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Dynamics of freight transport decarbonization: A simulation study for Brazil

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ABSTRACT

Freight transport decarbonization is challenging due to the slow implementation of policies to meet climate goals. This paper analyzes the dynamics of the implementation of freight decarbonization measures. A System Dynamics model was developed and applied to the Brazilian freight system to simulate the use of more sustainable modes and means of transport, including electrification, increased use of biofuels, acceleration of fleet renewal, and modal shift. Significant emission reductions are found in the scenarios combining a shift to alternative modes and a rapid phase-out of diesel vehicles. Even so, the Brazilian freight sector's emission budgets towards limiting global warming to 1.5 °C and 2 °C will be depleted during the current and next decade, respectively. An absolute reduction of carbon emissions before 2050 seems unlikely. Besides confirming the need to study the dynamics of the freight system, the findings corroborate the urgency for stronger actions on freight decarbonization.

1. Introduction

Freight transport is the reflection of a strong economy. However, this sector also brings emissions, traffic, and congestion among other negative externalities. The International Transport Forum (ITF, 2021) estimates that freight transport emits >40% of all transport CO_2; and its share is growing slightly. According to the International Energy Agency (IEA, 2022), achieving a net zero emissions target by 2050 requires transport sector emissions to fall by about 20% by 2030. This drop, however, depends on a broad set of policies, such as the rapid electrification of road vehicles, operational and technical energy efficiency measures, the commercialization and scale-up of low-carbon fuels, and policies to encourage a shift to lower carbon-intensive modes of transport. Moreover, achieving the desired results requires articulating multiple stakeholders' interests to design and implement actions consistent with long-term decarbonization goals (Bataille et al., 2016).

As a dynamic complex system, freight transport has multiple agents making decisions that can impact the whole system through feedback responses. Regardless of the decarbonization strategy adopted, decision-makers must be aware that their policies, decisions, and actions may have significant second-order or rebound effects, leading to the need for a system-wide perspective (Ghisolfi et al., 2022b). Besides the impacts of such feedback effects, the system's dynamics are also determined by the combined speed of changes, i.

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e., the time that decisions take to be implemented and together take effect. For example, developing alternative fuel vehicles (AFV) is a relevant strategy for freight decarbonization, but knowing when the technologies will be adopted and used on a large scale, is critical for crafting more realistic timing of decarbonization targets and addressing the problem more efficiently.

Developing economies emerge as interesting cases to analyze, since the freight demand in these countries is expected to increase on a larger scale (ITF, 2019), while social, economic, and political constraints impose unique conditions for policy design, commonly with fragmented logistics operations, inadequate infrastructure, and a lack of proper policy making (Díaz-Ramirez et al., 2017). Within the current commitments of the Brazilian Government to international agreements, in terms of emissions reductions, some policy initiatives have been implemented. Yet, the question "How does the implementation of policies need to be phased in time, to achieve the sector's decarbonization targets?" has remained unanswered. Even for other countries, no literature addresses this question. This study aims to investigate the effect of time of implementation of decarbonization policies focusing on sustainable fleets and alternative modes in freight transport.

To do so, we have taken a systems approach that focuses on the dynamics and interdependencies among policies and decisions made at different points in time. System Dynamics (SD) modeling stands out due to its adequacy for investigating the impact of policies and strategies over continuous time considering the dynamic complexity of feedback-structured systems (Abbas and Bell, 1994; Maalla and Kunsch, 2008; Shepherd, 2014).

The remainder of this paper is organized as follows. Section 2 brings a literature review of different approaches that address the dynamics of the freight transport system and justifies the choice of the methodology for this research. Section 3 presents the background of the case study and the interviews conducted with experts. Section 4 presents the model in detail, the data used, the model tests, and the uncertainty analysis. Section 5 presents the set of policy scenarios that were evaluated and the results of the simulations. Section 6 discusses the main results while Section 7 presents the conclusions and indicates future research directions.

2. Literature review

Dynamics are generally defined as changes within a system or process over time and a driving force for the growth or development of a system. The need to understand the dynamics of freight systems has grown in importance since policies are being formulated to help mitigate climate change and achieve time-definite objectives for decarbonization (Kikstra et al., 2022). To evaluate the effectiveness of policies, a basic understanding is needed of the dynamics of logistics decision making. However, such knowledge is still largely lacking (Tavasszy, 2020). This paper aims to model the dynamics of a limited number of rudimentary decisions on which the success of decarbonization policy depends, to allow an empirical treatment of the aggregate system. These decisions concern a change of fleets towards sustainable energy sources and the adoption of different modes of transport.

To model the dynamics of the system, we can take different approaches such as time series models, agent-based modeling (ABM), and system dynamics (SD). In empirical economic analysis, for example, time series models describe relevant links among observations through time, mainly used for forecasting future values (Gourieroux and Monfort, 1997). ABM, in turn, is a stochastic bottom-up event-driven modeling approach, based on a set of agents and sequential interaction rules. ABM models can express and characterize heterogeneity, including spatial interactions within and between agents (Maidstone, 2012). SD is a deterministic, top-down modeling approach that describes systems from a broader perspective, focusing on dynamic complexity that arises from the system's structure, feedback, and time lags (Shepherd and Emberger, 2010). The SD approach largely depends on assumptions about the homogeneity of modeling entities (Teose et al., 2011), and it is used for policy analysis and design in systems with information feedback, interdependence, and mutual interaction (Lewe et al., 2014). As such, SD provides a structured framework, through which large-scale systems can be modeled, analyzed, and tested (Abbas and Bell, 1994; Shepherd, 2014). This method evidences the relationship between interrelated variables (cause and effect) and demonstrates the impact of variables that change in different timeframes.

A limited number of studies have empirically addressed the time dimension in freight transport system models before. Di Febbraro et al. (2016) proposed a dynamic model for a freight delivery plan which is applied until an external event occurs and a new freight delivery plan is needed. To improve the financial model of an urban distribution center, Van Duin et al. (2012) investigated a dynamic fee for its usage. Anand et al. (2014) developed an ABM for analyzing the urban freight delivery processes, implementing a last-minute order scenario, which reduces the number of trucks and the total distance traveled in the urban system. Schröder and Liedtke (2017) used a multi-agent simulation in which congestion effects are fed back into the demand models. Agents can evaluate their plans with utility/cost functions and choose a different route, transport mode, departure times, or vehicle. Reis (2018) proposed an ABM of a freight transport market in which agents interact through simulated auctions of transport contracts with a dynamic price calculation mechanism to simulate agents' specific pricing strategies. Gatta et al. (2020) developed an ABM to simulate the optimal last-mile delivery process from the supermarkets to final consumers to evaluate the potential of e-grocery adoption. Anand et al. (2021) investigated a dynamic carbon abatement fee to motivate carriers to use sustainable vehicles. The above models mainly provided insights into the dynamic behavioral interaction between stakeholders in city logistics. Ferrari (2014) presented a dynamic modal split in a national multimodal freight transport system, which assumes that the evolution over time of transport demand is accompanied by a corresponding evolution of the transport mode characteristics. Lepitzki and Axsen (2018) developed a dynamic vehicle choice model to simulate how heterogeneous consumers purchase different vehicle technologies based on capital, energy, maintenance, and intangible costs. Regarding SD models, early research by Abbas and Bell (1994) discussed and evaluated their strengths and weaknesses in terms of suitability for modeling transport systems. As transport problems require ways of integrating knowledge as well as including long/short-term trade-offs, SD modeling is suitable for addressing strategic studies that are concerned with policy, analysis, and decision making as reviewed by Shepherd (2014).

Concerning the freight emissions problem, Ghisolfi et al. (2022a) reviewed SD models covering decisions about transport demand management, mode choice, assets capacity utilization, use of energy-efficient technologies, and alternative fuels. The authors concluded that the SD models referring to freight transport decarbonization have strict limits to represent the system and lack transparency regarding time-definite policy implementation. This is an issue since time is crucial to evaluate the potential and success of policies for achieving decarbonization targets within defined timeframes. In this context, Ghisolfi et al. (2022b) presented a broad qualitative model that integrates five decarbonization strategies, showing the importance of policymakers approaching decarbonization collaboratively and systemically, avoiding their actions being offset due to rebound effects within the system. Nassar et al. (2023) analyzed the empirical time factors related to the choice and change of transport mode in a Brazilian case study. The broader framework for decarbonization as presented in Ghisolfi et al. (2022b) has, however, not yet been translated into an empirical model. The proposed model aims to help fill this gap, with a focus on the use of more sustainable means of transport, via fleet renewal and modal shift. This constitutes the next step towards a model with a system-wide perspective, deepening the knowledge about the temporal factors relevant to the decarbonization of the entire freight system.

Within the above context, this study proposes an SD model to analyze the impact of decarbonization policies made at different points in time over the reduction of freight transport emissions. SD was the chosen method since we aim to analyze policy decisions in a large-scale system that explicitly considers the dynamics of the system's multiple feedback loops. The next section introduces the context of the Brazilian, largely road-based, freight system.

3. Empirical context: freight transport in Brazil

The fifth largest country in the world, with an area of 8.5 million square kilometers, and being one of its largest agricultural producers, Brazil has the challenge of creating and maintaining an immense transport network to ship its products whilst simultaneously supporting the mobility of its population. The system of Brazilian freight transport flows is heavily based on roadways, compared to other major regions, as shown in Fig. 1.

With over 60% of freight (tkm) being shipped through roadways, Fig. 1 suggests a great opportunity for Brazil to mitigate the emissions from freight transport, by investing in less emission-intensive (ton CO_2/tkm) transport modes such as railways and waterways. Table 1 shows the share of energy source per mode in the freight sector.

According to the Brazilian Greenhouse Gas Emissions and Removals Estimation System (SEEG, 2020), freight transport was responsible for 40% of the 196.5 million tons of CO_{2e} emitted by the whole transport sector in 2019. Brazil has established several policies to encourage the production and use of biofuels, such as the National Program for the Production and Use of Biodiesel (PNPB), the National Alcohol Program (Proalcool) in the 1970s, and, more recently, RenovaBio, which came into force at the beginning of 2020. This way, the country has placed itself among the largest producers and consumers of biofuels in the world. These policies were driven mainly by energy security issues. Also noteworthy is the Rota 2030 Program – Mobility and Logistics, launched in 2018, which establishes a series of energy efficiency, safety, and sustainability obligations for the automotive sector, with tax benefits as a counterpart for those who adhere to the program (MME and EPE, 2020).

To provide a conceptual foundation for our quantitative modeling, qualitative insights were gathered from stakeholders about their related logistics decisions. We interviewed six freight forwarders from the road transport sector based in Brazil to better understand the dynamics of their alternative fuel vehicle choices. This group of stakeholders was prioritized since they had the final decision on which alternative fuel vehicle to purchase. The participants were chosen since their companies are already planning, testing, or including alternative technologies in their truck fleets. Moreover, we also interviewed a project manager of a technological innovation program for the automotive sector in Brazil (FUNDEP, 2023). The companies interviewed have fleets that range from 10 to 200 vehicles with an average age between three and nine years. Semi-structured interviews allowed the interviewees to add their perspectives and experiences, also encouraging them to raise issues that were not included initially in the interview schedule (Figgou and Pavlopoulos, 2015). The interviews were carried out in May and June 2022 through virtual meetings with each interviewee individually, with an average duration of one hour. To ensure that interviewees provided honest and unbiased opinions, we committed to keeping their identities and affiliations confidential. The interviews focused on identifying and understanding the main time lags in the buying

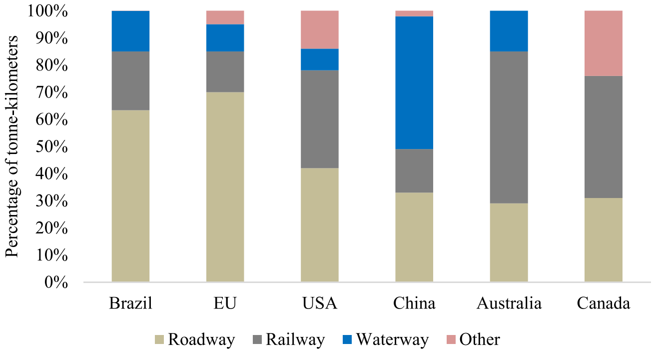

Fig. 1. Freight transport modal division in different regions of the world.
Source: Energy Research Company – EPE (2022); ITF (2022).

Table 1
Energy use per mode in the freight transport sector in 2020.

Mode	Energy source	Brazil (%)	EU (%)	USA (%)	China (%)
Road	Fossil fuel (diesel, CNG)	90	93	95	88.5
	Biodiesel	10	6.5	5	5.5
	Electricity	–	0.5	–	4
	Other	–	–	–	2
Railways	Fossil fuel (diesel)	90	54	95	28.5
	Biodiesel	10	1	5	1.5
	Electricity	–	45	–	70
Inland waterways	Fossil fuel (diesel, fuel oil,gasoline)	100	100	100	100

Source: MME and EPE (2022a), ACEA (2023), IEA (2023), European Biodiesel Board (2023), US Department of Energy (2023), Mao and Rodriguez (2022), Liu and Lin (2021), DieselNet (2019), and Geilenkirchen et al. (2023).

decision process of alternative fuel vehicles.

The analysis confirmed the need to better understand the user's dynamic perspectives, comprehend what they consider necessary when choosing new vehicles, how they include technology innovation and sustainability into their strategic planning, and how willing they are to shift from one technology to another. The interviews also addressed which factors contribute to the decision-making process and raised new insights into the timing for alternative fuel vehicle adoption by early adopter companies.

The review of strategic decisions on fleet management occurs every six months in all companies interviewed. The criteria for the replacement and acquisition of new vehicles by carriers can be seen in Table 2.

The main factors that influence the vehicle's scrapping are the mileage traveled and its age. The cost of vehicle maintenance is also a concern for managers, and it is considered important in the decision to change the truck model. The factors that influence the choice and acquisition of new vehicles are purchase cost, maintenance cost, and efficiency. However, the refueling/recharging facilities, brand, and embedded technology were also indicated.

The companies interviewed are in the process of planning for acquisition or have already acquired alternative fuel vehicles such as trucks powered by biomethane or compressed natural gas (CNG) and electric vehicles for urban delivery. Such companies are members of the Brazilian Green Logistics Program (PLVB, 2023), seeking a commitment to corporate social-environmental responsibility. Table 3 shows technologies and acquisition times (real or estimated from the beginning of the planning process to the actual purchase of the vehicle) by each company.

The reported interviews have been important in deepening knowledge about the barriers, challenges, and difficulties faced by the road freight sector in the adoption of alternative fuel vehicles in Brazil. Regardless of the size of the companies interviewed and the territorial scope in which they operate, two main problems were highlighted by all of them: the high purchase cost and the difficulty in recharging/supplying. Some companies install their solar power system, given the economic unfeasibility of using the conventional electrical grid, in addition to the scarce or complete absence of public charging points. For long-distance transport, the use of CNG or biomethane is also restricted by the availability of refueling stations along the routes due to the logistical difficulties of transporting these gases. The acquisition time of alternative technologies by the companies interviewed must be analyzed considering that they are early adopters and that they act without the collaboration of other sectors, although the last is considered imperative for the introduction of new technologies on a large scale in the market, such as the energy, regulatory, and infrastructure sectors. We believe that, as these sectors become involved in the process and facilitate access by transport companies, the technologies' acquisition times will be reduced. However, uncertainty remains about the time frame for the involvement of other sectors.

