacional de Transportes Terrestres (2020a) and Investment Partnerships Program (2020).

Based on Stelling (2014), in Table 7 we selected the following fiscal and regulatory measures: (i) Fossil fuel taxation for roads, (ii) Infrastructure fee (tolls) for roads, (iii) Marginal tax on CO_{2e} and (iv) Emission trading system. We defined a range value for each of them, as well as the respective year in which they will be implemented. We designed three-time windows for fiscal and regulatory measures, short-term (2020-2030), medium-term (2030–2040), and long-term (2040–2050). Because Brazil has no official values for marginal tax on CO_2e and emission trading systems, the model's values were the same as used in Europe but using the Brazilian currency. The variation in the price is based on the need to reduce CO_2e emissions; the higher the need, the higher the cost.

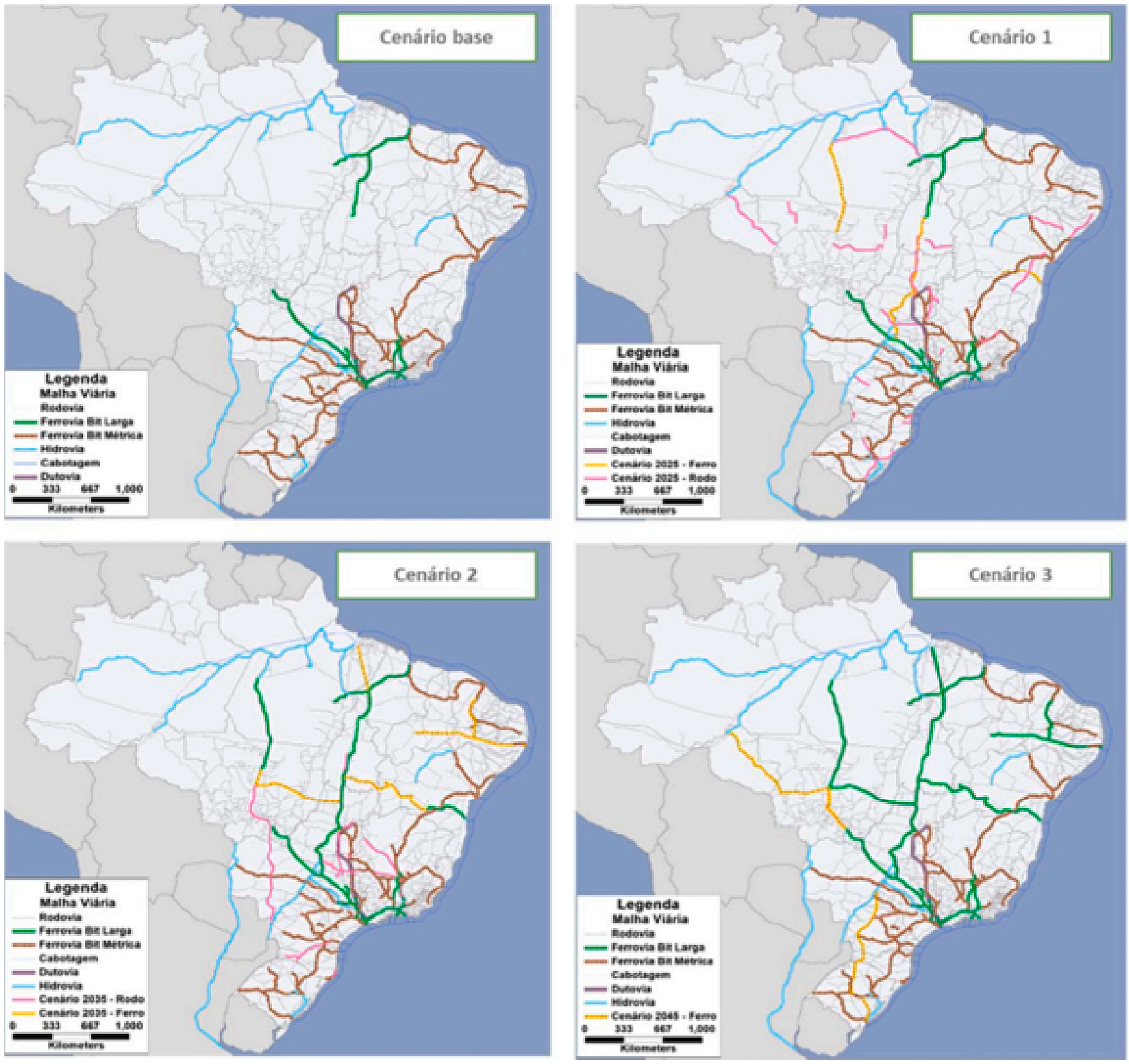

Fig. 16. Improvement of Brazil's infrastructure from 2020 to 2045.
Source: ANTT - Associação Nacional de Transportes Terrestres (2020a).

Table 7
Overall fiscal and regulatory measures used in the model.

Fiscal and regulatory measures	Minimum value	Maximum value	Policy time window	Implementation year
Fossil fuel taxation for road	100 (R $/m^3)	225 (R $/m^3)	Short-term (2020-2030)	2021
Infrastructure fee (tolls) for road	8.77 (R $/vehicle)	9.35 (R $/vehicle)	Short-term (2020-2030)	2026
Marginal tax on CO_{2e}	38 (R $/t$CO_{2e}$)	50 (R $/t$CO_{2e}$)	Medium-term (2030–2040)	2031
Emission trading system	23.47 (R $/t$CO_{2e}$)	41.15 (R $/t$CO_{2e}$)	Long-term (2040–2050)	2040

The results of the implementation of infrastructure investments show a moderate change in the modal share over the years, with road decreasing from around 64.5% to almost 49%, while rail increased from 15.9% to nearly 24.2%, and waterways going from 19.6% to 26.8%.

The application of fiscal and regulatory measures also has had an impact on the modal shift over the years, with road decreasing from around 64.5% to 36.8%, while waterways become the most attractive mode, increasing their market share from 19.6% to 37.6%. Meanwhile, rail increases from 15.9% to nearly 25.6%.

When combining both previous policy measures, the experiment in the base case shows that the modal shift changes more significantly, with road transportation reaching its lowest share, only 24%, while waterways become the primary mode, with 43.4% of the share, followed by railway with 32.6%. This information, combined with the shift seen in the volume transported per mode and the volume of emissions in the system, shows that the measures complement each other to promote freight decarbonization.

Some insights from this study are that rail volume benefits the most from infrastructure-related policies. In contrast, changes in waterways and road volume are more tied up to fiscal and regulatory measures than implementing the infrastructure itself. We can also see that, in an aggregated national model, fiscal and regulatory measures play a more critical role when promoting a modal shift than the need for new infrastructure. Fig. 17 shows the evolution of the modal shift over the years under the combination of the different policy measures and the respective modal split in percentage in a certain year.

Fig. 18 shows that by applying these measures we would achieve a reduction of nearly 200 *T* CO_{2e} in 30 years. We found that if we only implement the new infrastructures, the overall decrease in CO_{2e} in 30 years will only be 6.3%. By implementing only fiscal and regulatory

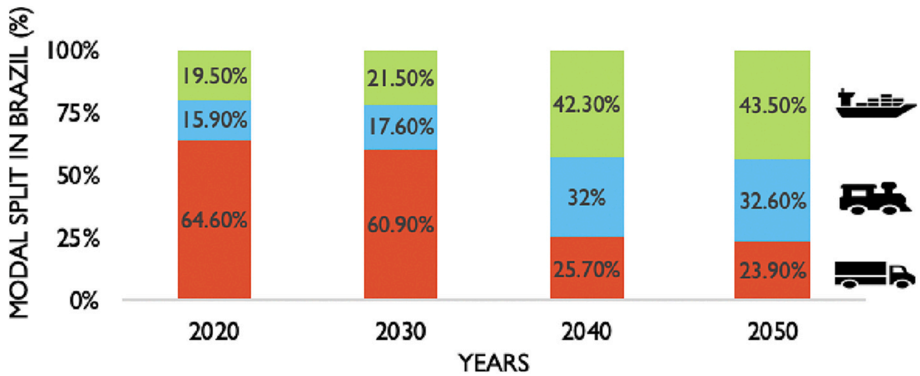

Fig. 17. Modal shift over time – combination of policy measures.

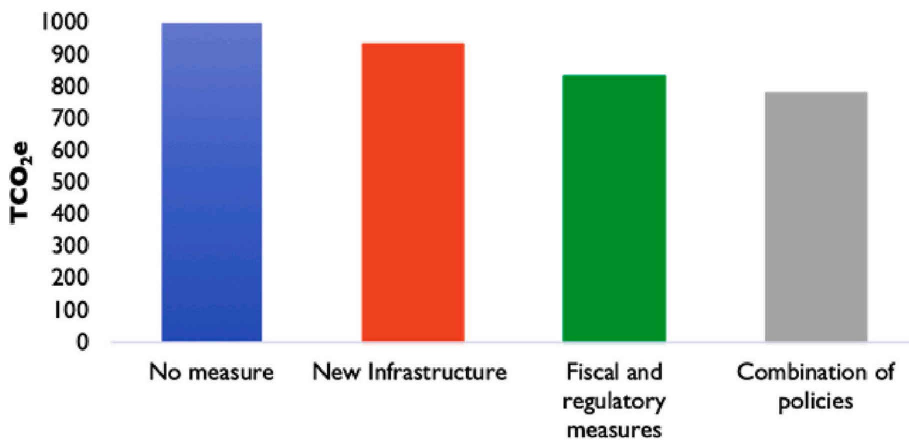

Fig. 18. Reduction of CO_{2e} – combination of policy measures.