4. The system dynamics model

The approach used to model the dynamics of freight transport decarbonization policies is based on an SD conceptual model represented through causal loop diagrams, as presented recently in Ghisolfi et al. (2022b). This conceptual model is composed of five submodels, each one representing the dynamics of a specific decarbonization strategy: reducing freight transport demand, shifting freight to low carbon-intensity modes, improving vehicle utilization, increasing energy efficiency, and promoting new energy sources. In terms of its dynamics, however, in the present model, we focus only on two decarbonization strategies: the mode shift and fleet renewal (for promoting new energy sources). Freight transport demand is an input based on historical series; vehicle utilization is constant, based on an input that accounts for the transport activity carried out by the vehicles; and, finally, the energy efficiency of vehicles has also been assumed known and fixed. The policy levels modeled relate to the strategies of shifting freight to low carbon-intensity modes, and to promoting new energy sources. These have the potential to change the dynamics of the system toward faster decarbonization. The choice of the strategy regarding new energy sources was made because it is the only policy measure that can deeply decarbonize the freight system, as long as the energy sources are clean, while the other four strategies can only mitigate freight emissions.

The simulation model is organized into three interconnected submodels, as presented in the next subsections, each one with its stock and flow diagram and its main flow equations. All detailed equations can be found in Appendix A.

Table 2
Factors that influence scrapping and the purchase of new vehicles.

Factors		**Carriers**					
		1	**2**	**3**	**4**	**5**	**6**
Vehicle replacement	Mileage	x	x			x	x
	Age	x		x	x	x	
	Maintenance cost					x	x
Purchase of new vehicles	Purchase cost	x	x	x		x	
	Maintenance cost	x		x	x	x	x
	Energy efficiency		x	x	x	x	x
	Refueling facilities				x		
	Brand	x					
	Embedded technology						x

Table 3
Times of acquisition/adaptation of each alternative fuel vehicle.

		Carrier 1	Carrier 2	Carrier 3	Carrier 4	Carrier 5	Carrier 6
Alternative energy source	CNG/ biomethane	x*			x		x
	Electricity		x*	x*		x	x
Acquisition time (months that it will take to obtain the vehicles)		24	12	24	24	1	8

* In the process of planning for acquisition. In these cases, the time is estimated.

4.1. Transport modes

The first submodel aims to simulate the modal share and the fleet size based on the activity assigned to each transport mode. Fig. 2 shows the stock and flow diagram of this submodel. Input parameters are marked in orange and experimental parameters are presented in blue.

The simulation starts with the stock and flow variables regarding the yearly freight transport activity, measured in tonne-kilometers (tkm),[1] which depend on the freight transport activity of the initial year of the simulation, in addition to an average percentage of the future variation, based on historical series (EPE, 2022).

The next step is the modal split, simulating the percentage of freight that will be carried by roadways, railways, or waterways. In our context, this is based on Brazilian's National Logistics Plan – NLP 2035 (Ministry of Infrastructure and EPL, 2021) which, by predicting a set of investments in national logistics infrastructure over the next years, simulates scenarios with different levels of achievement of the proposed goals, and consequently the use of the modal matrix. The NLP 2035 is then an infrastructure investment plan, which is modeled here by a ramp function. This function smoothly changes the variable value; its use is common in situations where it is necessary to simulate an increasing or decreasing flow that is not constant over time (Abidin et al., 2014). The ramp function assigns zero to the variable until the beginning of its behavior change. After this period, the curve changes the variable value until it reaches a predicted value and then remains constant. Thus, this function allows the simulation of the adaptation period of new policies (Coyle, 1996). During the simulation period, the level of NLP 2035 implementation starts in 2020 and will increase linearly until it reaches 100% by 2035. Therefore, the NLP is defined in Equation (1).

$$policies\ towards\ alternative\ modes = RAMP\ (0.067,\ 2020,\ 2035) \tag{1}$$

Based on the initial percentage and the NLP projections for the modal share, an S-shaped curve represents the relationship between the modal share and the level of NLP implementation. As highlighted before, each projection of NLP considers a set of logistics infrastructure investments, i.e., on strategic railway corridors, waterways, ports, multimodal integration, etc., which have the potential to change the modal share of the freight transport system. The dependency between the NLP implementation and the modal share is modeled through an S-shaped curve with the general form of Eq. (2).

$$modal\ share = a \times \tanh(b \times (NLP + c/b)) + d \tag{2}$$

where a determines the vertical stretch or compression (difference between the maximum and minimum of each mode share) as well as establishes if the curve is increasing or decreasing (i.e. the road share will decrease from 63% to 32% and rail share will increase from 22% to 47%); b determines the speed of change or the linear response of the curve (i.e. how quickly or slowly each mode share will change); $\frac{c}{b}$ determines the horizontal translation of the curve with respect to the standard function of $tanh(x)$, which was assumed to be

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[1] Tonne-kilometers (tkm) – unit of measurement of goods transport which represents the transport of one tonne of goods over a distance of one kilometer.

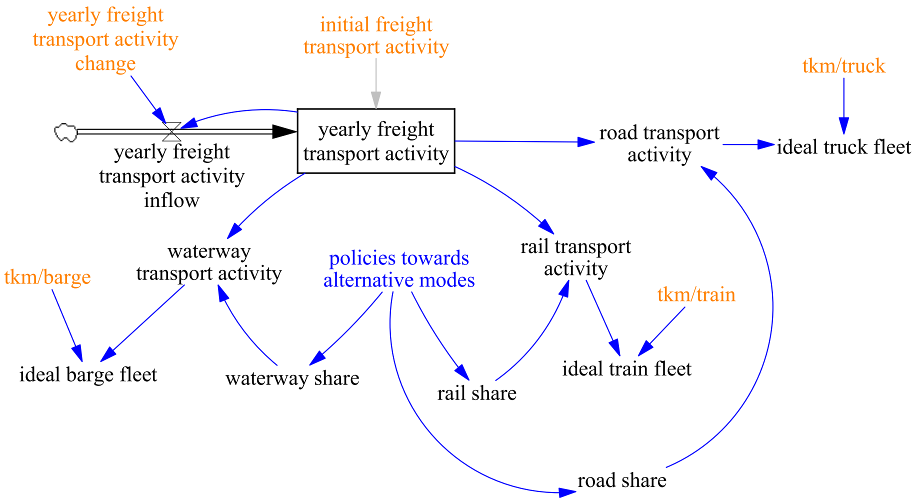


Fig. 2. Transport modes submodel.

−0,5 for all modes and scenarios, which means that the inflection point will occur at 50% of the policies implementation; *d* determines the vertical translation of the curve with respect to the standard function of $tanh(x)$, representing the expected value halfway through the policy implementation (i.e. rail share has to increase from 22% to 34%, *d* will be $((34 + 22)/2) = 28\%$); and *NLP* represents the policies toward alternative modes, which is a percentage of its implementation (0% refers to no implementation and 100% refers to the full implementation).

The choice of the sigmoid function to represent the mode share is due to the behavior of policy implementation where we have a concentrated interval of linear response between two phases of slower, bounded change, as commonly observed in SD (Sterman, 2000) and already applied in transportation studies (Fontoura et al., 2019, 2020; Georgiadis and Vlachos, 2004). Moreover, it lets us assume that half of the percentage change of a mode share will occur at 50% of policy implementation. Furthermore, we selected the parameter *b* under the assumption that the most significant change will happen between 40% and 60% of the policies implementation or about three years, according to the Ramp function (Eq. (1)).

As an example, a curve for the modal share is illustrated in Fig. 3. All the scale parameters for the modal share for all scenarios are provided in Appendix B.

Given the freight transport activity forecast and the percentage of freight being transported by each mode, we have the freight transport activity by mode. The next step is to simulate the fleet sizes of trucks, trains, and barges. As an example, the truck fleet is given by Eq. (3).

$$(ideal\ fleet)_m = \frac{(transport\ activity)_m}{(transport\ activity/vehicle)_m} \tag{3}$$

where $ideal\ fleet_m$ is the ideal fleet of mode *m*; $transport\ activity_m$ is the total transport activity measured in tkm carried out by mode *m*; $transport\ activity/vehicle_m$ is the amount of transport activity measured in tkm carried out by one vehicle of mode *m*.

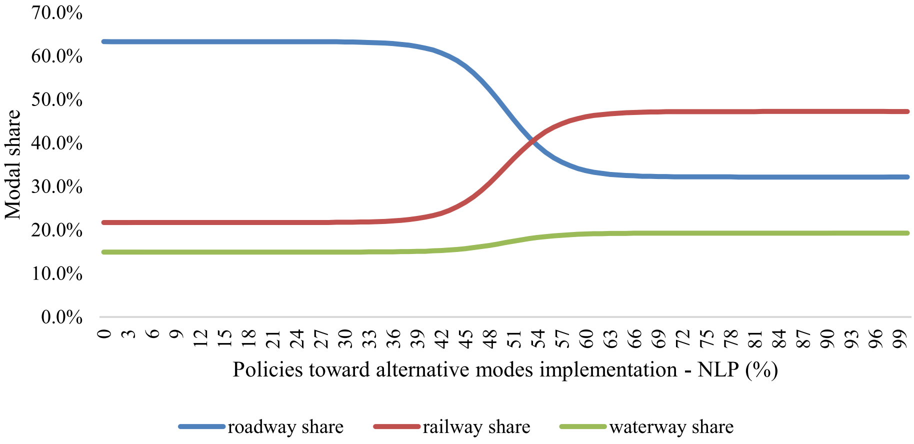


Fig. 3. Relationship between modal share and policies toward alternative modes.

The variable *transport activity*/*vehicle*$_m$ represents the efficiency index to be maintained concerning fleet usage. Such indexes assume that the vehicles will perform the same level of transport activity in the future. To calculate these input data, we have used the historical series of transport activity (tkm) by mode given by EPE (2022), the historical series of the road fleet given by SINDIPEÇAS and ABIPEÇAS (2022), and the historical series of the rail and waterway fleets obtained from the CNT Transport Yearbook (CNT, 2021). The results are used in the Fleet renewal submodel, as described in the following.

4.2. Fleet renewal

The second submodel aims to simulate the market share of different options of vehicle technology and fuels that will integrate the fleet of each transport mode. The total fleet is composed of vehicles already in the market at the beginning of the simulation (2020), powered by fossil fuels, and vehicles of each mode sold in 2020 onwards, assumed to be gradually powered by alternative fuels, according to Table 9.

In Fig. 4, each stock represents the sum of the trucks of a certain age group (six-year range) already in the market that was still being used in 2020. The age distribution of the active fleet of trucks, locomotives, and barges in the first year of the simulation is given by SINDIPEÇAS and ABIPEÇAS (2022), BNDES (2014) and CNT (2021), respectively.

There are two policy-related variables: “speed up fleet renewal-policy control” and “policies toward speeding up fleet renewal”. The first one assumes zero or one, according to the scenario where these policies are active (being implemented) or not. The second one is given by Equation (4). Such policy is based on the Brazilian Road Fleet Productivity Increase Program (Renovar Program), legalized by Decree No. 11276/2022 (Ministry of Economy, 2022). This decree aims to encourage, voluntarily, the withdrawal of vehicles that do not meet the current technical standards or that are >30 years old. We have assumed that this policy can be applied in different time ranges, for example, between 2020 and 2025 as in Eq. (4). Other time ranges for this policy implementation are part of the scenario simulation.

$$policies\ toward\ speeding\ up\ fleet\ renewal = RAMP\ (0.2,\ 2020,\ 2025) \tag{4}$$

If the policy towards speeding up fleet renewal is applied, the truck’s scrappage rate will be accelerated by this policy, otherwise, it will occur at the normal scrappage rate (Eq. (5)), calibrated by the Brazilian National Traffic Department – DENATRAN (Ministry of the Environment, 2014) using average age and total fleet data.

$$S(t) = 1 - \left[\frac{1}{1 + exp(a(t - t_0))} + \frac{1}{1 + exp(a(t + t_0))}\right] \tag{5}$$

where $S(t)$ is the portion of scrapped trucks; t is the trucks’ age in years; t_0 is 17.0 for trucks; and a is 0.10 for trucks.

Together, the previous parameters signal 90% of fleet renewal in 40 years. Complete truck fleet renewal would take up to 60 years. Given the Brazilian lack of data for the locomotive scrappage rate, we have used the function defined by Green et al. (2004) regarding the American locomotive fleet, as shown in Eq. (6).

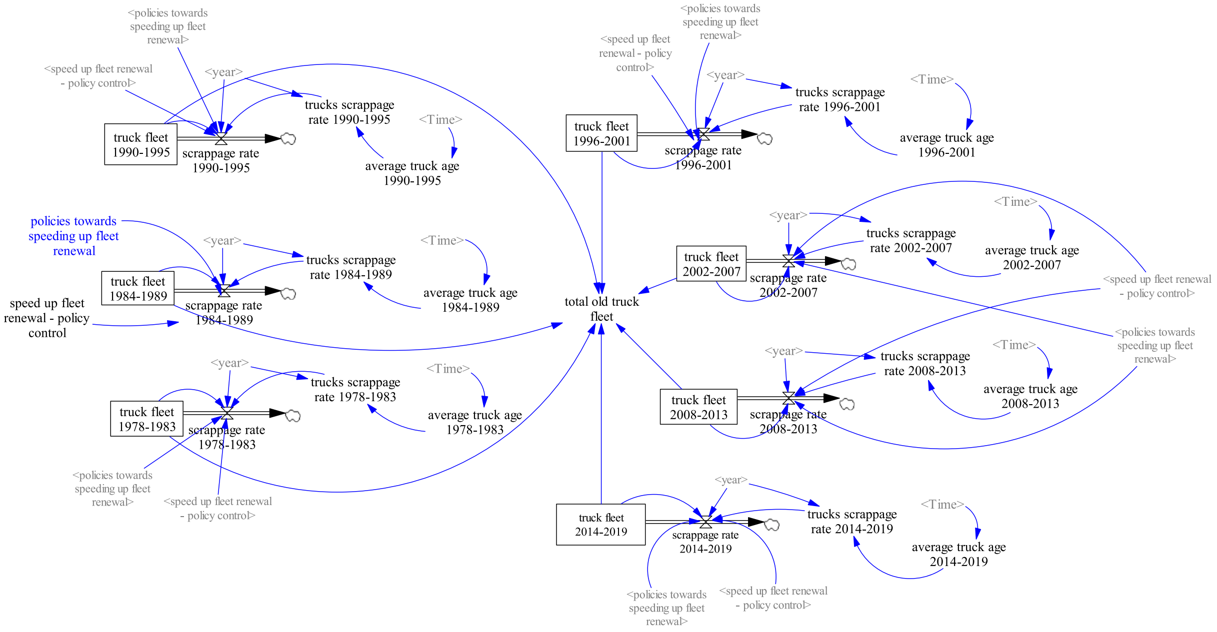


Fig. 4. Total existing truck fleet. (The shadow variables (in gray) have been defined in other parts of the diagram and are used to let it visually clean, besides connecting different submodels (placed in different views).)

$$S(t) = 1 - \frac{EXP\left(\frac{b-t}{a}\right) + EXP\left(\frac{2b-t}{a}\right)}{EXP\left(\frac{b}{a}\right) + EXP\left(\frac{2b-t}{a}\right)} \tag{6}$$

where $S(t)$ is the portion of scrapped locomotives; t is the locomotive's age in years; a is 7.971970; and b is 25.45011.

90% of the locomotive fleet would be scrapped in 43 years, while the complete renewal would take >60 years. The same lack of data occurs for the Brazilian barge fleet, which leads us to use the ship fleet scrappage function defined by Held et al. (2021), shown in Eq. (7).

$$S(t) = 1 - (1 + exp(a1 \times t - a2))^{-b} \tag{7}$$

where $S(t)$ is the portion of scrapped barges; t is the barge's age in years; $a1$ is 0.4105; $a2$ is 9.2562; and b is 0.2320.

These parameters mean that 90% of the barge fleet would be scrapped in 47 years, and the total barge fleet renewal would take up to 70 years. Qualitatively, Eqs. (5)-(7), behave as sigmoid functions, as shown in Fig. 5.

The fleet scrappage leads to the need for vehicle replacement over time. This fleet renewal process is modeled by the aging chain mechanism, which is used to represent situations where the outflows of items in a stock and flow structure are age-dependent and allow to model changes (through inflows and outflows) of any intermediate stock of the aging chain structure (Sterman, 2000). Thus, we have assumed that the rate at which companies discard and replace their fleets depends on the age of their vehicles and that the scrappage rates are based on the probabilities given by Eqs. (5)-(7).

Fig. 6 shows the aging chain structure for the truck renewal process. The chains for other modes follow the same structure. The truck fleet Inflow (at the left of Fig. 6) indicates the purchase of new vehicles, based on the total fleet, and the fleet to meet the freight transport demand. The next step involves the simulation of the share of each vehicle's propulsion technology through the variable "policies toward truck alternative fuels", highlighted in blue in Fig. 6.

From 2020 onwards, the vehicle fleet is split between different powering systems, separated in the diagram by the stock and flow chains for each fuel vehicle type. Regarding trucks, the policy is based on BCG and ANFAVEA (2021) which claims that the decarbonization of the automotive sector in Brazil will be driven by several forces, such as tighter regulations, pressure from investors and customers, industry and technology development, increased availability of infrastructure and reduced total cost of vehicle ownership.

During the simulation period, the level of policy implementation will increase linearly to reach 100% by 2035, as defined in Eq. (8).

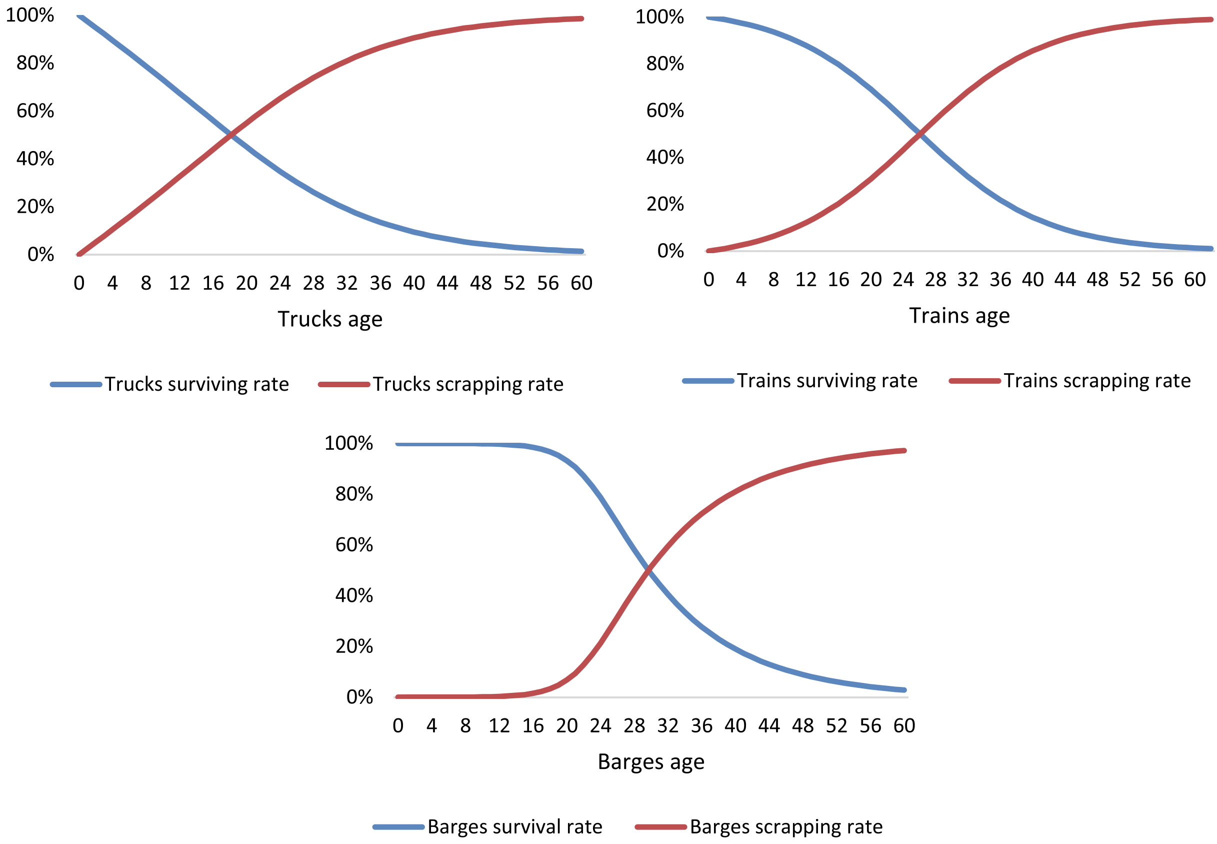


Fig. 5. Survival and scrapping rates of trucks, trains, and barges.

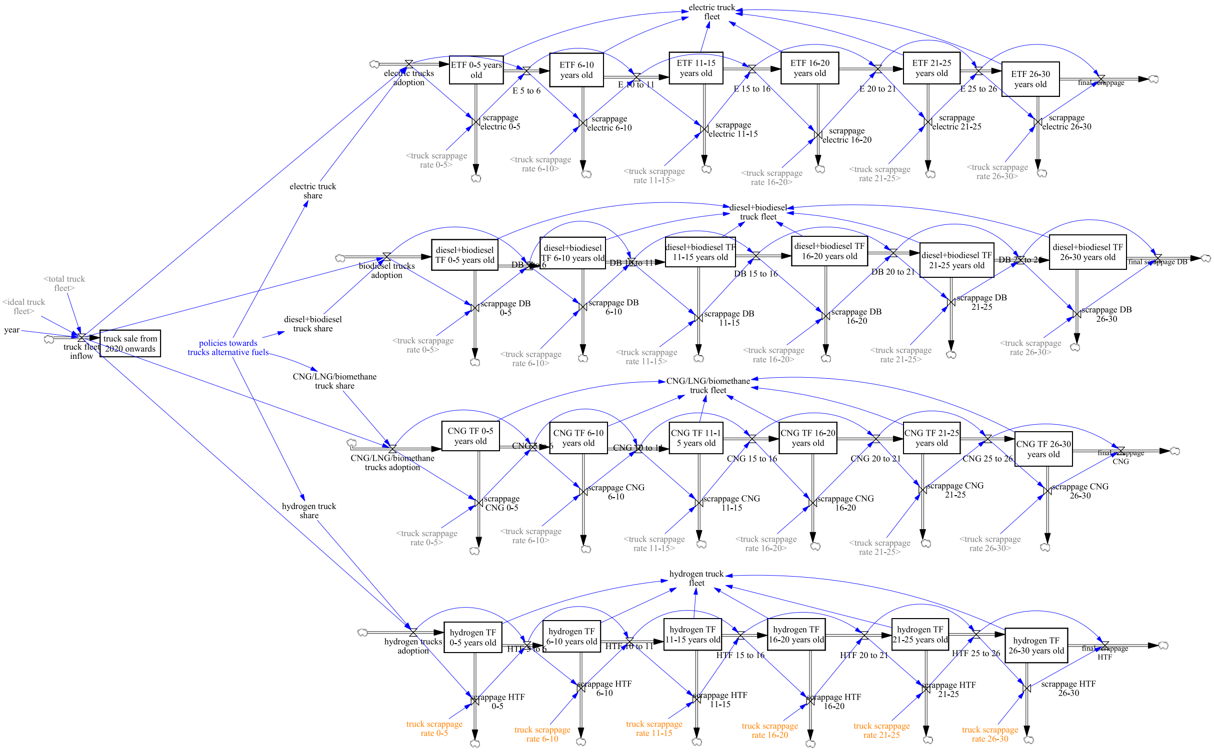


Fig. 6. Aging chain structure for the fleet renewal process.

$$\textit{policies toward truck alternative fuels} = \textit{RAMP}\ (0.067,\ 2020,\ 2035) \tag{8}$$

The scenarios predicted by BCG and ANFAVEA (2021) foresee the introduction of alternative fuels (natural gas/biomethane, electricity, and hydrogen) at different rates. They also project increasing percentages of biodiesel in diesel blends. In the model, these projections are modeled by an S-shaped curve (similar to the general Eq. (2) that represents the relationship between the fuel share and the level of policy implementation, as shown in the example of Eq. (9) for electric trucks. The other equations and parameters are presented in Appendix B as they are not essential to the understanding flow of the study but were made available for its replicability.

$$\textit{electric truck share} = 0.035 \times \tanh\ (15 \times \textit{policies towards truck alternative fuels} - 7.5) + 0.035 \tag{9}$$

For trains and barges, there are no studies or government plans for such policies toward alternative fuels. However, we considered independent initiatives announced by some concessionaires to simulate a scenario in which all modes are changing to a more sustainable outline. The projections of the share of energy sources for trucks, trains, and barges are presented in Section 5.1. Each year, newly sold vehicles enter the first stock of the aging chain (Fig. 6) and remain there for five years, being scrapped according to the

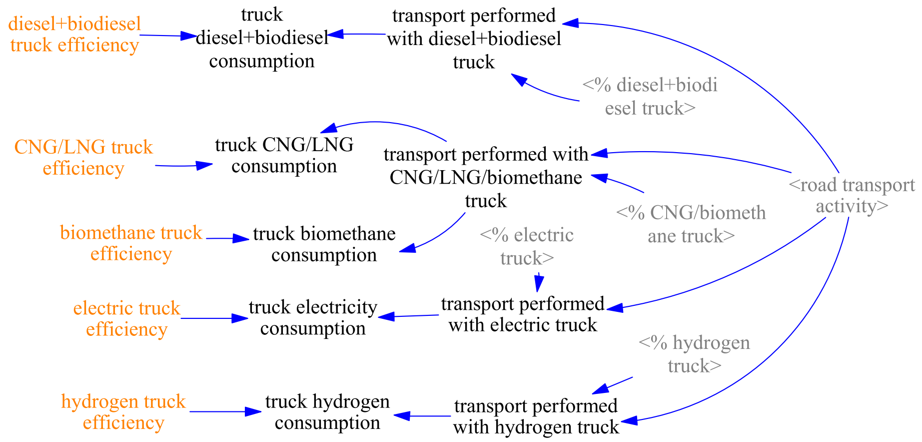


Fig. 7. Energy consumption submodel – trucks fleet.

respective scrapping rate probability. The flow variables linking the stocks are defined as a fixed delay function that ensures that vehicles only go to the next age group’s inventory at the end of five years. With the total fleet and the fleet technology share, the next submodel simulates energy consumption and emissions from the freight transport sector.

4.3. *Energy consumption and emissions*

The last submodel simulates the consumption of each type of fuel/energy and emissions, using the results of the previous submodels, referring to the freight transport activity by mode and percentage of each vehicle’s technology in the fleet. We have assumed that the amount of transport activity performed by each vehicle technology will be proportional to their fleet market share. Fig. 7 shows the diagram related to the energy consumption of the truck fleet.

The energy consumption is given by the transport activity performed with each type of fuel vehicle and its efficiency, as shown by Eq. (10).

$$c_{m,k} = T_{m,k} \times EE_{m,k} \tag{10}$$

where $c_{m,k}$ represents the fuel/energy consumption of mode m and propulsion technology k; $T_{m,k}$ represents the transport activity performed by mode m and propulsion technology k; and $EE_{m,k}$ represents the energy efficiency performed by mode m and propulsion technology k.

Fig. 8 shows the diagram to simulate the CO_{2e} emissions from the road mode. Similar diagrams were built to simulate the emissions from railways and waterways.

The emissions inflows are given by the fuel/energy consumption and the related CO_{2e} emission factor, as shown in Eq. (11).

$$E_{m,k} = c_{m,k} \times e_{m,k} \tag{11}$$

where $E_{m,k}$ represents the emissions from mode m and propulsion technology k; $c_{m,k}$ represents the fuel/energy consumption of mode m and propulsion technology k; and $e_{m,k}$ represents the emission factors of the fuel/energy of mode m and propulsion technology k.

Emissions rates are accumulated in a stock variable for each transport mode. Then, the emissions stocks are aggregated to estimate total emissions from freight transport. The data regarding efficiency and emission factors for each vehicle type and propulsion energy are given in Table 4. We have considered well-to-wheel emission factors.

The last part of the model, shown in Fig. 9, simulates a “check if” variable by comparing the total freight emissions with estimated budgets for the sector.

The “check if” is a binary variable that shows if the Brazilian freight emissions are within or beyond the defined emissions limits over time, as defined in Eq. (12).

$$\mathit{check\ if\ within}\ 1.5^{\circ}C\ \mathit{emissions\ budget} = \mathit{if\ then\ else}\ (\mathit{total\ freight\ emissions} < \%\ \mathit{budget}\ 1.5^{\circ}C\ \mathit{Brazilian\ freight}, 1, 0) \tag{12}$$

Given the absence of a target to reduce emissions from the Brazilian freight transport sector, the budgets are estimated based on the percentage of Brazilian freight emissions out of the global CO_2 emissions, and the CO_2 emission budgets for limiting global warming to 1.5 °C or 2 °C by 2050. Eq. (13) presents the definition of such a budget for limiting global warming to 1.5 °C. The budgets of the Brazilian freight transport sector are proportional to its percentage of emissions in 2020. The input data is shown in Table 5.