Table 8
Scenarios used to test the application of policy measures.

Scenario 1	Scenario 2	Scenario 3	Scenario 4
Constant GDP growth	A higher increase in freight volume	Economic crisis	External pressure to reduce CO_2 emissions

Table 9
Reduction of accumulated CO_2 emission.

	Accumulated CO_{2e} emission by inter-urban freight - no policy measures (gCO_2)	Accumulated CO_{2e} emission by inter-urban freight - combination of policy strategies (gCO_2)	Reduction (%)
Scenario 1	1.11×10^{15}	8.46×10^{14}	24.0
Scenario 2	1.28×10^{15}	9.54×10^{14}	25.4
Scenario 3	9×10^{14}	7.27×10^{14}	19.3
Scenario 4	9.87×10^{14}	6.23×10^{14}	36.9

measures, the reduction is 15.5%. By combining the three measures, the reduction increases to 20.9%.

6.2. Scenarios 1–4

By applying the base case scenario, we measured the impact that different policy measures have on the decarbonization of freight transport. However, we also wanted to understand how external events might impact the system's behavior and expand the robustness of the application of such policy measures. We did this via different scenarios, which enabled us to make better recommendations about the application of policy measures. In this section, four different scenarios were designed and applied to the model, as shown in Table 8.

The assumptions we made for each of these scenarios were:

Scenario 1: Constant GDP and freight growth. Slightly stricter policy measures and a slightly higher penetration rate of new vehicles, compared to the base case scenario.

Scenario 2: Higher freight growth. Slightly stricter policy measures and a slightly higher penetration rate of new vehicles, compared to the base case scenario.

Scenario 3: Lower GDP and freight growth. Changes in policy implementation and delays on the new infrastructure projects, compared to the base case scenario.

Scenario 4: Changes in policy implementation time. A higher penetration rate of new vehicles and higher reduction of CO_{2e} from sustainable vehicles, compared to the base case scenario.

Besides the external factors defined in Table 8, we also simulated the implementation of the policies (infrastructure investment - see Table 6, and fiscal and regulatory measures - see Table 7) for each scenario. Table 9 shows the results of accumulated CO_2 emissions with no policy implemented and with all policies combined. It was observed that, despite different externalities, the modal shift still occurs, and the volume of CO_2 emissions is reduced, highlighting the efficiency of the policies simulated.

The modal shift evolution for each of the different scenarios can be seen in Fig. 19. From the base case and these four different scenarios, we can conclude that the modal shift process is slow and most of the modal

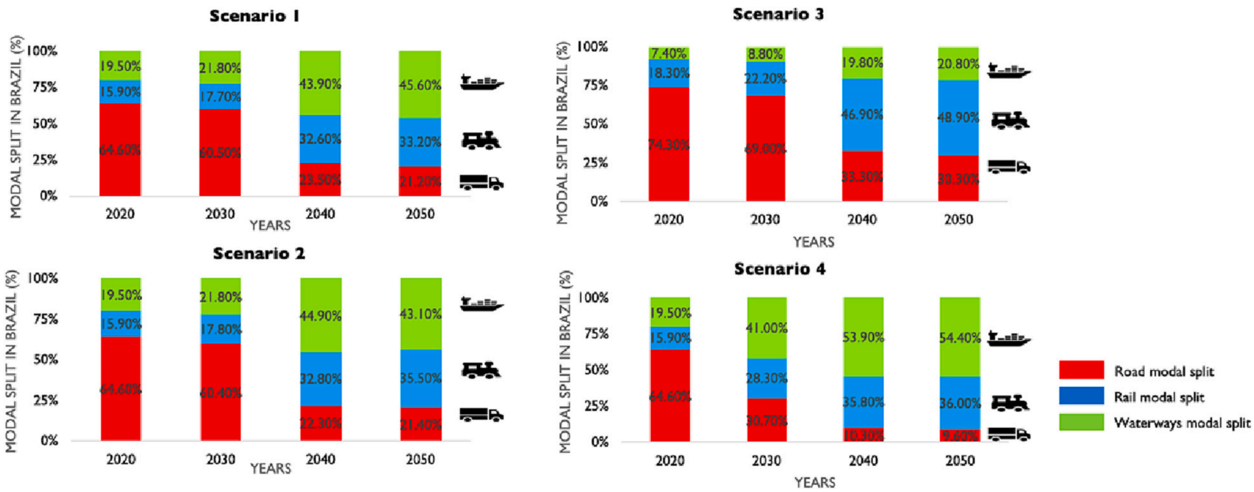

Fig. 19. Modal shift evolution over the years for the different scenarios.

Table 10
Reduction of CO_{2e} emissions - scenario 4 extended.

	Emissions (Trillion gCO_{2e})							
Year	2030	2040	2050	2060	2070	2080	2090	2100
Reduction (%)	10.0%	28.1%	36.9%	41.5%	44.9%	47.6%	49.6%	51.1%
Reduction per decade (%)	–	18.1%	8.8%	4.6%	3.4%	2.7%	2%	1.4%

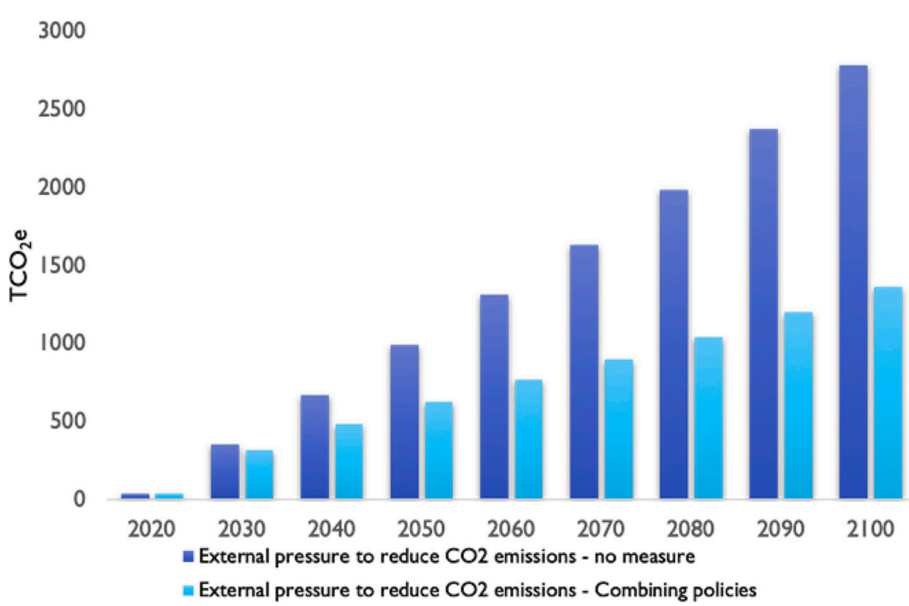

Fig. 20. Extended simulation time - evolution of the emission reduction.

shift will take place between 2030 and 2040, as shown by the modal split in percentage in each of the decades. The only way of achieving significant changes in the first decade (2020-2030) is by implementing strong policy measures early on, as shown in Scenario 4.

It should be mentioned that even in the stricter scenario, the maximum level of reduced emissions reached was 36.9%, showing that much more effort is required to decarbonize the freight system. This model only looks into two different policy measures for modal shifts (infrastructure investments and a tiny sample of all the possible fiscal and regulatory options). Other decarbonization strategies, such as reducing the demand for freight, optimizing vehicle usage and loading, increasing the efficiency of freight vehicles, and promoting alternative energy sources were left out of this research. Still, they play an essential role in the decarbonization process of freight transport. Nevertheless, these experiments shed a light on the challenge of decarbonizing the system within such a short period, and how much extra work and effort will be needed to reduce to meet even more ambitious targets, such as the EU zero emission by 2050 goal.

6.3. Extended simulation time

For this experiment, we chose the most successful scenario out of the four performed, this being the one in which we obtained the highest reduction of CO_{2e}, which was scenario 4. The following step was to extend the simulation time to find the year when we would achieve the 50% reduction, and to check the evolution of the decarbonization rate over the following decades, as shown in Table 10.

It can be seen from Table 10 and Fig. 20 that the 50% reduction will be achieved between 2090 and 2100 (2093). In the very long-term, the decarbonization process starts to slow down, which means that the system adapts itself to the policy measures and, starts to lose its efficiency. This is valuable information for policy makers when looking for the impact of policies in the very long term and how the system needs to insert external pressure every decade or so to avoid its stabilization.

Another aspect observed in this scenario is that promoting a modal shift might not be sufficient to decarbonize freight transport. Hence, it is important to explore other alternative measures as early as possible to complement the results achieved by modal shift policies.

6.4. Discussion

Regarding new infrastructure projects, the experiments show that the increase in rail and waterways networks makes the competition tighter when choosing the mode. However, when looking at an aggregated, national level, the infrastructure project on its own does not promote a significant modal shift. We found fiscal and regulatory policies to be more effective for promoting modal shifts. The simulation shows that policies targeting the taxation of CO_{2e} emission provide a greater contribution towards making low carbon modes more attractive, compared to taxation on fuel for trucks and an infrastructure fee for highways. However, we need to keep in mind that these measures will only promote a modal shift if there are other infrastructures available for shippers to migrate to. Hence, the combination of all policy measures proves to be the most effective approach.