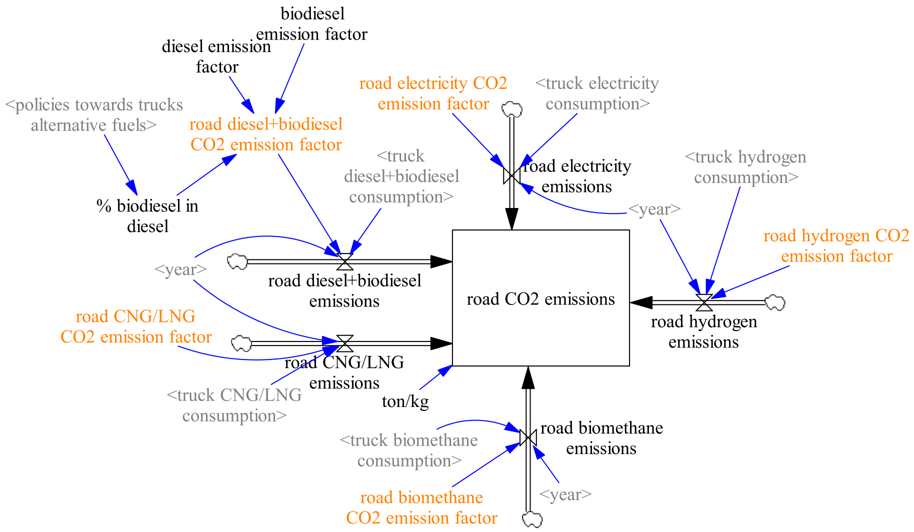


Fig. 8. Emissions submodel – trucks fleet.

Table 4
Efficiency and CO_{2e} emission factor for vehicles and propulsion energy options.

Vehicle	Propulsion energy	Energy efficiency factor	Source	CO_{2e} emission factor	Source
Truck	Diesel	0.0577 l/tkm	MME et al. (2020)	5.716 kg/l	MME and EPE (2022b)
	Biodiesel	0.0577 l/tkm	MME et al. (2020)	0.811 kg/l	MME and EPE (2022b)
	CNG	0.0629 m^3/tkm	MME et al. (2020)	6.072 kg/m^3	MME and EPE (2022b)
	Biomethane	0.0629 m^3/tkm	MME et al. (2020)	0.582 kg/m^3	MME and EPE (2022b), Ferreira (2022)
	Electricity	1.35 kWh/tkm	Mercedes-Benz (2022), Volvo (2022)	0.114 kg/kWh	MME and EPE (2022b)
	Hydrogen	0.10 kg/tkm	Hyzon (2022)	4.9 kg/kgH2	World Economic Forum (2023)
Train	Diesel	0.0047 l/tkm	EPL and IEMA (2021)	5.782 kg/l	MME and EPE (2022b), GHG Protocol (2021)
	Biodiesel	0.0047 l/tkm	EPL and IEMA (2021)	0.799 kg/l	MME and EPE (2022b), GHG Protocol (2021)
	Electricity	53.1 Wh/tkm	Ćwil et al. (2021)	0.114 kg/kWh	MME and EPE (2022b)
Barge	Diesel	0.0038 l/tkm	EPL and IEMA (2021)	5.792 kg/l	MME and EPE (2022b), GHG Protocol (2021)
	Fuel oil	0.0038 l/tkm	EPL and IEMA (2021)	3.31 kg/l	Smart Freight Centre (2019)
	Electricity	28 Wh/tkm	Bazaluk et al. (2021)	0.114 kg/kWh	MME and EPE (2022b)

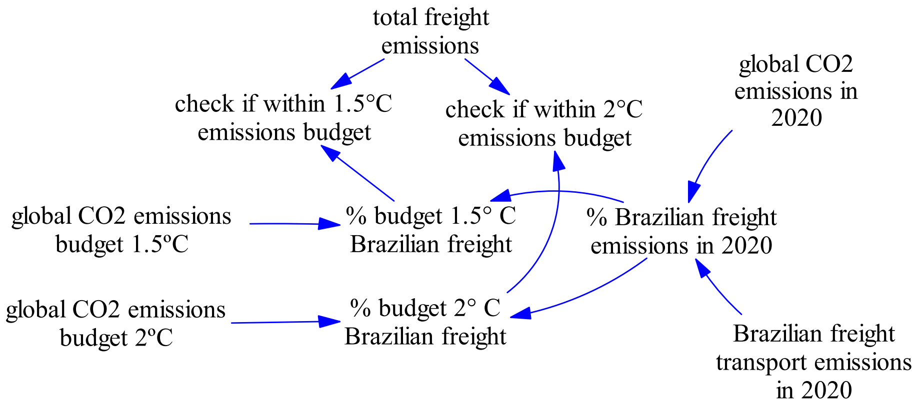


Fig. 9. Freight transport emissions control.

Table 5
Data related to transport emissions control.

Variable	Data input	Source
Global CO_2 emissions 2020	34.81×10^9 ton	Statista (2022)
Brazilian freight transport emissions 2020	79.7×10^6 ton	EPE (2022), EPL and IEMA (2021)
CO_2 budget 1,5°C	400×10^9 ton	Intergovernmental Panel on Climate Change (IPCC, 2021)
CO_2 budget 2 °C	1150×10^9 ton	IPCC (2021)

$$\% \ budget \ 1.5^{\circ} C \ Brazilian \ freight = global \ CO2 \ emissions \ budget \ 1.5^{\circ} C \times \% \ Brazilian \ freight \ emissions \ in \ 2020 \tag{13}$$

4.4. Implementation

The model was developed in Vensim® Pro (Ventana Systems, 2022), and the simulation timeframe ranges from 2020 to 2050. Zagonel and Corbert (2006) point out appropriate tests for SD quantitative models: boundary adequacy, structure assessment, dimensional consistency, integration error, extreme conditions, and behavior reproduction. These tests are detailed in Appendix C. After some adjustments, the model performed as expected in the testing phase and was considered appropriate for simulation. An uncertainty analysis was performed to assess the level of confidence concerning the model's representation of reality. The input parameters and their range of uncertainty are shown in Table 6.

The variation of yearly freight transport activity change considered the minimum and maximum values from 2010 to 2020 (EPE, 2022). The amount of transport service, measured in tkm, performed by truck, train, and barge considered the minimum and maximum values from the historical series of transport activity by mode (EPE, 2022) and the respective truck fleets (SINDIPEÇAS and ABIPEÇAS, 2022) and train and barge fleets (CNT, 2021). The variation of all energy efficiency factors was taken from different sources (MME

Table 6
Parameters used on the sensitivity analysis test.

Parameters	Average	Min	Max
Yearly freight transport activity change %	0.0343	−0.0032	0.0760
tkm/truck (10^3)	527	504	556
tkm/train (10^6)	104	86	131
tkm/barge (10^6)	114	92	160
Diesel/biodiesel truck efficiency (l/tkm)	0.058	0.027	0.114
CNG/biomethane truck efficiency (m^3/tkm)	0.063	0.030	0.124
Electric truck efficiency (kWh/tkm)	1.4	1.1	1.9
Hydrogen truck efficiency (kgH_2/tkm)	0.1	0.1	0.2
Diesel/biodiesel train efficiency (l/tkm)	0.005	0.003	0.007
Electric train efficiency (Wh/tkm)	53	44	60
Diesel barge efficiency (l/tkm)	0.002	0.001	0.004
Fuel oil barge efficiency (l/tkm)	0.002	0.001	0.004
Electric barge efficiency (Wh/tkm)	28	25	31
Road diesel emission factor (kgCO_{2e}/l)	5.716	5.144	6.288
Road biodiesel emission factor (kgCO_{2e}/l)	0.811	0.729	0.892
Road CNG emission factor (kg CO_{2e}/m^3)	6.0720	5.4648	6.6792
Road biomethane emission factor (kg CO_{2e}/m^3)	0.5820	0.5238	0.6402
Road electricity emission factor (kg CO_{2e}/kWh)	0.114	0.103	0.125
Road hydrogen emission factor (kg CO_{2e}/kg)	4.900	4.410	5.390
Rail diesel emission factor (kgCO_{2e}/l)	5.7820	5.2038	6.3602
Rail biodiesel emission factor (kgCO_{2e}/l)	0.7990	0.7191	0.8789
Rail electricity emission factor (kg CO_{2e}/kWh)	0.114	0.103	0.125
Waterway diesel emission factor (kgCO_{2e}/l)	5.7920	5.2128	6.3712
Waterway fuel oil emission factor (kgCO_{2e}/l)	3.31	2.979	3.6410
Waterway electricity emission factor (kg CO_{2e}/kWh)	0.114	0.103	0.125

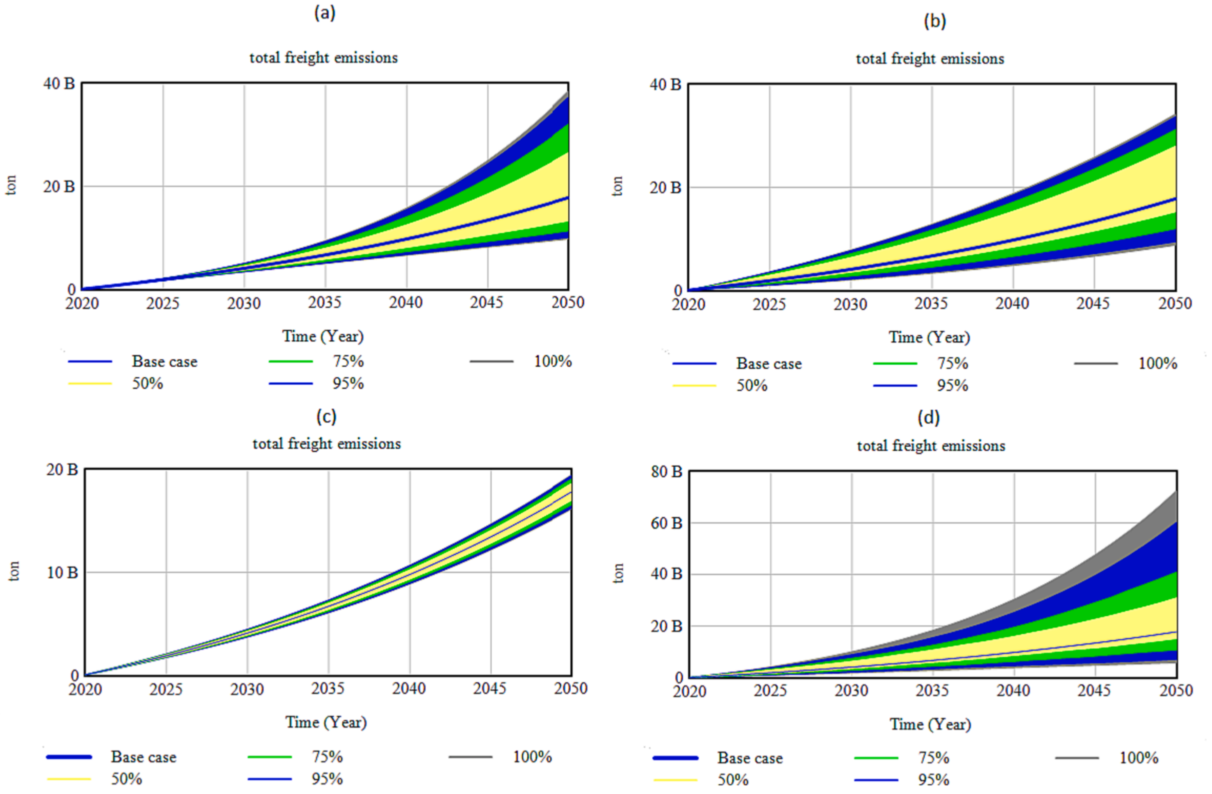


Fig. 10. Uncertainty analysis of cumulated CO_{2e} emissions due to the uncertainty range (+/−) of (a) yearly freight transport activity change (upper left); (b) diesel/biodiesel truck efficiency (upper right); (c) road diesel emission factor (lower left); and (d) simultaneous impact of the previous parameters (lower right).

et al., 2020; EPL and IEMA, 2021; Bazaluk et al., 2021; Ćwil et al., 2021; Hyzon, 2022; Mercedes-Benz, 2022; Volvo, 2022). For CO_{2e} emission factors, we have used the average value and ±10% as a range of uncertainty.

The test was performed with the Latin Hypercube Sampling method with 200 simulations (Ford, 2009), and the uncertainties in the parameters are described as uniformly distributed (Kwakkel and Pruyt, 2013). This means that for each time we perform the sensitivity analysis, 200 simulations are run with different values within the uncertainty range of the parameters considering a random uniform distribution. The graph shows the base case run as a solid blue line. The yellow area shows the 50% confidence bound. The green area shows 75% confidence, the blue area 95% confidence, and the grey area 100% confidence. Fig. 10 shows the uncertainty analysis for the cumulated CO_{2e} emissions in the BAU scenario. In this specific scenario, the uncertainty range of 3 individual parameters impacts the total freight emissions: yearly freight transport activity change, diesel/biodiesel truck efficiency, and road diesel emission factor. This is explained by the fact that in the BAU scenario, the road mode and diesel fuel are predominant over other modes and energy sources. As we change the share between different modes and fuels in the simulated scenarios, the other parameters in Table 6 will show greater influence over the emissions.

Table 7 shows the variation of the impact of the parameter's uncertainty on the cumulated CO_{2e} emissions by the end of the simulation period in comparison to the base case.

The uncertainty is low in the first decade and tends to increase in the last two decades, as a consequence of stock accumulations in the long term. From Fig. 10 and Table 7, we can observe the huge impact that the variation of freight transport activity has on the final emissions. This result indicates that there is more pressure to mitigate the impact of freight demand increase by decarbonization measures.

5. Results

The scenarios are based on a few key variables related to the decarbonization policies to change the behavior of the freight system: (i) policies toward alternative transport modes; (ii) policies toward alternative energy sources; (iii) policies toward increasing the percentage of biodiesel in diesel blend; and (iv) policies toward speeding up fleet renewal. Each policy has a configuration set regarding its implementation goals and deadlines.

Regarding policies toward alternative modes, Brazilian's National Logistics Plan – NLP 2035 (Ministry of Infrastructure and EPL, 2021) predicts three different implementation levels of modal share change (low, medium, and high) in 2035, each one depending on a set of infrastructure investments in the Brazilian transport network to reduce the roadway share and increase the railway and waterway share, as presented in Table 8.

Concerning the policies toward alternative fuels, Table 9 shows three implementation levels of fuel share change (low, medium, and high). Low and medium levels were predicted by BCG and ANFAVEA (2021), regarding the percentage of use of each energy source by trucks in 2035. For railways and waterways, we have considered independent initiatives announced by some concessionaires to be met in 2050. For all modes, the high implementation level of fuel share change was added to assess the impact of a more restricted policy in the longer term (2050).

For policies towards increasing the percentage of biodiesel in diesel blend, Table 10 shows two implementation levels (low and medium), also predicted by BCG and ANFAVEA (2021) for 2035.

Lastly, the policy towards speeding up fleet renewal was proposed to assess the impact of accelerating the scrappage rate of the old truck fleet. Such policy is based on the Brazilian Road Fleet Productivity Increase Program (Renovar Program) (Ministry of Economy, 2022), which aims to encourage the withdrawal of old diesel trucks voluntarily. As this program does not have specific targets to be achieved, we have assumed that it can be applied in different time ranges, for example, between 2020 and 2025. In this case, the scrappage rate will increase by 20% in each year between 2020 and 2025 in comparison to the normal scrappage rate (Eq. (5)). If the policy takes place between 2020 and 2030, the increase in scrappage speed is assumed to be 10% each year. The model simulates the application of the policy at different time ranges (2020–2025; 2020–2030; 2020–2035).

Besides the business-as-usual (BAU) scenario in which no policy is applied, Fig. 11 shows all the proposed scenarios, each of which with a specific combination of the policies' implementation levels (low, medium, high). In total, 32 scenario tests were carried out and a detailed table of their setup combinations is provided in Appendix D.

The collection of scenarios named "Individual policies" aims to evaluate the individual impact of each implementation level of policies toward alternative modes, policies toward alternative fuels, and policies toward increasing the percentage of biodiesel in diesel blends. The collection of scenarios named "Combined policies" aims to evaluate the impact of different implementation levels of the policies toward alternative modes and policies toward alternative fuels. Then, in the collection of scenarios "Accelerate scrappage rate" we have applied and varied the time limit of the policy towards speeding up fleet renewal, in which the goal should be met: 2025, 2030, or 2035. Finally, given the uncertainty of the time frame in which the policies will be met, in the collection of scenarios named

Table 7
Variation of the impact of parameters' uncertainty on cumulated CO_{2e} emissions.

Parameters	Lower bound	Upper bound
Yearly freight transport activity change %	−45%	+116%
Diesel/biodiesel truck efficiency (l/tkm)	−51%	+92%
Road diesel emission factor ($kgCO_{2e}$/l)	−7%	+9%
Combined three parameters above	−67%	+308%

Table 8
Initial modal share (tkm) and projections for 2035 (%).

	Initial modal share (tkm)	Implementation levels of modal share (tkm) for 2035		
Modes	2020	Low	Medium	High
Roadway	63.3	55	40	32
Railway	21.7	31	43	47
Waterway	14.9	13	16	19

Source: EPE (2022); Ministry of Infrastructure and EPL (2021).

Table 9
Energy share and projections for 2035 (road) and 2050 (rail and waterways) (%).

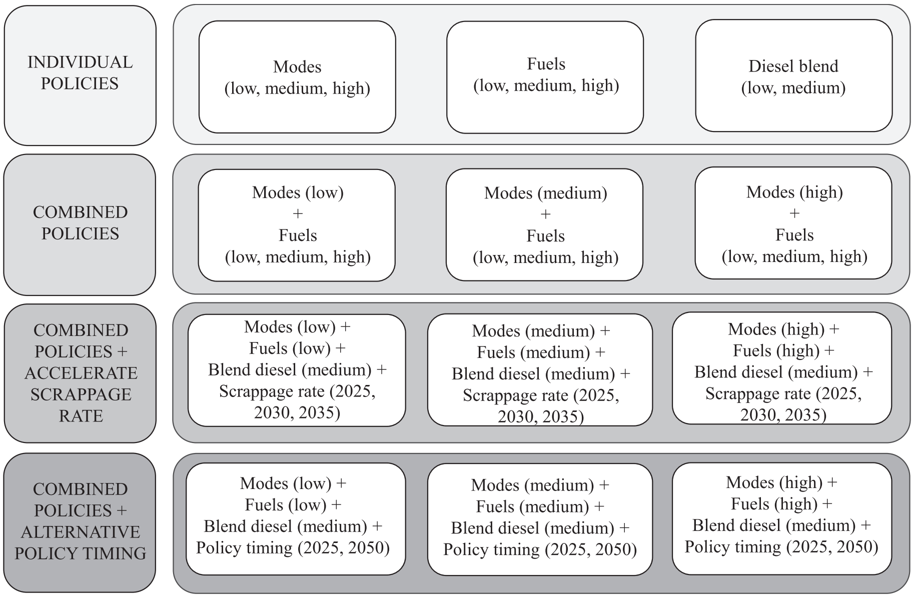
		Initial fuel share	Implementation levels of fuel change		
Modes	Fuels	2020	Low	Medium	High
Roadway	(Bio) Diesel	100	86	68	0
	CNG/biomethane	0	7	10	50
	Electricity	0	7	15	40
	Hydrogen	0	0	7	10
Railway	(Bio) Diesel	100	100	50	0
	Electricity	0	0	50	100
Waterway	Diesel	28	50	30	0
	Fuel oil	72	50	20	0
	Electricity	0	0	50	100

Source: based on BCG and ANFAVEA (2021), VLI (2022), Rumo (2022), Vale (2022).

Table 10
Biodiesel percentage in diesel blend and projections for 2035.

	Initial blend	Implementation levels of (bio) diesel blend change	
Fuels	2020	Low	Medium
Diesel	88	82	70
Biodiesel	12	18	30

Source: based on BCG and ANFAVEA (2021).



INDIVIDUAL POLICIES	Modes (low, medium, high)	Fuels (low, medium, high)	Diesel blend (low, medium)
COMBINED POLICIES	Modes (low) + Fuels (low, medium, high)	Modes (medium) + Fuels (low, medium, high)	Modes (high) + Fuels (low, medium, high)
COMBINED POLICIES + ACCELERATE SCRAPPAGE RATE	Modes (low) + Fuels (low) + Blend diesel (medium) + Scrappage rate (2025, 2030, 2035)	Modes (medium) + Fuels (medium) + Blend diesel (medium) + Scrappage rate (2025, 2030, 2035)	Modes (high) + Fuels (high) + Blend diesel (medium) + Scrappage rate (2025, 2030, 2035)
COMBINED POLICIES + ALTERNATIVE POLICY TIMING	Modes (low) + Fuels (low) + Blend diesel (medium) + Policy timing (2025, 2050)	Modes (medium) + Fuels (medium) + Blend diesel (medium) + Policy timing (2025, 2050)	Modes (high) + Fuels (high) + Blend diesel (medium) + Policy timing (2025, 2050)

Fig. 11. Description of simulated scenarios.

"Alternative policy timing", we also simulated two different limits of time (2025 and 2050) for policies toward alternative modes and alternative fuels.

5.1. BAU Scenario

In the BAU scenario, the total truck fleet will increase from nearly 2 million in 2020 to >5.5 million in 2050. The truck sales will range between 250 and 570 thousand units per year to replace the scrapped vehicles and meet the growing demand. This trend also shows that diesel consumption will almost triple in 20 years, with which road transport will be responsible for 95% of this consumption, while rail and waterway modes only for 3% and 2%, respectively. This will be reflected in the CO_{2e} emissions of each transport mode. Fig. 12 shows the cumulated freight emissions from 2020 to 2050 and the emissions budgets suggested for the sector.

Most CO_{2e} emissions come from the road transport mode, reaching an accumulation of approximately 17 billion tons in 2050. In this case, the estimated emissions budget for the Brazilian freight sector for limiting global warming to 1.5 °C or 2 °C will be reached in 2023 and 2027, respectively. However, it is important to highlight that the well-to-wheel approach was considered for calculating emissions. If the tank-to-wheel approach was adopted, emissions would be about 90% lower, but even so, the estimated emissions budget would be reached in 2025 (1.5 °C) and 2032 (2 °C).

5.2. Individual policies

In the first collection of scenarios, we assess the individual impact of each one of the different policy implementation levels on freight emissions. First, we analyze the gradual increase (low, medium, and high) in the use of alternative modes, then the gradual increase (low, medium, and high) in the use of alternative fuels, and finally, the gradual increase (low and medium) in the percentage of biodiesel in the diesel blend. Fig. 13 shows the results of the first six scenarios in comparison with the BAU scenario.

It is interesting to note that the medium and high implementation of alternative modes have a higher impact on decreasing emissions than all the scenarios of policies regarding alternative fuels. This is true at least for the time horizon simulated (2050) since the high implementation of policies towards alternative fuels aims to eliminate the sale of diesel-powered vehicles by 2050. In the longer term, this scenario would probably be the best in terms of reducing CO_{2e} emissions, as we can see an inversion in its slope around 2045. Rail and waterway emissions, however, would increase under policies promoting these alternative modes of transport, as expected, while policies promoting alternative energy sources would be the best solution, already in the considered timeframe.

We also compared the total freight emissions under policies toward increasing the percentage of biodiesel in the diesel blend from the current 12–18% and 30%. The results show that these policies would lead to 5% and 14% of emissions reduction under 18% and 30% of biodiesel in the diesel blend, respectively. In all the scenarios, the estimated emissions budget for the Brazilian freight sector for limiting global warming to 1.5 °C would be reached in 2023. Regarding the budget for limiting global warming to 2 °C, it would be reached in 2027. This result means that implementing isolated policies is not enough to achieve a significant emissions reduction, and joint efforts seem necessary to achieve a noteworthy impact.

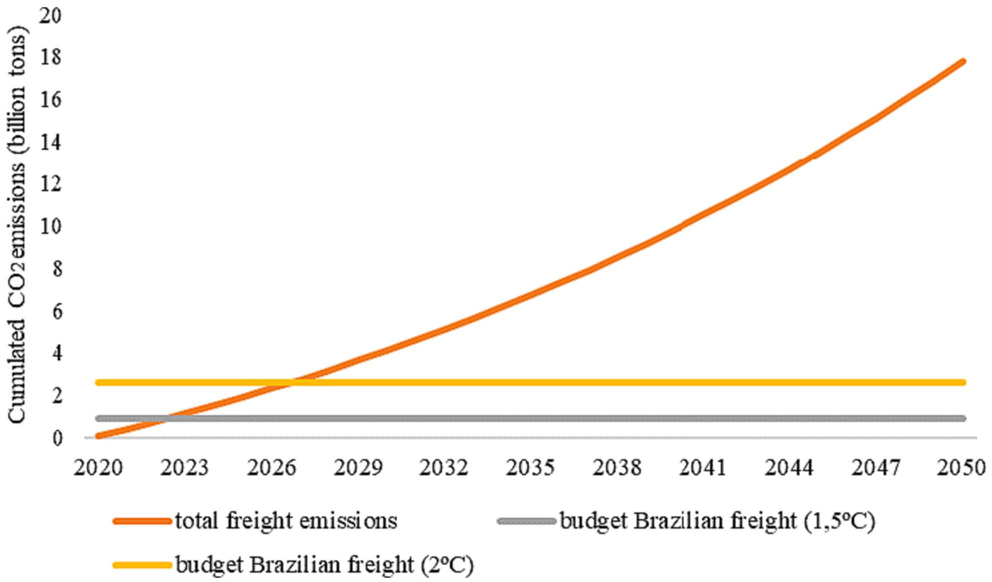


Fig. 12. Cumulated CO_{2e} emissions from road, rail, and waterways.

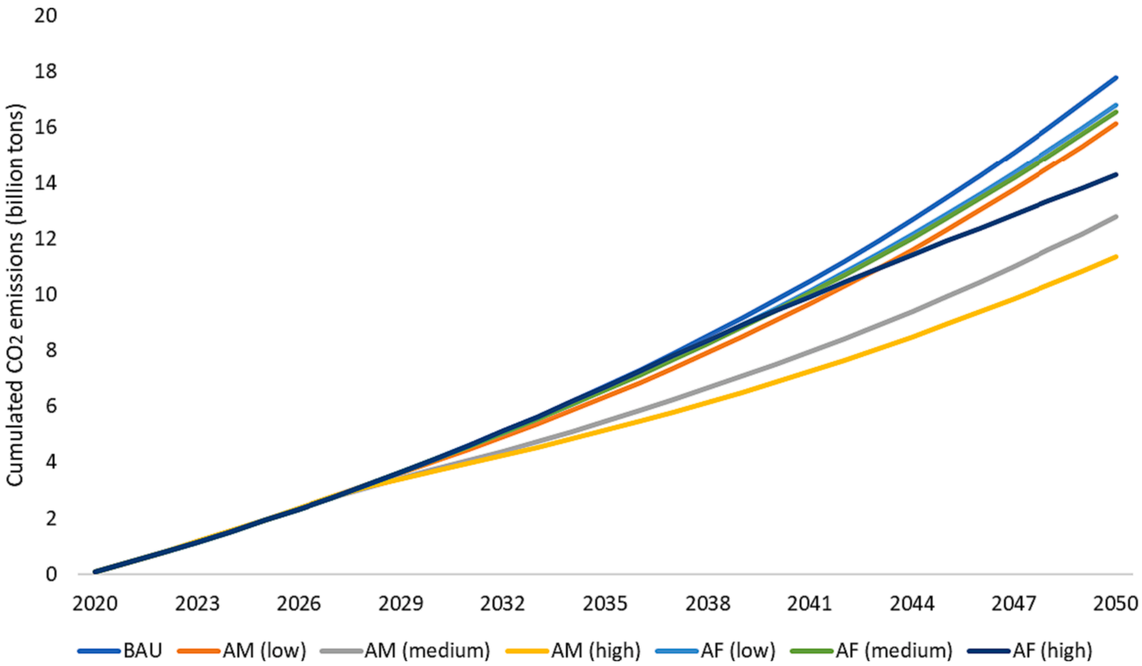


Fig. 13. Cumulated CO_{2e} emissions for different levels of individual policies' implementation (low, medium, and high) for alternative modes (AM) and alternative fuels (AF).

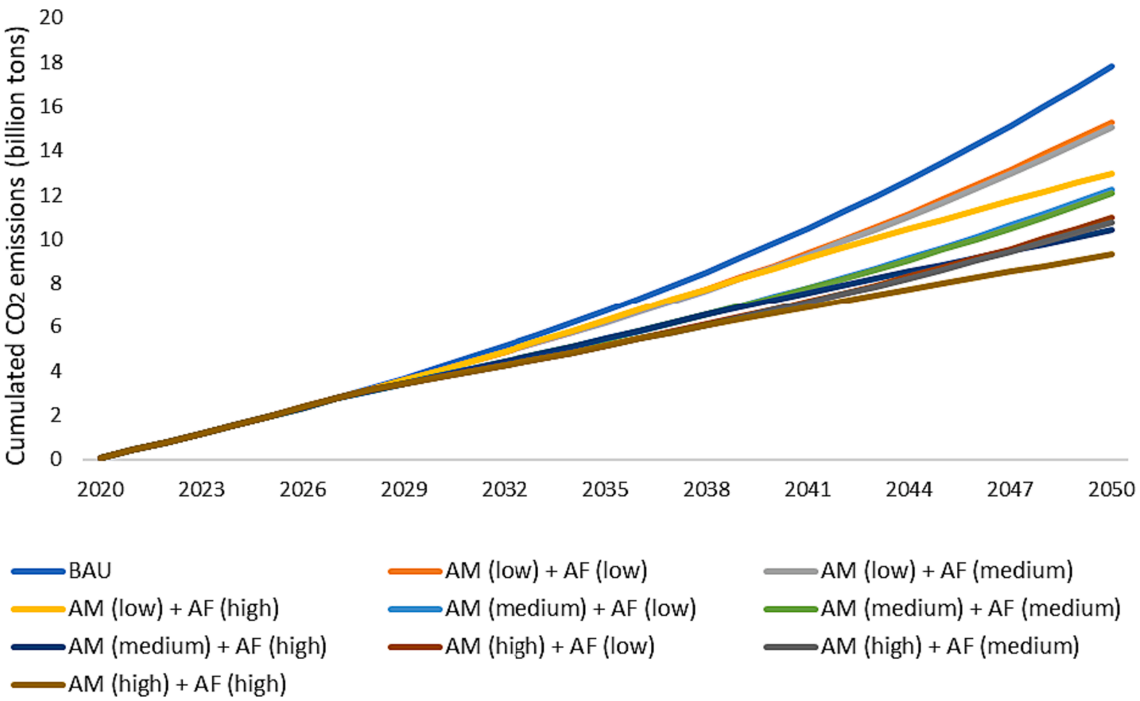


Fig. 14. Cumulated CO_{2e} emissions combining policies of alternative modes (AM) and alternative fuels (AF) and their levels of implementation (low, medium, and high).