Interviews highlighted the bureaucratic features of implementing modal shift policies. The implementation relies on the commitments and alignments of the different stakeholders and actors involved and their interest in carrying out such a project. These aspects could lead to it taking a decade or more to implement a new infrastructure project, depending, of course, on its characteristics and complexity.

The scenario analysis proved how powerful these policy measures are, showing that decarbonization will occur under different circumstances. However, the system tends to adjust to the policy measures in the very long-term. Its impact on the overall performance tends to decrease over time. Experiments also highlighted the slow modal shift process due to the freight dynamics, which are sometimes neglected in such studies, and how this could impact the modal shift process.

Our research also shows that the SD approach allowed us to look into the complexity of the dynamics of the system and its interconnections. We studied how the variables influence each other, their non-linear cause-and-effect relationship, and the evaluation of accumulated delays and time-dependent states, analyzing how the system reacts to the policy measures. Moreover, our study looked into ways of reducing CO_{2e} emissions. For these specific policy measures, it is interesting to look at the yearly CO_{2e} emission level and its accumulated value over the years. SD enabled us to do so, providing an overview of the reduction at an accumulated level. Lastly, SD proved to be an excellent tool to measure the time aspect. Despite the benefits, SD is a method that needs some level of aggregation to be implemented, which means we have to make assumptions that could impact the reality of the system being simulated. These assumptions might lead to the loss of individual behavior, as we have to generalize carriers, shippers, and government actions. Moreover, the SD model also limits the detailed geographical differentiation, which has a significant role in studying mode choice. Lastly, the SD approach only allows equations to be used, constraining how we built some relations in the simulation model.

Regarding the generalizability of our results, we consider the direction of our main results (e.g. freight modal shift processes are slow) as being valid for other economically developing countries. The differences between this Brazilian case and other economies would mainly be related to the degree of policy inertia. The behavior of shippers and carriers, and the extent to which the political and legal system can implement new policies are important factors that will determine the speed of implementation of a modal shift and other policies and their effectiveness. These factors can differ greatly among countries.

7. Conclusions

In this paper, we explored the role of time in decarbonization policies by promoting a modal shift in freight transportation. We looked into the critical time aspects that need to be considered in this process, shedding light on the time needed to promote a shift to low carbon-intensity modes. We created an SD model that enabled us to evaluate different policy measures with different intensity levels at different times. In our research, we presented both a qualitative model (causal loop diagram) and a quantitative model (stock and flow diagram). We also used empirical data collected from interviews with experts, which gives greater validation to the model rather than using only theoretical data. The simulations showed that time issues play a crucial role in modal shift policies. In the long term, the growth of the amount of freight will impact the amount of CO_{2e} emitted into the system. Therefore, supporting a shift to more sustainable modes relatively quickly seems vital to ensure that this growth of CO_{2e} is mitigated, despite the increase in the freight volume transported. This research showed how sustainable solutions should not be overlooked when planning for new infrastructure, and, when aligned with it, the results can be seen early on.

The simulation results showed that modal shift processes are slow, which is in line with what is observed in practice. Helping to accelerate these processes by implementing strict policy measures within the next decade could reduce CO_2 in the Brazilian context by upwards of 10% in the next thirty years, compared to the business-as-usual case. The simulation reveals that, apart from scenario 4, most of the modal shifts would take place between 2030 and 2040. Thus, its impact on the decarbonization of freight transport will mainly be seen around 10 to 20 years from now.

For future research, we recommend analyzing different fiscal and regulatory measures or even different freight decarbonization strategies, such as freight demand management, better capacity use of vehicles and assets, vehicle efficiency improvement, and the promotion of alternative fuels. Moreover, detailed behavior analysis is important to understand and reproduce shippers' and carriers' decision-making processes, which should be taken into consideration, as well as the cost-benefit analysis of the different policy measures assessed.

We also conclude that the SD modeling proved to be suitable in our case. Although it is assumption-based, we think the approach gives useful and plausible findings for policymakers about the role of time in freight CO_2 policy-making and the effectiveness of policies over time. Although the magnitude of the quantified findings should be taken with a grain of salt, the direction of the findings seems plausible and insightful. We think, therefore, that this paper contributes to knowledge, also by showing that in situations with 'messy' or incomplete data, SD can be a useful tool to help policy making by showing the decision-makers what the time dynamics of their policy proposals may be and their effectiveness in the short and long run.

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CRediT authorship contribution statement

Raphael Ferrari Nassar: Conceptualization, Methodology, Writing – original draft. **Verônica Ghisolfi:** Conceptualization, Supervision, Writing – review & editing. **Jan Anne Annema:** Conceptualization, Supervision, Writing – review & editing. **Arjan van Binsbergen:**

Conceptualization, Supervision, Writing – review & editing. **Lóránt Antal Tavasszy:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. SD model equations

Table A1
Sub-model: equations for economic-related variables.

Economic related variables			
Names	Type of variables	Equations	Units
GDP Growth rate	Auxiliary	RANDOM NORMAL (−0.096, 0.077, 0.005, 0.02, 0)	1/Year
Freight growth rate	Auxiliary	GDP Growth rate	1/Year
Change in Freight volume	Auxiliary	Freight growth rate * Freight Volume	Tons/Year
Freight Volume	Level	Change in Freight volume	Tons
Change in GDP	Auxiliary	GDP * GDP Growth rate	Real/Year
GDP	Level	Change in GDP	Real
% of total GDP invested in transport infrastructure per year	Auxiliary	0.00561	1/Year
Amount of GDP invested in infrastructure projects per year	Auxiliary	GDP * % of total GDP invested in transport infrastructure per year	Real/Year
Change in volume of investment	Auxiliary	Amount of GDP invested in infrastructure projects per year * Final year for investment analysis	Real/Year
Final year for investment analysis	Auxiliary	PULSE (2020, 20)	1
Volume of investment	Level	Change in volume of investment- Pre-project phase	Real
Pre-project phase	Auxiliary	Volume of investment/time needed for pre-project phase	Real/Year
Time needed for pre-project phase	Constant	2	Year
Infrastructure project study	Level	Pre-project phase - Choosing project	Real/Year
Choosing project	Auxiliary	Infrastructure project study / Time needed to peak a project	Real/Year
Time needed to peak a project	Constant	4	Year
Project approval	Level	Choosing project - Environmental license and expropriation	Real
Environmental license and expropriation	Auxiliary	Project approval / Time needed to obtain environmental licences and land perform expropriation	Real/Year
Time needed to obtain environmental licences and land perform expropriation	Constant	1	Year
Investments in new infrastructure	Level	Environmental license and expropriation-Yearly investment in infrastructure projects for private sector- Yearly investment in infrastructure project for public sector	Real
Yearly investment in infrastructure projects for public sector	Auxiliary	Investments in new infrastructure *(1- Ratio of total investment allocated to private sector/year)	Real/Year
Yearly investment in infrastructure projects for private sector	Auxiliary	Investments in new infrastructure * Ratio of total investment allocated to private sector/year	Real/Year
Ratio of total investment allocated to private sector/year	Constant	0.7	1/Year
Public sector investment in roads	Auxiliary	Yearly investment in infrastructure project for public sector *Percentage of yearly investment by public sector put into roads	Real/Year
Percentage of yearly investment by public sector put in roads	Constant	0.8	1
Public sector investment in rail	Auxiliary	Yearly investment in infrastructure project for public sector *percentage of yearly investment by public sector put into rail	Real/Year
Percentage of yearly investment by public sector put into rail	Constant	0	1
Public sector investment in waterways	Auxiliary	Percentage of yearly investment by public sector put in waterways *Yearly investment in infrastructure projects for public sector	Real/Year
Percentage of yearly investment by public sector put into waterways	Constant	0.2	1
Private sector investment in roads	Auxiliary	Percentage of yearly investment by private sector put into roads *Yearly investment in infrastructure projects for private sector	Real/Year
Percentage of yearly investment by private sector put into roads	Constant	0.3	1
Private sector investment in rail	Auxiliary	Percentage of yearly investment by private sector put into rail *Yearly investment in infrastructure projects for private sector	Real/Year
Percentage of yearly investment by private sector put into rail	Constant	0.7	1
Private sector investment in waterways	Auxiliary	Percentage of yearly investment by private sector put into waterways *Yearly investment in infrastructure projects for private sector	Real/Year
Percentage of yearly investment by private sector put into waterways	Constant	0	1

Table A2
Sub-model: equations for freight demand generation.

Freight demand generation			
Names	Type of variables	Equations	Units
Road Demand	Auxiliary	Freight Volume * Road modal split	Tons
Change in the value of road volume	Auxiliary	(Road Demand - Value of road volume)/SAVEPER	Tons/Year
Value of road volume	Level	Change in the value of road volume	Tons
Road volume	Auxiliary	Value of road volume / SAVEPER	Tons/Year
Rail Demand	Auxiliary	Freight Volume * Rail modal split	Tons
Change in the value of rail volume	Auxiliary	(Rail Demand - Value of rail volume) / SAVEPER	Tons/Year
Value of rail volume	Level	Change in the value of rail volume	Tons
Rail volume	Auxiliary	Value of rail volume / SAVEPER	Tons/Year
Waterway Demand	Auxiliary	Freight Volume * Waterway modal split	Tons
Change in the value of waterway volume	Auxiliary	(Waterway Demand - Value of waterway volume)/SAVEPER	Tons/Year
Value of waterway volume	Level	Change in the value of waterway volume	Tons
Waterway volume	Auxiliary	Value of waterway volume / SAVEPER	Tons/Year

Table A3
Sub-model: equations for the multimodal network.