5.3. Combined policies

In the second collection of scenarios, we assess the effect of all combinations of the policies toward alternative modes and policies toward alternative fuels. It allows us to measure and assess the compounded effect of these policies on the freight decarbonization potential and therefore, offer a more realistic set of scenarios to forecast the possible emissions drop. Fig. 14 shows the results of total freight emissions in comparison with the BAU scenario.

From Fig. 14, we can observe the same growth behavior in all scenarios, except for those with a high implementation level of alternative fuel policies. These scenarios aim to banish the sales of diesel-powered vehicles by 2050, which means that they can present better results in the longer term in comparison with the other scenarios. Total emissions can decrease by up to 48% in the best case, in which policies aim at a drastic reduction in the use of road transport (high implementation of alternative modes), besides zeroing out the sales of diesel-powered vehicles by 2050 (high implementation of alternative fuels).

In all scenarios, the estimated emissions budget for the Brazilian freight sector for limiting global warming to 1.5 °C would already be reached in 2023. Regarding the budget for limiting global warming to 2 °C, it would be reached in 2027.

5.4. *Accelerated scrappage rate*

In this set of scenarios, we have analyzed the impact of the policy towards speeding up fleet renewal. The goal of this policy is to accelerate the scrappage rate of old diesel-powered trucks to increase the demand for trucks powered by alternative fuels.

Fig. 15 shows the cumulated CO_{2e} emissions from the scenarios in which the fleet scrappage is accelerated. The scenarios in which there is an acceleration of truck scrapping present a slight reduction in emissions compared to the scenarios in which there is no such acceleration (15%, 12%, and 7% reduction in emissions for low, medium, and high implementation in both alternative modes and fuels, respectively). That is because we accelerate the scrappage of old diesel vehicles, while from 2020 onwards, it is assumed that vehicles powered by electricity, hydrogen, and biomethane will take place in the fuel-vehicle sales share.

In all the scenarios, the estimated emissions budget for the Brazilian freight sector for limiting global warming to 1.5 °C would be reached in 2023. Regarding the budget for limiting global warming to 2 °C, it would be reached in 2027.

5.5. *Alternative policy timing*

In the last scenario collection, we have simulated scenarios with different time limits for implementing policies regarding alternative modes and alternative fuels. By assuming that the initial implementation of all policies starts in 2020, the simulated deadlines for the policies' targets to be reached are 2025, 2035, and 2050, which means that these policies can be more or less strict, taking up to 5, 15, or 30 years to be fully implemented. Fig. 16 shows the percentage of emissions abatement in each case individually.

When considering a low level of implementation for policies towards both alternative modes and alternative fuels (blue bars), the accumulated emissions drop would vary between 10% and 29%, depending on the policies' time limit. In this case, if the policies are fully implemented by 2025 instead of 2035, for instance, we could gain 15% of accumulated emissions reduction in 2050. When considering a medium level of implementation instead (green bars), this variation is between 29% and 46%. Finally, for a high level of implementations (orange bars), the accumulated emissions drop is between 39% and 67%.

The estimated emissions budget for the Brazilian freight sector for limiting global warming to 1.5 °C would be reached in 2023. Regarding the emissions budget for limiting global warming to 2 °C, it would be reached in 2033 in the best scenario (high level of policies implementation towards both alternative modes and fuels to be fully implemented by 2025). Such results show that even with the implementation of ambitious targets in terms of transport modes and fuels in the very short term, it would not be enough to zero freight emissions by 2050.

6. Discussion

Based on the results of Scenarios "Individual policies", it is evident that stronger policy incentives are required in the country to obtain the desired decarbonization result. When compared against the BAU scenario, all policies lead to a lower rate of total emissions generated in the freight transport system. However, these are insufficient from the perspective of the carbon budget available. The best scenario of the "Individual policies" set yields a 36% emissions reduction in comparison to the BAU scenario, which would require a reduction in the percentage of use of the roadways from 63% to 32% in 15 years. Railways and waterways would have to increase their shares from 22% to 47% and from 15% to 19%, respectively, which depend on a set of more aggressive infrastructure investments in strategic railways and waterways in addition to supporting logistics infrastructure. Moreover, our results show the lagged response of emissions mitigation to the tested incentive policies. Scenarios show little difference from each other in the short to mid-term (until 2030 approximately) and only begin to show higher differences from 2030 onwards. In other words, focusing on short-term effects may hinder the policies' benefits in the long term if implementation delays are not considered.

From the results of the scenarios "Combined policies", lower emissions can be achieved by jointly implementing different decarbonization measures such as shifting to alternative fuels and using less emission-intensive transport modes. The best scenario of the "Combined policies" set achieved a 48% emissions reduction in comparison to the BAU scenario, while the worst achieved a 14% emissions decrease. Then, the "Accelerated scrappage rate" scenarios set showed that the acceleration of truck scrapping modifies the market share between vehicles powered by different energy sources and slightly reduces the emissions. From a policymaking perspective, the composite policy set investigated herein offers novel insights into the effects of policy timing to obtain the best possible outcomes in the long term. For instance, the activation and deactivation of the policies could be sequenced for longer timeframes until there are diesel-powered trucks in the market, working as an extra incentive for some agents such as the investors of alternative energy sources.

The "Alternative policy timing" scenarios showed that the most effective results come by implementing the policies as fast as

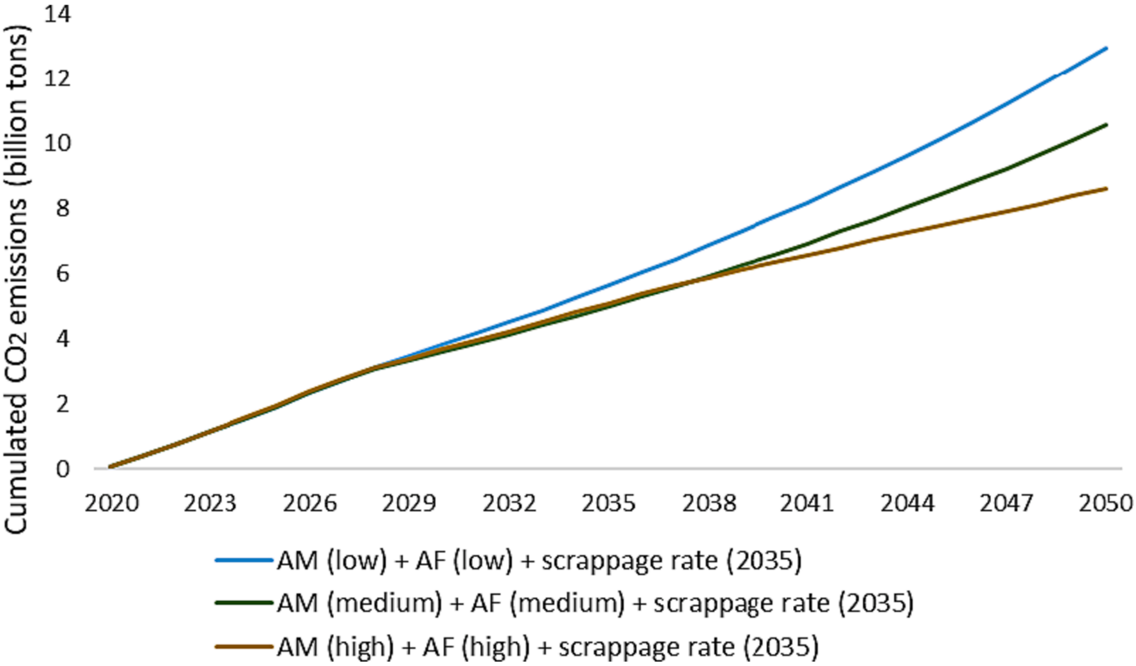


Fig. 15. Cumulated CO_{2e} emissions with policies to speed up the fleet renewal process.

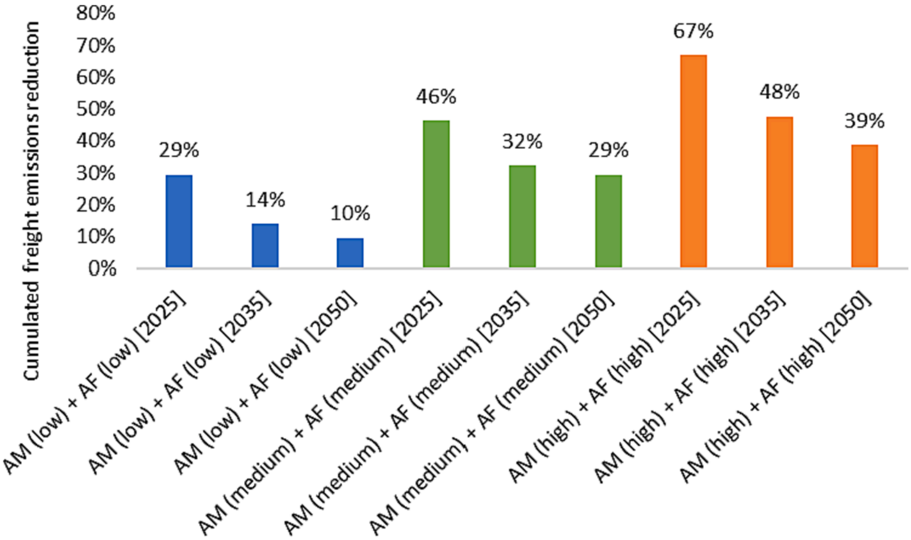


Fig. 16. Percentage of emissions drop by varying the implementation timeframe (2020–2025/2035/2050) of policies regarding alternative modes (AM) and alternative fuels (AF).

possible. In all cases, the faster policies are implemented, the more significant the improvements in terms of emissions drop. Naturally, it means a highly aggressive effort to implement and achieve ambitious targets in the short term, including radical changes in energy, technology, and infrastructure systems, which feasibility or cost-benefit should be better analyzed.

From the results and discussions presented, it is clear that the considered measures will not be sufficient to keep freight emissions within the assigned emissions budgets for the sector. Even considering very ambitious targets, such as decreasing the use of roadways by 50% and zeroing out the sales of diesel-powered vehicles in only five years, we would still have to deal with a big fleet of internal combustion vehicles for years ahead. Then, it is also important to consider other measures not included in our model, such as managing the freight demand, improving logistics assets utilization, and energy efficiency. Regarding the choice of alternative fuels, it is crucial to consider energy from green sources, which is still a great challenge to be addressed by many countries. In Brazil, about 80% of the electricity mix is renewable. However, electricity production will have to increase to meet this new demand without affecting other sectors, while the large-scale production of green hydrogen in the country is still being discussed by decision-makers. Without this consideration, the results of emissions mitigation can be even less satisfactory, and decarbonization would not be feasible at all. This points to the urgency for coordinated cooperation and broad participation of the government and other stakeholders capable of sustaining, encouraging, and enabling innovative policies that bring compelling results for the freight transport decarbonization in Brazil. All the policies presented are important to a greater or lesser extent on the path to decarbonization. Naturally, some policies are easier and faster to implement than others. Increasing the percentage of biodiesel in the diesel blend and applying policies to speed up the fleet renewal process take less effort and investment than changing the fleet technologies and the modal split. Policymakers have to be aware of this trade-off to make decisions aligned with their specific emissions targets and timeframes. The joint implementation of policies brings greater benefits in a shorter time and becomes important due to joint efforts to balance the effect of increased demand for freight transport in the coming years. As mentioned in Section 3, the individual effort of stakeholders is neither sufficient nor capable of achieving the necessary goals. It takes a joint effort from various sectors so that the change in the system occurs on a large scale and, consequently, the results of decarbonization can be enhanced and achieved within the desired timeframes.

On the other hand, it is worth highlighting that the budget estimated for the sector's emissions, suggested in this study due to the absence of official targets, should be interpreted with caution. Firstly, the estimate is based on the percentage of freight emissions in 2020 compared to global emissions, which may not be constant over the next years. Secondly, this percentage of emissions should not necessarily guarantee or impose the same percentage of the global budget for future freight emissions. It is necessary to consider a fairer balance between countries that have historically developed and polluted more and countries that are still developing and that tend to suffer more from the consequences of global warming. However, the proposal of a specific target to reduce sectoral emissions is outside the scope of this work, being suggested as a topic for future research. Despite this limitation, the results corroborate the urgency for more forceful actions to promote freight decarbonization.

Naturally, the assumptions made in our model regarding the timeframes of policy implementation have a big role in the results. For example, if the fleet renewal process takes 15 years, or if it ranges between 5 and 30 years, this will influence the time in which the emissions budgets will be reached. However, the reality of the time that this fleet renewal process will take on a large scale is still quite uncertain. As discussed in Section 3, the time for freight carrier companies to acquire alternative fuel vehicles can reach two years if their conditions are favorable. For instance, highly capitalized companies can take initiatives more easily, while alternative fuel vehicles are imported and the high purchase cost is still a market barrier. The degree of technological maturity is an important aspect to be considered, as it shows a big discrepancy between Brazilian and a few international contexts, where the results may differ concerning the speed of alternative fuel vehicle adoption. In the Brazilian context, the collaboration of other sectors is imperative for the introduction of new technologies on a large scale in the market, reducing their adoption times by small companies and autonomous drivers. However, uncertainty remains about the time frame for the involvement of other stakeholders, such as infrastructure, regulation, and energy sectors.

Moreover, the results presented by our model depend on the successful implementation of the considered policies, as the policies toward alternative modes, based on the National Logistics Plan that predicts a set of infrastructure investments in railways, waterways, and other logistics assets, and policies toward alternative fuels, based on technical studies predicting the market share of different fuels for the coming years. This is a limitation, as the successful outcomes of these policies are quite uncertain.

Even though our model provides a comprehensive perspective of freight decarbonization policies, it lacks how the considered policies should be implemented, i.e., investing in the generation and distribution of alternative energy to meet the increasing power demand, investing in vehicle' technologies development in the national market, providing tax and fee exemptions, subsidies, promoting the expansion of refueling/recharging facilities, or investing in electric road systems such as overhead lines (pantographs) and conductive/inductive ground-level power supply, imposing higher taxes on fossil fuels, imposing barriers or financial levers to discourage or promote different modes of transport, etc.

Moreover, the model lacks other decarbonization policies, such as those related to the improvement of vehicles' energy efficiency, vehicle use optimization, and freight demand management and the factors that influence its variation, especially considering the future market trends. If addressed, these other policies could lead to different emissions mitigation results. The dynamics of freight demand, for instance, is very important given its high influence on the rest of the system. Variables related to population, economic development, market factors, and patterns of consumption play a role in such dynamics to be modeled.

The model has a high level of aggregation, i.e., the homogeneity of vehicles without distinction of types, sizes, and other technical specificities that influence transport activity per year and fuel consumption. However, it is important to highlight that they can be modified and updated as more data becomes available, depending on the desired level of detail and accuracy. Finally, the lack of scrappage functions for the national fleet of trains and barges led us to use external references, which may not accurately represent the scrappage rate of those vehicles at the national level.

7. Conclusions

Considering the freight transport decarbonization, in this study, we developed an SD model and conducted several simulation experiments to investigate the impact of policies toward alternative modes and means of transport, including electrification, increased use of biofuels, acceleration of fleet renewal, and modal shift.

The steepest decline in freight emissions comes by combining the most ambitious targets for mode shift and introduction of alternative fuels into the market, which resulted in a 67% emissions reduction compared to the BAU Scenario. The worst emissions results come from scenarios in which only policies toward increasing the percentage of biodiesel in diesel blends are applied, showing that those policies alone are not effective.

Most importantly, the results show that the sector budget to limit global warming to 1.5 °C would be already reached in 2023, regardless of the scenario, as the system does not have enough time for the implementation of policies to meet the urgency of a such restricted budget. On the other hand, the budget to limit global warming to 2 °C would be reached in 2027, 2029, 2030, or 2033, depending on the set of policies and their implementation timeframes. Such results indicate that limiting global warming to 1.5 °C or 2 °C until 2100, as defined in the Paris Agreement, is not attainable in our proportional analysis of freight emissions budgets, given how close we are to reaching the limits defined for global warming. Thus, even more forceful actions are required to be implemented urgently to face such a great challenge with the serious and collaborative engagement of all stakeholders.

Certainly, several economic, social, and technological conditions are unknown in the long term and, therefore, this simulation exercise should be taken with caution. For example, a new technological paradigm and more efficient solutions can emerge within the simulated timeframe, which should be continuously reviewed and updated. Rather than offering a precise forecast of emissions reduction, its essence is to offer a perspective of the need to reinforce policies in the forthcoming years and decades if we are willing to decarbonize the freight transport system.

Scientifically, our model contributes with a simulation model with multiple freight decarbonization policy measures in a system-wide perspective, deepening the knowledge about the temporal factors that govern the dynamics of the system's responses to policy implementation, even by highlighting the real data or the unavoidable assumptions in a clear and replicable model.

From the government perspective, our model helps by showing the potential of emissions mitigation results considering the combined effect of multiple decarbonization policies. Priority should be given to policies toward promoting alternative fuels, especially green energy sources since they are the only pathway to deep freight decarbonization. Other measures, however, are also important to mitigate the emissions in the meantime, given that the total fleet replacement will take considerable time. Despite the timeframe for policy implementation and emissions budget assumptions, which are subject to improvements, our model supports policymaking in the freight transport sector by presenting possible emissions drops according to alternative policies. It is important to assist decisions in a sector with a limited emission budget and a short deadline imposed by the urgency of global climate actions.

Future research could provide the basis for implementing freight decarbonization policies at an operational level. This could integrate a choice modeling approach from the freight forwarders' perspective to better investigate the most influencing parameters of their choice decisions regarding the adoption of alternative fuel vehicles and transport modes. The model could be expanded and other policies added, such as improving the vehicle's energy efficiency, optimizing vehicles and other logistics assets use, and managing freight demand. Also, as more data becomes available, especially regarding new technology and alternative fuels, the model can be useful to run different scenarios. Moreover, the model can be modified to consider a higher detailed or heterogeneity level, depending on the desired accuracy.

Other studies are needed to determine the scrappage functions for the Brazilian national train and barge fleets for a better analysis of the fleet renewal dynamics. The time limits for policy targets to be met require to be continuously monitored and updated according to the real agents' engagement. Future empirical research could be carried out with the energy generation and distribution sector, investors of infrastructure, governmental policymakers, and consumers to raise better knowledge of the impact of their decisions on freight system dynamics.

More research is needed about the factors that can boost the dynamic of vehicle replacement, but also how we should deal with a large amount of scrap resulting from this process. It is important to bear in mind the responsibility of reusing and recycling, reintroducing materials from the old fleet into the supply chain. In addition, a life cycle analysis of the new fleets is also essential, for example, to planning future use of batteries and their scarce elements.

Finally, the model holds potential applicability to various regions or countries, given the transferability of decarbonization policies and the principles of freight system dynamics. It's important to note, however, that the results obtained are tailored to the specific nuances of the Brazilian freight system. For instance, the process of fleet renewal outlined in the model may not align with practices in European countries. In Europe, stringent emission standards drive the rapid introduction of energy-efficient and cleaner trucks, a pace distinct from that observed in emerging economies like Brazil. To address this, urgent measures, such as economic incentives for fleet replacement, are necessary to accelerate fleet renewal in emerging economies. Simultaneously, modal shifts and other decarbonization measures should still be considered. These not only contribute to emissions reduction but also mitigate various negative externalities, including road congestion and safety concerns. Moreover, applying the model to diverse contexts, such as other South American or European countries, would be valuable for comparative analysis. Adapting the model for different contexts may necessitate adjustments in decarbonization goals, such as mode shift and alternative energy sources. The model's flexibility allows for the incorporation of new variables to reflect evolving decarbonization policies. Employing Group Model Building (Saryazdi et al., 2020), a workshop method involving diverse system-related agents, facilitates the refinement of the conceptual model by identifying and prioritizing factors that require modification or retention, ensuring its responsiveness to emerging challenges.

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CRediT authorship contribution statement

Verônica Ghisolfi: Conceptualization, Data curation, Methodology, Validation, Writing – original draft. **Lóránt Antal Tavasszy:** Supervision, Writing – review & editing. **Gonçalo Homem de Almeida Rodriguez Correia:** Supervision, Writing – review & editing.

Gisele de Lorena Diniz Chaves: Conceptualization, Supervision, Writing – review & editing. **Glaydston Mattos Ribeiro:** Funding acquisition, Project administration, Supervision, 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.

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Appendices.

This section presents the appendices referenced throughout the paper. Appendix A presents the model equations and their respective units. Appendix B presents the policy equations with different parameters used for each scenario. Appendix C presents the tests performed for the proposed SD model. Lastly, Appendix D presents the setup of scenarios carried out in this study.

A. Model equations

Appendix A presents all the equations and their respective units from the proposed system dynamics model developed in Vensim® Pro (VENTANA SYSTEMS, 2022).

(001) “% biodiesel in diesel”= 0 * TANH (15 * policies towards trucks alternative fuels + 0) + 0.12 - Units: Dmnl.
(002) “% Brazilian freight emissions”= Brazilian freight transport emissions 2020/global CO2 emissions 2020 - Units: Dmnl.
(003) “% budget 1.5° C Brazilian freight”= “CO2 budget 1.5 °C” * “% Brazilian freight emissions” - Units: ton.
(004) “% budget 2° C Brazilian freight”= CO2 budget 2 °C * “% Brazilian freight emissions” - Units: ton.
(005) “% CNG/biomethane truck”= “CNG/biomethane truck fleet”/total truck fleet - Units: Dmnl.
(006) “% diesel + biodiesel barge”= (“diesel + biodiesel barge fleet”+old barge fleet)/total barge fleet - Units: Dmnl.
(007) “% diesel + biodiesel train”= (“diesel + biodiesel train fleet”+total old train fleet)/total train fleet - Units: Dmnl.
(008) “% diesel + biodiesel truck”= (“diesel + biodiesel truck fleet”+total old truck fleet)/total truck fleet - Units: Dmnl.
(009) “% electric barge”= electric barge fleet/total barge fleet - Units: Dmnl.
(010) “% electric train”= electric train fleet/total train fleet - Units: Dmnl.
(011) “% electric truck”= electric truck fleet/total truck fleet - Units: Dmnl.
(012) “% hydrogen truck”= hydrogen truck fleet/total truck fleet - Units: Dmnl.
(013) average barge age = Time-2005 - Units: Year.
(014) “average train age 1960-1969” = Time-1964 - Units: Year.
(015) “average train age 1970-1979” = Time-1974 - Units: Year.
(016) “average train age 1980-1989” = Time-1984 - Units: Year.
(017) “average train age 1990-1999” = Time-1994 - Units: Year.
(018) “average train age 2000-2009” = Time-2004 - Units: Year.
(019) “average train age 2010-2019” = Time-2004 - Units: Year.
(020) “average train age > 1959” = Time-1954 - Units: Year.
(021) “average truck age 1978-1983” = Time-1983 - Units: Year.
(022) “average truck age 1984-1989” = Time-1989 - Units: Year.
(023) “average truck age 1990-1995” = Time-1995 - Units: Year.
(024) “average truck age 1996-2001” = Time-2001 - Units: Year.
(025) “average truck age 2002-2007” = Time-2007 - Units: Year.
(026) “average truck age 2008-2013” = Time-2013 - Units: Year.
(027) “average truck age 2014-2019” = Time-2019 - Units: Year.
(028) barge diesel consumption = transport performed with diesel barge * diesel barge efficiency Units: l.
(029) barge electricity consumption = transport performed with electric barge * electric barge efficiency Units: Wh.
(030) barge fleet from 2020 onwards = INTEG (barge fleet inflow, 0) Units: veh.
(031) barge fleet inflow = IF THEN ELSE (total barge fleet < ideal barge fleet, (ideal barge fleet-total barge fleet)/year, 0) Units: veh/Year.
(032) “barge scrappage rate 0-5” = 1-(1 + EXP (0.2037 * 3–6.9993))ˆ-0.8679 Units: Dmnl.
(033) “barge scrappage rate 11-15” = 1-(1 + EXP (0.2037 * 13–6.9993))ˆ-0.8679 Units: Dmnl.
(034) “barge scrappage rate 16-20” = 1-(1 + EXP (0.2037 * 18–6.9993))ˆ-0.8679 Units: Dmnl.
(035) “barge scrappage rate 21-25” = 1-(1 + EXP (0.2037 * 23–6.9993))ˆ-0.8679 Units: Dmnl.
(036) “barge scrappage rate 26-30” = 1-(1 + EXP (0.2037 * 28–6.9993))ˆ-0.8679 Units: Dmnl.

(037) “barge scrappage rate 6-10” = 1-(1 + EXP (0.2037 * 8–6.9993))ˆ-0.8679 Units: Dmnl.

(038) barges scrappage rate = 1-(1 + EXP (0.2037 * (average barge age/year)-6.9993))ˆ-0.8679 Units: Dmnl.

(039) biodiesel barge adoption = barge fleet inflow * “diesel + biodiesel barge share” Units: veh/Year.

(040) biodiesel trains adoption = train fleet inflow * “diesel + biodiesel train share” Units: veh/Year.

(041) biodiesel trucks adoption = truck fleet inflow * “diesel + biodiesel truck share” Units: veh/Year.

(042) biomethane truck efficiency = 0.0629 Units: m^3/(ton * km).

(043) CNG 10 to 11 = DELAY FIXED (CNG 5 to 6-“scrappage CNG 6-10”, 5, 0) Units: veh/Year.

(044) CNG 15 to 16 = DELAY FIXED (CNG 10 to 11-“scrappage CNG 11-15”, 5, 0) Units: veh/Year.

(045) CNG 20 to 21 = DELAY FIXED (CNG 15 to 16-“scrappage CNG 16-20”, 5, 0) Units: veh/Year.

(046) CNG 25 to 26 = DELAY FIXED (CNG 20 to 21-“scrappage CNG 21-25”, 5, 0) Units: veh/Year.

(047) CNG 5 to 6 = DELAY FIXED (“CNG/biomethane trucks adoption”-“scrappage CNG 0-5”, 5, 0) Units: veh/Year.

(048) “CNG TF 0–5 years old”= INTEG (“CNG/biomethane trucks adoption”-CNG 5 to 6-“scrappage CNG 0-5”, 0) Units: veh.

(049) “CNG TF 11–15 years old”= INTEG (CNG 10 to 11-CNG 15 to 16-“scrappage CNG 11-15”, 0) Units: veh.

(050) “CNG TF 16–20 years old”= INTEG (CNG 15 to 16-CNG 20 to 21-“scrappage CNG 16-20”, 0) Units: veh.

(051) “CNG TF 21–25 years old”= INTEG (CNG 20 to 21-CNG 25 to 26-“scrappage CNG 21-25”, 0) Units: veh.

(052) “CNG TF 26–30 years old”= INTEG (CNG 25 to 26-final scrappage CNG-“scrappage CNG 26-30”, 0) Units: veh.

(053) “CNG TF 6–10 years old”= INTEG (CNG 5 to 6-CNG 10 to 11-“scrappage CNG 6-10”, 0) Units: veh.

(054) “CNG truck efficiency”= 0.0629 Units: m^3/(ton * km).

(055) “CNG/biomethane truck fleet”= “CNG TF 0–5 years old”+“CNG TF 6–10 years old”+“CNG TF 11–15 years old”+“CNG TF 16–20 years old” +“CNG TF 21–25 years old”+“CNG TF 26–30 years old” Units: veh.

(056) “CNG/biomethane truck share”= 0 * TANH (15 * policies towards trucks alternative fuels + 0) + 0 Units: Dmnl.

(057) “CNG/biomethane trucks adoption”= truck fleet inflow * “CNG/biomethane truck share” Units: veh/Year.

(058) CO2 budget 2 °C = 1.15e + 12 Units: ton.

(059) control 2 °C = IF THEN ELSE (total freight emissions<“% budget 2° C Brazilian freight”, 0, 1) Units: Dmnl.

(060) DB 10 to 11 = DELAY FIXED (DB 5 to 6-“scrappage DB 6-10”, 5, 0) Units: veh/Year.

(061) DB 15 to 16 = DELAY FIXED (DB 10 to 11-“scrappage DB 11-15”, 5, 0) Units: veh/Year.

(062) DB 20 to 21 = DELAY FIXED (DB 15 to 16-“scrappage DB 16-20”, 5, 0) Units: veh/Year.

(063) DB 25 to 26 = DELAY FIXED (DB 20 to 21-“scrappage DB 21-25”, 5, 0) Units: veh/Year.

(064) DB 5 to 6 = DELAY FIXED (biodiesel trucks adoption-“scrappage DB 0-5”, 5, 0) Units: veh/Year.

(065) “DBBF 0–5 years old”= INTEG (biodiesel barge adoption-DBBF 5 to 6-“scrappage DBBF 0-5”, 0) Units: veh.

(066) “diesel + biodiesel TF 26–30 years old”= INTEG (DB 25 to 26-final scrappage DB-“scrappage DB 26-30”, 0) Units: veh.

(067) “diesel + biodiesel truck share”= 0 * TANH (15 * policies towards trucks alternative fuels + 0) + 1 Units: Dmnl.

(068) E 25 to 26 = DELAY FIXED (E 20 to 21-“scrappage electric 21-25”, 5, 0) Units: veh/Year.

(069) electric truck share = 0 * TANH (15 * policies towards trucks alternative fuels + 0) + 0 Units: Dmnl.