Multimodal network			
Names	Type of variables	Equations	Units
Yearly increase in railway funding	Auxiliary	Private sector investment in rail + Public sector investment in rail	Real/Year
Total funding for railways	Level	Yearly increase on railway funding - Money needed to implement rail infrastructure blocks in their respective years - Yearly railway routine maintenance cost	Real
Yearly railway routine maintenance cost	Auxiliary	Maintenance cost /Km of rail *Rail network length	Real/Year
Maintenance cost /Km of rail	Constant	5000	Real/Year/Km
Money needed to implement rail infrastructure blocks in their respective years	Auxiliary	(IF THEN ELSE(Total funding for railways≥ 1.04916e+11:AND: Time = 2030, 1.04916e+11, 0)) + (IF THEN ELSE(Total funding for railways ≥ 1.12332e+11:AND:Time = 2035, 1.12332e+11, 0)) + (IF THEN ELSE(Total funding for railways≥ 5.3681e+10:AND:Time = 2045, 5.3681e+10, 0))	Real/Year
Implementing new railway projects in their respective years	Auxiliary	IF THEN ELSE(Money needed to implement rail infrastructure blocks in their respective years >0:AND:Time = 2030, 3007, 0) + (IF THEN ELSE(Money needed to implement rail infrastructure blocks in their respective years >0: AND:Time = 2035, 4220, 0)) + (IF THEN ELSE (Money needed to implement rail infrastructure blocks in their respective years>0:AND:Time = 2045, 3801, 0))	Km/Year
Change in Railway infrastructure length	Auxiliary	Implementing new railway projects in their respective years	Km/Year
Rail network length	Level	Change in Railway infrastructure length - Rail infrastructure erosion	Km
Rail infrastructure erosion	Auxiliary	Rail network length * Time for rail infrastructure erosion	Km/Year
Time for rail infrastructure erosion	Constant	0.0001	1/Year
Rail capacity improvement	Auxiliary	IF THEN ELSE(Change in Railway infrastructure length = 3007, 6.11e+07, 0) + IF THEN ELSE (Change in Railway infrastructure length = 4220, 1.54134e+08, 0) + IF THEN ELSE(Change in Railway infrastructure length = 3801, 2.03467e+08, 0)	Tons/Year
Total rail capacity increase	Level	Rail capacity improvement - Increase on rail operational capacity	Tons
Increase on rail operational capacity	Auxiliary	IF THEN ELSE(Total rail capacity increase>0:AND: Time = 2031, Total rail capacity increase*0.2/SAVEPER,0) + IF THEN ELSE(Total rail capacity increase >0:AND: Time = 2032, (Total rail capacity increase*0.875/SAVEPER),0) + IF THEN ELSE(Total rail capacity increase>0:AND: Time = 2033, (Total rail capacity increase/SAVEPER),0) + IF THEN ELSE (Total rail capacity increase>0:AND: Time = 2036, Total rail capacity increase*0.2/SAVEPER,0) + IF THEN ELSE(Total rail capacity increase>0:AND: Time = 2037, (Total rail capacity increase*0.875/SAVEPER),0) + IF THEN ELSE(Total rail capacity increase>0:AND: Time = 2038, (Total rail capacity increase/SAVEPER),0) + IF THEN ELSE(Total rail capacity increase >0:AND: Time = 2046, Total rail capacity increase*0.2/SAVEPER,0) + IF THEN ELSE(Total rail capacity increase>0:AND: Time = 2047, (Total rail capacity increase*0.875/SAVEPER),0) + IF THEN ELSE(Total rail capacity increase>0:AND: Time = 2048, (Total rail capacity increase/ SAVEPER), 0)	Tons/Year
Rail ramp-up time	Auxiliary	Increase on rail operational capacity	Tons/Year
Change in rail infrastructure capacity	Auxiliary	Rail ramp-up time	Tons/Year
Rail infrastructure capacity	Level	Change in rail infrastructure capacity - Rail capacity erosion	Tons
Rail capacity erosion	Auxiliary	Rail infrastructure capacity * Rail transport capacity erosion rate	Tons/Year
Rail transport capacity erosion rate	Constant	0.01	1/Year
Train trips needed to serve total network capacity	Auxiliary	Rail infrastructure capacity / Train capacity	Train
Train capacity	Auxiliary	Number of wagons * Capacity per wagon	Tons/Train
Number of wagons	Level	175	Wagons/Train
Capacity per wagon	Level	1000	Tons/Wagons
New trains trips needed to serve 100% of demand	Auxiliary	(Train trips needed to serve total network capacity / SAVEPER) - (Maximum number of trains trips in the network / SAVEPER)	Train/Year

(*continued on next page*)

Table A3 (*continued*)

Multimodal network			
Names	Type of variables	Equations	Units
Maximum number of trains trips in the network	Level	New trains trips needed to serve 100% of demand	Train
Maximum number of daily trains	Auxiliary	(Maximum number of trains trips in the network)/(Days per year / Seasonality index)	Train/days
Change in number of train trips/Year	Auxiliary	(Rail volume / Train capacity) - (Number of train trips / SAVEPER)	Train/Year
Number of train trips	Level	Change in number of train trips/Year	Train
Daily number of train trips	Auxiliary	(Number of train trips) / (Days per year / Seasonality index)	Train/days
Seasonality index	Constant	1.21	Dmnl
Days per year	Constant	365	Days
Limitation of the daily number of trains based on number of train trips available	Auxiliary	IF THEN ELSE(Daily number of train trips≥ Maximum number of daily trains, Maximum number of daily trains, Daily number of train trips)	Train/days
Rail transport saturation	Auxiliary	Limitation of the daily number of trains based on number of train trips available/Installed capacity in number of daily trains	Dmnl
Installed capacity in number of daily trains	Auxiliary	(Minutes per day * K1 * K2)/(Round trip train time + Teta (per train))	Train/days
K1	Constant	0.9208	Dmnl
K2	Constant	0.8	Dmnl
Teta (per train)	Constant	5	Min/Train
Minutes per day	Constant	1440	Min/days
Round trip train time	Auxiliary	(Average round trip distance between each rail yard/terminal (per train)*2) / Rail speed * Hour to minute	Min/Train
Hour to minute	Constant	60	Min/h
Rail speed	Constant	36.73	Km/h
Average round trip distance between each rail yard/terminal (per train)	Constant	15.85	Km/Train
Yearly increase in waterways funding	Auxiliary	Private sector investment in waterways + Public sector investment in waterways	Real/Year
Total funding for waterways	Level	Yearly increase in waterways funding - Money needed to implement waterways infrastructure blocks in their respective year - Yearly waterways routine maintenance cost	Real
Yearly waterways routine maintenance cost	Auxiliary	Waterways network length * Maintenance cost/km of waterway	Real/Year
Maintenance cost/km of waterway	Constant	5000	Real/Year/Km
Money needed to implement waterways infrastructure blocks in their respective year	Auxiliary	IF THEN ELSE(Total fund for waterways≥ 0:AND: Time ≥ 0, 0, 0)	Real/Year
Implementing new waterway projects in their respective years	Auxiliary	IF THEN ELSE(Money needed to implement waterways infrastructure blocks in their respective year ≥ 0:AND: Time ≥ 0, 0, 0)	Km/Year
Change in waterways infrastructure length	Auxiliary	Implementing new waterway projects in their respective years	Km/Year
Waterways network length	Level	Change in waterways infrastructure length - Waterway infrastructure erosion	Km
Waterway infrastructure erosion	Auxiliary	Waterways network length * Time for waterways infrastructure erosion	Km/Year
Time for waterways infrastructure erosion	Constant	0.0001	1/Year
Waterway capacity improvement	Auxiliary	IF THEN ELSE(Change in waterways infrastructure length ≥ 0, 0, 0)	Tons/Year
Total waterway capacity increase	Level	Waterway capacity improvement - Increase on waterways operational capacity	Tons
Increase in waterways operational capacity	Auxiliary	IF THEN ELSE(Total waterway capacity increase ≥ 0:AND: Time ≥ 0, 0, 0)	Tons/Year
Waterways ramp-up time	Auxiliary	Increase in waterways operational capacity	Tons/Year
Change in waterways infrastructure capacity	Auxiliary	Waterways ramp-up time	Tons/Year
Waterways infrastructure capacity	Level	Change in waterways infrastructure capacity - Waterways capacity erosion	Tons
Waterways capacity erosion	Auxiliary	Waterways infrastructure capacity * Waterways transport capacity erosion rate	Tons/Year
Waterways transport capacity erosion rate	Constant	0.01	1/Year
Vessel trips needed to serve total network capacity	Auxiliary	Waterways infrastructure capacity / Vessel capacity	Vessel
New vessel trips needed to serve 100% of demand	Auxiliary	(Vessel trips needed to serve total network capacity / SAVEPER) - (Maximum number of vessel trips in the network / SAVEPER)	Vessel/Year
Maximum number of vessels trips in the network	Level	New vessels trips needed to serve 100% of demand	Vessel
Maximum number of daily vessels	Auxiliary	(Maximum number of vessel trips in the network)/ (Days per year / Seasonality index)	Vessel/days
Vessel capacity	Level	18,000	Tons/Vessel
Change in number of vessel trips/year	Auxiliary	(Waterway volume / Vessel capacity) - (Number of vessel trips / SAVEPER)	Vessel/Year
Number of vessel trips	Level	Change in number of vessel trips/year	Vessel
Daily number of vessel trips	Auxiliary	Number of vessel trips / (Days per year / Seasonality index)	Vessel/days
Limitation of the daily number of trains based on the number of vessel trips available	Auxiliary	IF THEN ELSE(Daily number of vessel trips ≥ Maximum number of daily vessels, Maximum number of daily vessels, Daily number of vessels trips)	Vessel/days
Waterways transport saturation	Auxiliary	Limitation of the daily number of trains based on number of vessel trips available / Maximum number of daily vessels	Dmnl

Table A4
Sub-model: equations for road saturation.

Names	Type of variables	Equations	Units
Road saturation			
Yearly increase in highway funding	Auxiliary	Private sector investment in roads + Public sector investment in roads	Real/Year
Total funding for highways	Level	Yearly increase in highway funding - Money needed to implement highway construction infrastructure projects in their respective years - Money needed to implement highway extension infrastructure projects in their respective years - Yearly highway maintenance cost	Real
Yearly highway maintenance cost	Auxiliary	Total single lane road routine maintenance cost + Total double lane road routine maintenance cost	Real/Year
Total single lane road routine maintenance cost	Auxiliary	Maintenance cost/Km of single lane road *Single lane highway network length	Real/Year
Maintenance cost/Km of single lane road	Constant	13.43	Real/Year/Km
Total double lane road routine maintenance cost	Auxiliary	Double lane highway network length *Maintenance cost/km of double lane road	Real/Year
Maintenance cost/km of double lane road	Constant	24.17	Real/Year/Km
Money needed to implement highway construction infrastructure projects in their respective years	Auxiliary	IF THEN ELSE(Total funding for highways ≥ 3.3e+10:AND: Time = 2030, 3.3e+10,0) + IF THEN ELSE(Total funding for highways ≥ 1.37302e+11:AND: Time = 2035, 1.37302e+11,0)	Real/Year
Construction of new highways	Auxiliary	(IF THEN ELSE(Money needed to implement highway construction infrastructure projects in their respective years >0:AND:Time = 2030, 3839.67, 0)) + (IF THEN ELSE(Money needed to implement highway construction infrastructure projects in their respective years >0:AND:Time = 2035, 5471.9, 0))	Km/Year
Change in Km implemented	Auxiliary	Construction of new highways	Km/Year
Amount of Km implemented	Level	Change in Km implemented - Partially inaugurating new highway	Km
Partially inaugurating new highway	Auxiliary	Amount of Km implemented/Time needed for highway to be fully opened	Km/Year
Time needed for highway to be fully opened	Constant	3	Year
Change in highway infrastructure length for single lane highways	Auxiliary	Partially inaugurating new highway	Km/Year
Single lane highway network length	Level	Change in highway infrastructure length for single lane highways - Single lane highways infrastructure erosion	Km
Single lane highway infrastructure erosion	Auxiliary	Single lane highway network length * Time for highway infrastructure erosion	Km/Year
Time for highway infrastructure erosion	Constant	0.0001	1/Year
Money needed to implement highway extension infrastructure projects in their respective years	Auxiliary	IF THEN ELSE(Total funding for highways ≥ 5.07504e+10:AND: Time = 2030,5.07504e+10,0) + IF THEN ELSE(Total funding for highways ≥ 1.425e+11:AND: Time = 2035, 1.425e+11,0)	Real/Year
Highway extension	Auxiliary	(IF THEN ELSE(Money needed to implement highway extension infrastructure projects in their respective years >0:AND:Time = 2030, 4201.63, 0)) + (IF THEN ELSE(Money needed to implement highway extension infrastructure projects in their respective years >0:AND: Time = 2035, 3007, 0))	Km/Year
Change in Km extended	Auxiliary	Highway extension	Km/Year
Number of Km extended	Level	Change in Km extended - Partially inaugurating extended highway	Km
Partially inaugurating extended highway	Auxiliary	Number of Km extended / Time needed for highway extension to be fully delivered	Km/Year
Time needed for highway extension to be fully delivered	Constant	3	Year
Change in highway infrastructure length for double lane highways	Auxiliary	Partially inaugurating extended highway	Km/Year
Double lane highway network length	Level	Change in highway infrastructure length for double lane highways - Double lane highways infrastructure erosion	Km
Double lane highway infrastructure erosion	Auxiliary	Double lane highway network length *Time for Highway infrastructure erosion	Km/Year
Total amount of highway network length	Auxiliary	Double lane highway network length + Single lane highway network length	Km
Vehicle capacity	Constant	57	Tons/Vehicle
Increase in heavy vehicle traffic	Auxiliary	Road volume / Vehicle capacity	Vehicle/Year
Accumulated value for heavy vehicles	Level	Increase in heavy vehicle traffic	Vehicle
Accumulated value of heavy vehicles for next year	Auxiliary	Heavy vehicle traffic volume	Vehicle
Heavy vehicle flow	Auxiliary	(Accumulated value of heavy vehicles for next year - Accumulated value for heavy vehicles)/SAVEPER	Vehicle/Year
Accumulated value for heavy vehicles	Level	Heavy vehicle flow	Vehicle
Heavy vehicle	Auxiliary	Accumulated value for heavy vehicles / SAVEPER	Vehicle/Year
LDV's growth rate	Constant	0.003	Vehicle/ Vehicle/Year
Average AADT per stretch	Constant	22,029.6	Vehicle/days
Increase in AADT per stretch	Auxiliary	Average AADT per stretch* LDV's growth rate	Vehicle/ (Year*days)
AADT per stretch	Level	Increase in AADT per stretch	Vehicle/days
Average number of vehicles/stretch/year	Auxiliary	AADT per stretch * Days per year / SAVEPER	Vehicle/Year
Average number of vehicles/year	Auxiliary	Number of highway stretch * Average number of vehicles/stretch/year	Vehicle/Year
Increase in light vehicle traffic	Auxiliary	(Average number of vehicles/year)-(Light vehicle traffic volume/SAVEPER)	Vehicle/Year
Light vehicle traffic volume	Level	Increase in light vehicle traffic	Vehicle
Accumulated value of light vehicles for next year	Auxiliary	Light vehicle traffic volume	Vehicle
Light vehicle flow	Auxiliary	(Accumulated value of light vehicles for next year - Accumulated value for light vehicles) / SAVEPER	Vehicle/Year
Accumulated value for light vehicles	Level	Light vehicle flow	Vehicle
Light vehicles	Auxiliary	Accumulated value for light vehicles / SAVEPER	Vehicle/Year
Total highway traffic	Level	Heavy vehicles + light Vehicles - Total vehicles	Vehicle
Total vehicles	Auxiliary	Total highway traffic / SAVEPER	Vehicle/Year
Total vehicles / Highway stretch	Auxiliary	Total vehicles / Length of highway stretch	Vehicle/Year

(*continued on next page*)

Table A4 (*continued*)

Road saturation

Names	Type of variables	Equations	Units
Length of highway stretch	Auxiliary	Total amount of highway network length / Average stretch distance analyzed	Dmnl
Average stretch distance analyzed	Constant	15	Km
Amount of vehicles travelling in double lane network	Auxiliary	Ratio of double lane highway in total highway network* Total vehicles / Highway stretch	Vehicle/Year
Vvhp for double lane	Auxiliary	Amount of vehicles travelling in double lane network/ (Hours per year * Number of lanes* Peak hour factor (PHF))	Vehicle/ (Hour*Lane)
Number of lanes	Constant	2	Lane
Percentage of heavy vehicles travelling in double lane network	Auxiliary	Total heavy vehicles /Highway stretch / Amount of vehicles travelling in double lane network	Dmnl
Heavy vehicle adjustment factor (Fhv) for capacity in double lane	Auxiliary	1/((1 + percentage of heavy vehicles travelling in double lane network)*("Passenger-car equivalent for truck in a double lane network"))	Vehicle/ucp
Passenger-car equivalent for truck in a double lane network	Constant	2.5	ucp/Vehicle
Equivalent traffic volume for double lane	Auxiliary	Vvhp for double lane / Heavy vehicle adjustment factor (Fhv) for capacity in double lane	ucp/ (Hour*Lane)
Speed limit	Constant	80	Km/h
Maximum capacity for double lane highways	Auxiliary	IF THEN ELSE(Speed limit≥ 100, 2200, IF THEN ELSE(Speed limit≥ 90, 2100, IF THEN ELSE(Speed limit≥ 80, 2000,1900)))	ucp/ (Hour*Lane)
Vehicle/capacity ratio for double lanes	Auxiliary	Equivalent traffic volume for double lanes/Maximum capacity for double lane highways	Dmnl
Total heavy vehicles/Highway stretch	Auxiliary	Heavy vehicle / Amount of highway stretch	Vehicle/Year
Percentage of heavy vehicles travelling in single lane network	Auxiliary	Total heavy vehicles/Highway stretch / Amount of vehicles travelling in single lane network	Vehicle/Vehicle
Heavy vehicle adjustment factor (Fhv) for capacity in single lane	Auxiliary	1/(1 + Percentage of heavy vehicles travelling in single lane network*(Heavy vehicle equivalent capacity adjustment for single lane-1))	Dmnl
Heavy vehicle equivalent capacity adjustment for single lane	Constant	1.3	Dmnl
Average capacity for single lane	Auxiliary	Maximum capacity for single lane highway* "Heavy vehicle adjustment factor (Fhv) for capacity in single lane"*Grade factor for capacity adjustment	ucp/Hour
Grade factor for capacity adjustment	Constant	1	Dmnl
Maximum capacity for single lane highway	Auxiliary	Maximum capacity for single-lane highway*"Heavy vehicle adjustment factor (Fhv) for capacity in single lane"*Grade factor for capacity adjustment	ucp/Hour
Heavy vehicle adjustment factor (Fhv) for volume	Auxiliary	1/((1 + Percentage of heavy vehicles travelling in single lane network)*("Passenger-car equivalent for trucks - volume adjustment"-1))	Vehicle/ucp
Amount of vehicles travelling in single lane network	Auxiliary	Total vehicles / Highway stretch *(1-Ratio of double lane highway in total highway network)	Vehicle/Year
Vvhp for single lane	Auxiliary	Amount of vehicles travelling in single lane network/"Hours per year")/"Peak hour factor (PHF)	Vehicle/Hour
Hours per year	Constant	8760	Hour/Year
Peak hour factor (PHF)	Constant	0.9	Dmnl
Passenger-car equivalent for trucks - volume adjustment	Auxiliary	IF THEN ELSE(Vvhp for single lane≤100, 2.7, IF THEN ELSE(Vvhp for single lane≤200, 2.3, IF THEN ELSE(Vvhp for single lane≤300, 2.1, IF THEN ELSE(Vvhp for single lane≤400, 2, IF THEN ELSE(Vvhp for single lane≤500, 1.8, IF THEN ELSE(Vvhp for single lane≤600, 1.7, IF THEN ELSE(Vvhp for single lane≤700, 1.6, IF THEN ELSE(Vvhp for single lane≤800, 1.4, 1.3))))))))	ucp/Vehicle
Grade factor - volume adjustment	Auxiliary	IF THEN ELSE(Vvhp for single lane≤100, 0.67, IF THEN ELSE(Vvhp for single lane≤200, 0.75, IF THEN ELSE(Vvhp for single lane≤300, 0.83, IF THEN ELSE(Vvhp for single lane≤400, 0.9, IF THEN ELSE(Vvhp for single lane≤500, 0.95, IF THEN ELSE(Vvhp for single lane≤600, 0.97, IF THEN ELSE(Vvhp for single lane≤700, 0.98, IF THEN ELSE(Vvhp for single lane≤800, 0.99, 1))))))))	Dmnl
Equivalent traffic volume for single lane	Auxiliary	Vvhp for single lane/("Grade factor - volume adjustment"*"Heavy vehicle adjustment factor (Fhv) for volume")	ucp/Hour
Vehicle/capacity ratio for single lanes	Auxiliary	Equivalent traffic volume for single lane / Average capacity for single lane	Dmnl
Road average travel time	Auxiliary	Free flow time*(1 + Alpha*("Vehicle/capacity ratio for single lanes" *Beta*))	Hour/Vehicle
Beta	Constant	4	Dmnl
Alpha	Constant	0.15	Dmnl
Free flow time	Auxiliary	Road Distance / Free flow speed	Hour/Vehicle
Free flow speed	Constant	80	Km/h
Ratio of double lane highway in total highway network	Auxiliary	Double lane highway network length /total amount of highway network length	1
Weighted vehicle/capacity ratio	Auxiliary	((Double lane highway network length* "Vehicle/capacity ratio for double lanes") + (Single lane highway network length* "Vehicle/capacity ratio for single lanes"))/(Double lane highway network length + Single lane highway network length)	1

Table A5
Sub-model: equations for fiscal and regulatory policy measures.

Fiscal and regulatory policy measures			
Names	Type of variables	Equations	Units
Starting year of fossil fuel taxation for road policy	Constant	2020	Year
Fuel taxation increase rate	Lookup	[(0,0) - (20,300)], (0,0), (1100), (2125), (3150), (4200), (5225)	Real/M^3
Fossil fuel taxation for Road	Auxiliary	STEP (Fuel taxation increase rate (Policy measures intensity), Starting year of fossil fuel taxation for road policy)	Real/M^3
Fossil fuel Cost for Road	Auxiliary	Fossil fuel taxation for Road * Truck fuel capacity	Real/Vehicle
Truck fuel capacity	Constant	0.05	M^3/Vehicle
Fossil fuel cost added per Ton transported by road	Auxiliary	Fossil fuel Cost for Road / Vehicle capacity	Real/Tons
Starting year of road infrastructure fee	Constant	2025	Year
Number of stretches (Road)	Auxiliary	Road Distance / 630.45	Km
Road infrastructure fee increase rate	Lookup	[(0,0)-(20,10,000)],(0,0),(1,8.77),(5,9.35)	Real/Km/ Vehicle
Infrastructure fee (tolls etc.) for Road	Auxiliary	STEP ("Number of stretches (Road)"*("Road infrastructure fee increase rate"(Policy measures intensity)), Starting year of road infrastructure fee)	Real/Vehicle
Infrastructure fee per Ton transported by road	Auxiliary	Infrastructure fee (tolls etc.) for Road / Vehicle capacity	Real/Tons
Starting year of road marginal tax policy	Constant	2031	Year
Marginal Tax on CO_2 increase rate	Lookup	[(0,0)-(20,7000)],(0,0),(1,38),(2,40),(3,50),(4,55)	Real/tCO_{2e}
Finding Marginal Tax on CO_2 Cost	Auxiliary	STEP (Marginal Tax on CO2 increase rate (Policy measures intensity), Starting year of road marginal tax policy)	Real/tCO_{2e}
Marginal tax on CO_2	Auxiliary	IF THEN ELSE (Emission trading systems = 0, Finding Marginal Tax on CO_2 Cost, IF THEN ELSE (Finding Marginal Tax on CO_2 Cost≥ Emission trading systems Finding Marginal Tax on CO_2 Cost-Emission trading systems, Finding Marginal Tax on CO_2 Cost))	Real/tCO_{2e}
Marginal tax on CO_2 per tCO_{2e}	Auxiliary	Marginal tax on CO_2	Real/tCO_{2e}
Marginal tax on CO_2 per gCO_{2e}	Auxiliary	Marginal tax on CO_2 per tCO_{2e}/Converting tCO_{2e} to gCO_{2e}	Real/gCO_{2e}
Converting tCO_{2e} to gCO_{2e}	Constant	10^6	gCO_{2e}/tCO_{2e}
Marginal tax cost for road	Auxiliary	Road CO_{2e} emission*Marginal tax on CO_2 per gCO_{2e}	Real/Year
Marginal cost per ton transported	Auxiliary	Marginal tax cost for road/Road volume	Real/Tons
Starting year of road ETS policy	Constant	2040	Year
Emission trade increase rate	Lookup	[(0,0) - (20,7000)], (0,0), (1,23.47), (2,39.93), (3,41.15), (4,45)	Real/tCO_{2e}
Emission trading systems	Auxiliary	STEP (Emission trade increase rate (Policy measures intensity), Starting year of road ETS policy)	Real/tCO_{2e}
Cost of ETS per tCO_{2e}	Auxiliary	Emission trading systems	Real/tCO_{2e}
Cost of ETS per gCO_{2e}	Auxiliary	Cost of ETS per tCO_{2e}/Converting tCO_{2e} to gCO_{2e}	Real/gCO_{2e}
ETS cost Road	Auxiliary	Road CO_{2e} emission*Cost of ETS per gCO_{2e}	Real/Year
ETS cost per ton transported	Auxiliary	ETS cost Road / Road volume	Real/Tons
Change in road cost per ton transported	Auxiliary	((ETS cost per ton transported + Fossil fuel cost added per Ton transported by road +Infrastructure fee per Ton transported by road + Marginal cost per ton transported) - Impact of economic instruments on road generalized cost)/SAVEPER	Real/ (Tons*Year)
Impact of economic instruments on road generalized cost	Level	Change in road cost per ton transported	Real/Tons
ETS cost Rail	Auxiliary	Railway CO_{2e} emission*Cost of ETS per gCO_{2e}	Real/Year
ETS cost for rail per ton	Auxiliary	ETS cost Rail/Rail volume	Real/Tons
Marginal tax cost for rail	Auxiliary	Marginal tax on CO_2 per gCO_{2e}*Railway CO_{2e} emission	Real/Year
Marginal tax for rail per train trip	Auxiliary	Marginal tax cost for rail/Rail volume	Real/Tons
Change in railway cost per ton transported	Auxiliary	((ETS cost for rail per ton + Marginal tax for rail per train trip) - Impact of economic instruments on rail generalized cost)/SAVEPER	Real/ (Tons*Year)
Impact of economic instruments on rail generalized cost	Level	Change in railway cost per ton transported	Real/Tons
ETS cost waterways	Auxiliary	Cost of ETS per gCO_{2e}*Waterways CO_{2e} emission	Real/Year
ETS cost for waterways per ton	Auxiliary	ETS cost waterways/Waterway volume	Real/Tons
Marginal tax cost for waterways	Auxiliary	Marginal tax on CO_2 per gCO_{2e}*Waterways CO_{2e} emission	Real/Year
Marginal tax for waterways per ton	Auxiliary	Marginal tax cost for waterways/Waterway volume	Real/Tons
Change in waterway cost per ton transported	Auxiliary	(((ETS cost for waterways per ton + Marginal tax for waterways per ton)) - (Impact of economic instruments on waterways generalized cost))/SAVEPER	Real/ (Tons*Year)
Impact of economic instruments on waterways generalized cost	Level	Change in waterway cost per ton transported	Real/Tons

Table A6
Sub-model: equations for vehicle related technological innovation.

Vehicle related technological innovation			
Names	Type of variables	Equations	Units
Change in penetration rate of new vehicles based on policy measures	Lookup	[(0,0)-(20,300)], (0,0), (1,0.003), (2,0.00675), (3,0.0105), (4,0.015), (5,0.02)	Vehicle/ Vehicle/Year

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Table A6 (*continued*)

Vehicle related technological innovation			
Names	Type of variables	Equations	Units
Penetration rate of new road vehicle types	Auxiliary	Change in penetration rate of new vehicles based on policy measures (Policy measures intensity)	1/Year
Increase in new technology vehicles (Road)	Auxiliary	("Number of new technology vehicles (Road)"*"Penetration rate of new road vehicle types (170)") + Sustainable vehicles retired	Vehicle/Year
Number of new technology vehicles (Road)	Level	("Increase in new technology vehicles (Road)"-Sustainable vehicles retired)	Vehicle
Sustainable vehicles retired	Auxiliary	Number of new technology vehicles (Road) / sustainable vehicles lifespan	Vehicle/Year
Sustainable vehicles lifespan	Constant	15	Year
Amount of new road vehicle types	Auxiliary	Number of new technology vehicles (Road)	Vehicle
Number of sustainable vehicles in the network per day	Auxiliary	Amount of new road vehicle types / Days per year	Vehicle/days
Number of heavy vehicles in the network per day	Auxiliary	Accumulated value for heavy vehicles / Days per year	Vehicle/days
Maximum number of sustainable vehicles in the network per day	Auxiliary	IF THEN ELSE (Number of sustainable vehicles in the network per day≥ Number of heavy vehicles in the network per day, Number of heavy vehicles in the network per day, Number of sustainable vehicles in the network per day)	Vehicle/days
Change in penetration rate of new trains based on policy measures	Lookup	[(0,0) - (20,300)], (0,0), (1,0.003), (2,0.00675), (3,0.0105), (4,0.015), (5,0.02)	Train/Train/Year
Penetration rate of new rail vehicle types	Auxiliary	Change in penetration rate of new trains based on policy measures (Policy measures intensity)	1/Year
Increase in new technology vehicles (Rail)	Auxiliary	("Number of new technology vehicles (Rail)"*"Penetration rate of new rail vehicle types") + Sustainable trains retired	Train/Year
Number of new technology vehicles (Rail)	Level	("Increase in new technology vehicles (Rail)"- Sustainable trains retired)	Train
Sustainable trains retired	Auxiliary	Number of new technology vehicles (Rail) / Sustainable train lifespan	Train/Year
Sustainable train lifespan	Constant	40	Year
Amount of new rail vehicle types	Auxiliary	Number of new technology vehicles (Rail)	Train
Number of sustainable trains in the network per day	Auxiliary	Amount of new rail vehicle types / (Days per year/Seasonality index)	Train/days
Maximum number of sustainable trains in the network per day	Auxiliary	IF THEN ELSE (Number of sustainable trains in the network per day≥ Daily number of train trips, Daily number of train trips, Number of sustainable trains in the network per day)	Train/days
Change in penetration rate of new vessels based on policy measures	Lookup	[(0,0) - (20,300)], (0,0), (1,0.003), (2,0.00675), (3,0.0105), (4,0.015), (5,0.02)	Vessel/Vessel/Year
Penetration rate of new vessel types	Auxiliary	Change in penetration rate of new vessels based on policy measures (Policy measures intensity)	1/Year
Increase in new technology vehicles (Vessel)	Auxiliary	("Number of new technology vehicles (Waterways) * "Penetration rate of new vessel type") + Sustainable vessels retired	Vessel/Year
Number of new technology vehicles (Waterways)	Level	Increase in new technology vehicles (Vessel) - Sustainable vessels retired	Vessel
Sustainable vessels retired	Auxiliary	Number of new technology vehicles (Waterways)/Sustainable vessels lifespan	Vessel/Year
Sustainable vessels lifespan	Constant	35	Year
Amount of new waterways vehicle types	Auxiliary	Number of new technology vehicles (Waterways)	Vessel
Number of sustainable vessels in the network per day	Auxiliary	Amount of new waterways vehicle types / (Days per year/Seasonality index)	Vessel/days
Maximum number of sustainable vessels in the network per day	Auxiliary	IF THEN ELSE (Number of sustainable vessels in the network per day≥ Daily number of vessel trips, Daily number of vessel trips, Number of sustainable vessels in the network per day)	Vessel/days

Table A7
Sub-model: equations for modal split.

Modal split			
Names	Type of variables	Equations	Units
Road Distance	Constant	630.45	Km
Km unit	Constant	1	Km
Dimensionless conversion for total road distance cost	Auxiliary	Road Distance / Km unit	1
Road monetary value	Lookup	[(0,0) - (1500,300)], (1,15.42), (100,30.18), (200,45.08), (300,59.99), (400,74.9), (500,89.9), (600,104.71), (700,119.62), (800,134.52), (900,149.43), (1000,164.34), (1100,179.24), (1200,194.15), (1300,209.06), (1400,223.96), (1500,238.87)	Real
Total road distance cost	Auxiliary	Road monetary value (Dimensionless conversion for total road distance cost)	Real
Impact of road saturation on freight rate	Constant	0.10	Real
Saturation of road network cost	Auxiliary	Impact of road saturation on freight rate * Weighted vehicle/capacity ratio	Real
Per ton	Constant	1	Tons
Road economic instrument cost/ton	Auxiliary	Impact of economic instruments on road generalized cost*per ton	Real
Road freight transport cost	Auxiliary	((Road economic instrument cost/ton + Saturation of road network cost + Total road distance cost))	Real
Difference between road and rail distance	Constant	0	Km
Rail Distance	Auxiliary	Road Distance + Difference between road and rail distance	Km
Dimensionless conversion for total rail distance cost	Auxiliary	Rail Distance / Km unit	1

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Table A7 (*continued*)

Modal split			
Names	Type of variables	Equations	Units
Rail monetary value	Lookup	[(0,0) - (1500,90)], (1,7.03), (100,12.44), (200,17.91), (300,23.37), (400,28.84), (500,34.31), (600,39.77), (700,45.24), (800,50.7), (900,56.17), (1000,61.63), (1100,67.1), (1200,72.57), (1300,78.03), (1400,83.5), (1500,88.96)	Real
Total rail distance cost	Auxiliary	Rail monetary value (Dimensionless conversion for total rail distance cost)	Real
Positive or negative impact of rail saturation	Auxiliary	IF THEN ELSE ("Rail transport saturation" ≤ 1, −"Rail transport saturation", +"Rail transport saturation"/10)	1
Impact of railway saturation on freight rate	Constant	0.10	Real
Saturation of rail network cost	Auxiliary	Impact of railway saturation on freight rate* Positive or negative impact of rail saturation	Real
Railway economic instrument cost/Ton	Auxiliary	Impact of economic instruments on rail generalized cost * per ton	Real
External costs related to rail transport	Constant	0	Real
Railway transshipment cost	Auxiliary	18.56	Real
Dimensionless conversion for rail network density	Auxiliary	Rail network length/Km unit	1
Impact of rail network density on the amount of Km needed to be travelled by road	Lookup	[(0,0)-(80,000,60)],(0,0),(27,886.5,1e-05),(36,500,2.5),(80,000,5)	Km
Decrease in Km needed to access/egress transhipment point for railways	Auxiliary	Impact of rail network density on the amount of Km needed to be travelled by road (Dimensionless conversion for rail network density)	Km
Initial distance needed to access/egress transhipment point for railways	Constant	68	Km
Road transport to access/egress transhipment point for railways	Auxiliary	Initial distance needed to access/egress transhipment point for railways - ("Decrease on Km needed to access/egress transhipment point for railways")	Km
Dimensionless conversion for road transport to access/egress transhipment point for railway	Auxiliary	Road transport to access/egress transhipment point for railways/Km unit	1
Road distance cost (access/egress) for railway	Auxiliary	Road monetary value ("Dimensionless conversion for road transport to access/egress transhipment point for railway")	Real
Total road transport cost to access/egress transhipment point for railway	Auxiliary	Road distance cost (access/egress) for railway *"Cost to access point x 2 (access/egress)"	Real
Cost to access point x 2 (access/egress)	Constant	2	Dmnl
Total rail freight transport cost	Auxiliary	("Railway economic instrument cost/Ton" + Railway transhipment cost + Saturation of rail network cost + "Total road transport cost to access/egress transhipment point for railway" + Total rail distance cost + "External costs related to rail transport")	Real
Difference between road and waterways distance	Constant	0	Km
Waterways Distance	Auxiliary	Road Distance + Difference between road and waterways distance	Km
Dimensionless conversion for total waterways distance cost	Auxiliary	Waterways Distance / Km unit	1
Waterways monetary value	Lookup	[(0,0)-(1500,60)],(1,5.64),(100,8.79),(200,11.97),(300,15.15), (400,18.34),(500,21.52), (600,24.7),(700,27.88), (800,31.06), (900,34.25),(1000,37.43),(1100,40.61),(1200,43.79), (1300,46.98),(1400,50.16),(1500,53.34)	Real
Total waterway distance cost	Auxiliary	Waterway monetary value (Dimensionless conversion for total waterway distance cost)	Real
Positive or negative impact of waterway saturation	Auxiliary	IF THEN ELSE (Waterways transport saturation ≤ 1, -Waterways transport saturation, +Waterways transport saturation/10)	1
Impact of waterway saturation on freight rate	Auxiliary	0.10	Real
Saturation of waterway network cost	Auxiliary	Positive or negative impact of waterway saturation * Impact of waterway saturation on freight rate	Real
Waterways economic instrument cost/Ton	Auxiliary	Impact of economic instruments on waterways generalized cost*per ton	Real
External cost related to waterways transport	Constant	0	Real
Waterways transhipment cost	Auxiliary	20.61	Real
Dimensionless conversion for road network density	Auxiliary	Total amount of highway network length/Km unit	1
Impact of road network density on the amount of km needed to be travelled by road	Lookup	[(0,0)-(5e+06,10)],(0,0),(109,000,1e-05),(125,400,2),(500,000,3)	Km
Decrease in Km needed to access/egress transhipment point for waterways	Auxiliary	Impact of road network density on the amount of km needed to be travelled by road (Dimensionless conversion for road network density)	Km
Initial distance needed to access/egress transhipment point for waterways	Constant	113	Km
Road transport to access/egress transhipment point for waterways	Auxiliary	Initial distance needed to access/egress transhipment point for waterways - ("Decrease on Km needed to access/egress transhipment point for waterways")	Km
Dimensionless conversion for road transport to access/egress transhipment point for waterways	Auxiliary	Road transport to access/egress transhipment point for waterways/Km unit	1
Road distance cost (access/egress) for waterways	Auxiliary	Road monetary value("Dimensionless conversion for road transport to access/egress transhipment point for waterways")	Real
Cost to access transhipment point for waterways x 2 (access/egress)	Constant	2	Dmnl
Total road transport cost to access/egress transhipment point for waterways	Auxiliary	Cost to access transhipment point for waterways x 2 (access/egress) *"Road distance cost (access/egress) for waterways"	Real
Total waterways freight transport cost	Auxiliary	(Total waterways distance cost + "Total road transport cost to access/egress transhipment point for waterways" + "Waterways economic instrument cost/Ton" + Waterways transhipment cost + Saturation of waterways network cost + External cost related to waterways transport)	Real
Dimensionless exponent	Constant	1	Real
Road modal split	Auxiliary	(EXP(−Road freight transport cost/Dimensionless exponent) / ((EXP(−Total rail freight transport cost/Dimensionless exponent))+(EXP(−Road freight transport cost/Dimensionless exponent)) + (EXP(−Total waterways freight transport cost/Dimensionless exponent))))	Dmnl
Rail modal split	Auxiliary	(EXP(−Total rail freight transport cost/Dimensionless exponent) / ((EXP(−Total rail freight transport cost/Dimensionless exponent)) + (EXP(−Road freight transport cost/Dimensionless exponent)) + (EXP(−Total waterways freight transport cost/ Dimensionless exponent))))	Dmnl
Waterway modal split	Auxiliary	1- (Rail modal split + Road modal split)	Dmnl

Table A8
Sub-model: equations for CO_{2e} emissions.

CO_{2e} emissions			
Names	Type of variables	Equations	Units
Ratio of sustainable vehicles in waterway network	Auxiliary	Maximum number of sustainable vessels in the network per day / Daily number of vessel trips	1
Ratio of sustainable vehicles in road network	Auxiliary	Maximum number of sustainable vehicles in the network per day /Daily number of heavy vehicles in the network	1
Ratio of sustainable vehicles in rail network	Auxiliary	Maximum number of sustainable trains in the network per day/ Daily number of train trips	1
Amount of Tons Road	Auxiliary	Road volume * Road Distance	Km*Tons/Year
Road transportation CO_{2e} emission rate	Constant	52	gCO_{2e}/(Tons*Km)
Road transport CO_{2e} emission rate for sustainable vehicles	Auxiliary	Road transportation CO_{2e} emission rate * 0.75	gCO_{2e}/(Tons*Km)
Road emission coming from sustainable vehicles	Auxiliary	Road transport CO_{2e} emission rate for sustainable vehicles* Ratio of sustainable vehicles in road network	gCO_{2e}/(Tons*Km)
Road emission coming from normal vehicles	Auxiliary	Road transportation CO_{2e} emission rate * (1-Ratio of sustainable vehicles in road network)	gCO_{2e}/(Tons*Km)
Road CO_{2e} emission	Auxiliary	Amount of Tons Road*(Road emission coming from normal vehicles + Road emission coming from sustainable vehicles)	gCO_{2e}/Year
Amount of Tons Railways	Auxiliary	Rail volume * Rail Distance	Km*Tons/Year
Rail transportation CO_{2e} emission rate	Constant	18	gCO_{2e}/(Tons*Km)
Rail transportation CO_{2e} emission rate for sustainable vehicles	Auxiliary	0.75 * Rail transportation CO_{2e} emission rate	gCO_{2e}/(Tons*Km)
Rail emission coming from sustainable vehicles	Auxiliary	Rail transportation CO_{2e} emission rate for sustainable vehicles*Ratio of sustainable vehicles in rail network	gCO_{2e}/(Tons*Km)
Rail emission coming from normal vehicles	Auxiliary	Rail transportation CO_{2e} emission rate * (1-Ratio of sustainable vehicles in rail network)	gCO_{2e}/(Tons*Km)
Railway CO_{2e} emission	Auxiliary	(Rail emission coming from normal vehicles+ Rail emission coming from sustainable vehicles) * Amount of Tons Railways	gCO_{2e}/Year
Amount of Tons waterways	Auxiliary	Waterways volume * Waterways Distance	Km*Tons/Year
Waterways transportation CO_{2e} emission rate	Constant	11	gCO_{2e}/(Tons*Km)
Waterways transport C_{O2} emission rate for sustainable vehicles	Auxiliary	Waterways transportation CO_{2e} emission rate * 0.75	gCO_{2e}/(Tons*Km)
Waterways emission coming from sustainable vehicles	Auxiliary	Ratio of sustainable vehicles in waterways network* Waterways transport CO_2 emission rate for sustainable vehicles	gCO_{2e}/(Tons*Km)
Waterways emission coming from normal vehicles	Auxiliary	(1-Ratio of sustainable vehicles in waterways network) * Waterways transportation CO_{2e} emission rate	gCO_{2e}/(Tons*Km)
Waterways CO_{2e} emission	Auxiliary	Amount of Tons waterways*(Waterways emission coming from normal vehicles + Waterways emission coming from sustainable vehicles)	gCO_{2e}/Year
Total CO_{2e} Emission by inter-urban freight	Level	(Railway CO2e emission+Road CO2e emission+ Waterways CO2e emission)-CO2e Emission per year	gCO_{2e}
CO_{2e} Emission per year	Auxiliary	Total CO_{2e} Emission by inter-urban freight / SAVEPER	gCO_{2e}/Year
Year unit	Constant	1	Year
Dimensionless conversion to achieve goal	Auxiliary	Time/Year unit	1
CO_2 Emission decrease rate	Lookup	[(0,0) - (3000,80)], (2020,0.999), (2030,0.895), (2040,0.737), (2050,0.55), (2060,0.363), (2070,0.176)	Dmnl
Brazilian goal for freight emission	Auxiliary	CO_2 Emission decrease rate (Dimensionless conversion to achieve goal)	1
Reduction of CO_{2e} emissions level to achieve goal	Auxiliary	Initial value CO_{2e}*Brazilian goal for freight emission	gCO_{2e}/Year
Amount of CO_2 emission higher than Brazilian threshold	Auxiliary	CO_{2e} Emission per year - reduction of CO_{2e} emissions level to achieve goal	gCO_{2e}/Year
gCO_{2e} unit	Constant	1	gCO_{2e}/Year
Dimensionless conversion for policy measures	Auxiliary	Amount of CO_2 emission higher than Brazilian threshold/gCO_{2e} unit	1
Need to regulate C_{O2} emission	Lookup	[(−5e+12,0) - (7.5e+13,20)], (−5e+12,1), (2e+12,1), (2e+12,1.5), (4e+12,1.5), (4e+12,2), (6e+12,2), (6e+13,3)	Dmnl
Policy measures intensity	Auxiliary	Need to regulate CO_2 emission (Dimensionless conversion for policy measures)	Dmnl
Accumulated CO_{2e} emission from road	Auxiliary	Road CO_{2e} emission	gCO_{2e}/Year
Accumulated CO_{2e} emission from waterways	Auxiliary	Waterways CO_{2e} emission	gCO_{2e}/Year
Accumulated CO_{2e} emission from rail	Auxiliary	Railway CO_{2e} emission	gCO_{2e}/Year
Accumulated CO_{2e} emission from inter-urban freight	Level	Accumulated CO_{2e} emission from rail + Accumulated CO_{2e} emission from road + Accumulated CO_{2e} emission from waterways	gCO_{2e}

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