(070) electric trucks adoption = truck fleet inflow * electric truck share Units: veh/Year.

(071) “ETF 26–30 years old”= INTEG (E 25 to 26-final scrappage-“scrappage electric 26-30”, 0) Units: veh.

(072) Brazilian freight transport emissions 2020 = 7.97e + 07 Units: ton.

(073) “CO2 budget 1.5 °C”= 4e + 11 Units: ton.

(074) “control 1.5 °C”= IF THEN ELSE (total freight emissions<“% budget 1.5° C Brazilian freight”, 0, 1) Units: Dmnl.

(075) DBBF 10 to 11 = DELAY FIXED (DBBF 5 to 6-“scrappage DBBF 6-10”, 5, 0) Units: veh/Year.

(076) “DBBF 11–15 years old”= INTEG (DBBF 10 to 11-DBBF 15 to 16-“scrappage DBBF 11-15”, 0) Units: veh.

(077) DBBF 15 to 16 = DELAY FIXED (DBBF 10 to 11-“scrappage DBBF 11-15”, 5, 0) Units: veh/Year.

(078) “DBBF 16–20 years old”= INTEG (DBBF 15 to 16-DBBF 20 to 21-“scrappage DBBF 16-20”, 0) Units: veh.

(079) DBBF 20 to 21 = DELAY FIXE (DBBF 15 to 16-“scrappage DBBF 16-20”, 5, 0) Units: veh/Year.

(080) “DBBF 21–25 years old”= INTEG (DBBF 20 to 21-DBBF 25 to 26-“scrappage DBBF 21-25”, 0) Units: veh.

(081) DBBF 25 to 26 = DELAY FIXED (DBBF 20 to 21-“scrappage DBBF 21-25”, 5, 0) Units: veh/Year.

(082) “DBBF 26–30 years old”= INTEG (DBBF 25 to 26-“scrappage DBBF 26-30”, 0) Units: veh.

(083) DBBF 5 to 6 = DELAY FIXED (biodiesel barge adoption-“scrappage DBBF 0-5”, 5, 0) Units: veh/Year.

(084) “DBBF 6–10 years old”= INTEG (DBBF 5 to 6-DBBF 10 to 11-“scrappage DBBF 6-10”, 0) Units: veh.

(085) “DBTR 0–5 years old”= INTEG (biodiesel trains adoption-DBTR 5 to 6-“scrappage DBTR 0-5”, 0) Units: veh.

(086) DBTR 10 to 11 = DELAY FIXED (DBTR 5 to 6-“scrappage DBTR 6-10”, 5, 0) Units: veh/Year.

(087) “DBTR 11–15 years old”= INTEG (DBTR 10 to 11-DBTR 15 to 16-“scrappage DBTR 11-15”, 0) Units: veh.

(088) DBTR 15 to 16 = DELAY FIXED (DBTR 10 to 11-“scrappage DBTR 11-15”, 5, 0) Units: veh/Year.

(089) “DBTR 16–20 years old”= INTEG (DBTR 15 to 16-DBTR 20 to 21-“scrappage DBTR 16-20”, 0) Units: veh.

(090) DBTR 20 to 21 = DELAY FIXED (DBTR 15 to 16-“scrappage DBTR 16-20”, 5, 0) Units: veh/Year.

(091) “DBTR 21–25 years old”= INTEG (DBTR 20 to 21-DBTR 25 to 26-“scrappage DBTR 21-25”, 0) Units: veh.

(092) DBTR 25 to 26 = DELAY FIXED (DBTR 20 to 21-“scrappage DBTR 21-25”, 5, 0) Units: veh/Year.

(093) “DBTR 26–30 years old”= INTEG (DBTR 25 to 26-“scrappage DBTR 26-30”, 0) Units: veh.

(094) DBTR 5 to 6 = DELAY FIXED (biodiesel trains adoption-“scrappage DBTR 0-5”, 5, 0) Units: veh/Year.

(095) “DBTR 6–10 years old”= INTEG (DBTR 5 to 6-DBTR 10 to 11-“scrappage DBTR 6-10”, 0) Units: veh.

(096) diesel barge efficiency = 0.0038 Units: l/(ton * km).

(097) diesel train efficiency = 0.0047 Units: l/(ton * km).

(098) “diesel + biodiesel barge fleet”= “DBBF 0–5 years old”+“DBBF 6–10 years old”+“DBBF 11–15 years old”+“DBBF 16–20 years old” +“DBBF 21–25 years old”+“DBBF 26–30 years old” Units: veh.

(099) “diesel + biodiesel barge share”= 0 * TANH (15 * policies towards barges alternative fuels + 0) + 1 Units: Dmnl.

(100) “diesel + biodiesel TF 0–5 years old”= INTEG (biodiesel trucks adoption-DB 5 to 6-“scrappage DB 0-5”, 0) Units: veh.

(101) “diesel + biodiesel TF 11–15 years old”= INTEG (DB 10 to 11-DB 15 to 16-“scrappage DB 11-15”, 0) Units: veh.

(102) “diesel + biodiesel TF 16–20 years old”= INTEG (DB 15 to 16-DB 20 to 21-“scrappage DB 16-20”, 0) Units: veh.

(103) “diesel + biodiesel TF 21–25 years old”= INTEG (DB 20 to 21-DB 25 to 26-“scrappage DB 21-25”, 0) Units: veh.

(104) “diesel + biodiesel TF 6–10 years old”= INTEG (DB 5 to 6-DB 10 to 11-“scrappage DB 6-10”, 0) Units: veh.

(105) “diesel + biodiesel train fleet”= “DBTR 0–5 years old”+“DBTR 6–10 years old”+“DBTR 11–15 years old”+“DBTR 16–20 years old” +“DBTR 21–25 years old”+“DBTR 26–30 years old” Units: veh.

(106) “diesel + biodiesel train share”= 0 * TANH (15 * policies towards trains alternative fuels + 0) + 1 Units: Dmnl.

(107) “diesel + biodiesel truck efficiency”= 0.0577 Units: l/(ton * km).

108) “diesel + biodiesel truck fleet”= “diesel + biodiesel TF 0–5 years old”+“diesel + biodiesel TF 6–10 years old”+“diesel + biodiesel TF 11–15 years old”+“diesel + biodiesel TF 16–20 years old” +“diesel + biodiesel TF 21–25 years old”+“diesel + biodiesel TF 26–30 years old” Units: veh.

(109) E 10 to 11 = DELAY FIXED (E 5 to 6-“scrappage electric 6-10”, 5, 0) Units: veh/Year.

(110) E 15 to 16 = DELAY FIXED (E 10 to 11-“scrappage electric 11-15”, 5, 0) Units: veh/Year.

(111) E 20 to 21 = DELAY FIXED (E 15 to 16-“scrappage electric 16-20”, 5, 0) Units: veh/Year.

(112) E 5 to 6 = DELAY FIXED (electric trucks adoption-“scrappage electric 0-5”, 5, 0) Units: veh/Year.

(113) “EBF 0–5 years old”= INTEG (electric barges adoption-EBF 5 to 6-“scrappage electric barge 0-5”, 0) Units: veh.

(114) EBF 10 to 11 = DELAY FIXED (EBF 5 to 6-“scrappage electric barge 6-10”, 5, 0) Units: veh/Year.

(115) EBF 15 to 16 = DELAY FIXED (EBF 10 to 11-“scrappage electric barge 11-15”, 5, 0) Units: veh/Year.

(116) EBF 20 to 21 = DELAY FIXED (EBF 15 to 16-“scrappage electric barge 16-20”, 5, 0) Units: veh/Year.

(117) “EBF 21–25 years old”= INTEG (EBF 20 to 21-EBF 25 to 26-“scrappage electric barge 21-25”, 0) Units: veh.

(118) EBF 25 to 26 = DELAY FIXED (EBF 20 to 21-“scrappage electric barge 21-25”, 5, 0) Units: veh/Year.

(119) “EBF 26–30 years old”= INTEG (EBF 25 to 26-“scrappage electric barge 26-30”, 0) Units: veh.

(120) EBF 5 to 6 = DELAY FIXED (electric barges adoption-“scrappage electric barge 0-5”, 5, 0) Units: veh/Year.

(121) “EBF 6–10 years old”= INTEG (EBF 5 to 6-EBF 10 to 11-“scrappage electric barge 6-10”, 0) Units: veh.

(122) “EBF 11–15 years old”= INTEG (EBF 10 to 11-EBF 15 to 16-“scrappage electric barge 11-15”, 0) Units: veh.

(123) “EBF 16–20 years old”= INTEG (EBF 15 to 16-EBF 20 to 21-“scrappage electric barge 16-20”, 0) Units: veh.

(124) electric barge efficiency = 28 Units: Wh/(ton * km).

(125) electric barge fleet= “EBF 0–5 years old”+“EBF 6–10 years old”+“EBF 11–15 years old”+“EBF 16–20 years old”+“EBF 21–25 years old”+“EBF 26–30 years old” Units: veh.

(126) electric barge share = 0 * TANH (15 * policies towards barges alternative fuels + 0) + 0 Units: Dmnl.

(127) electric barges adoption = barge fleet inflow * electric barge share Units: veh/Year.

(128) electric train efficiency = 53.1 Units: Wh/(ton * km).

(129) electric train fleet= “ETR 0–5 years old”+“ETR 6–10 years old”+“ETR 11–15 years old”+“ETR 16–20 years old” +“ETR 21–25 years old”+“ETR 26–30 years old” Units: veh.

(130) electric train share = 0 * TANH (15 * policies towards trains alternative fuels + 0) + 0 Units: Dmnl.

(131) electric trains adoption = train fleet inflow * electric train share Units: veh/Year.

(132) electric truck efficiency = 1.35 Units: kWh/(ton * km).

(133) electric truck fleet= “ETF 0–5 years old”+“ETF 6–10 years old”+“ETF 11–15 years old”+“ETF 16–20 years old” +“ETF 21–25 years old”+“ETF 26–30 years old” Units: veh.

(134) “ETF 0–5 years old”= INTEG (electric trucks adoption-E 5 to 6-“scrappage electric 0-5”, 0) Units: veh.

(135) “ETF 11–15 years old”= INTEG (E 10 to 11-E 15 to 16-“scrappage electric 11-15”, 0) Units: veh.

(136) “ETF 16–20 years old”= INTEG (E 15 to 16-E 20 to 21-“scrappage electric 16-20”, 0) Units: veh.

(137) “ETF 21–25 years old”= INTEG (E 20 to 21-E 25 to 26-“scrappage electric 21-25”, 0) Units: veh.

(138) “ETF 6–10 years old”= INTEG (E 5 to 6-E 10 to 11-“scrappage electric 6-10”, 0) Units: veh.

(139) “ETR 0–5 years old”= INTEG (electric trains adoption-ETR 5 to 6-“scrappage electric train 0-5”, 0) Units: veh.

(140) ETR 10 to 11 = DELAY FIXED (ETR 5 to 6-“scrappage electric train 6-10”, 5, 0) Units: veh/Year.

(141) “ETR 11–15 years old”= INTEG (ETR 10 to 11-ETR 15 to 16-“scrappage electric train 11-15”, 0) Units: veh.

(142) ETR 15 to 16 = DELAY FIXED (ETR 10 to 11-“scrappage electric train 11-15”, 5, 0) Units: veh/Year.

(143) “ETR 16–20 years old”= INTEG (ETR 15 to 16-ETR 20 to 21-“scrappage electric train 16-20”, 0) Units: veh.

(144) ETR 20 to 21 = DELAY FIXED (ETR 15 to 16-“scrappage electric train 16-20”, 5, 0) Units: veh/Year.

(145) “ETR 21–25 years old”= INTEG (ETR 20 to 21-ETR 25 to 26-“scrappage electric train 21-25”, 0) Units: veh.

(146) ETR 25 to 26 = DELAY FIXED (ETR 20 to 21-“scrappage electric train 21-25”, 5, 0) Units: veh/Year.

(147) “ETR 26–30 years old”= INTEG (ETR 25 to 26-“scrappage electric train 26-30”, 0) Units: veh.

(148) ETR 5 to 6 = DELAY FIXED (electric trains adoption-“scrappage electric train 0-5”, 5, 0) Units: veh/Year.

(149) “ETR 6–10 years old”= INTEG (ETR 5 to 6-ETR 10 to 11-“scrappage electric train 6-10”, 0) Units: veh.

(150) final scrappage = DELAY FIXED (E 25 to 26-“scrappage electric 26-30”, 5, 0) Units: veh/Year.

(151) final scrappage CNG = DELAY FIXED (CNG 25 to 26-“scrappage CNG 26-30”, 5, 0) Units: veh/Year.

(152) final scrappage DB = DELAY FIXED (DB 25 to 26-“scrappage DB 26-30”, 5, 0) Units: veh/Year.

(153) final scrappage HTF = DELAY FIXED (HTF 25 to 26-“scrappage HTF 26-30”, 5, 0) Units: veh/Year.

(154) FINAL TIME = 2050 Units: Year The final time for the simulation.

(155) global CO2 emissions 2020 = 3.481e + 10 Units: ton.

(156) HTF 10 to 11 = DELAY FIXED (HTF 5 to 6-“scrappage HTF 6-10”, 5, 0) Units: veh/Year.

(157) HTF 15 to 16 = DELAY FIXED (HTF 10 to 11-“scrappage HTF 11-15”, 5, 0) Units: veh/Year.

(158) HTF 20 to 21 = DELAY FIXED (HTF 15 to 16-“scrappage HTF 16-20”, 5, 0) Units: veh/Year.

(159) HTF 25 to 26 = DELAY FIXED (HTF 20 to 21-“scrappage HTF 21-25”, 5, 0) Units: veh/Year.

(160) HTF 5 to 6 = DELAY FIXED (hydrogen trucks adoption-“scrappage HTF 0-5”, 5, 0) Units: veh/Year.

(161) “hydrogen TF 0–5 years old”= INTEG (hydrogen trucks adoption-HTF 5 to 6-“scrappage HTF 0-5”, 0) Units: veh.

(162) “hydrogen TF 11–15 years old”= INTEG (HTF 10 to 11-HTF 15 to 16-“scrappage HTF 11-15”, 0) Units: veh.

(163) “hydrogen TF 16–20 years old”= INTEG (HTF 15 to 16-HTF 20 to 21-“scrappage HTF 16-20”, 0) Units: veh.

(164) “hydrogen TF 21–25 years old”= INTEG (HTF 20 to 21-HTF 25 to 26-“scrappage HTF 21-25”, 0) Units: veh.

(165) “hydrogen TF 26–30 years old”= INTEG (HTF 25 to 26-final scrappage HTF-“scrappage HTF 26-30”, 0) Units: veh.

(166) “hydrogen TF 6–10 years old”= INTEG (HTF 5 to 6-HTF 10 to 11-“scrappage HTF 6-10”, 0) Units: veh.

(167) hydrogen truck efficiency = 0.1 Units: kg/(ton * km).

(168) hydrogen truck fleet= “hydrogen TF 0–5 years old”+“hydrogen TF 6–10 years old”+“hydrogen TF 11–15 years old” +“hydrogen TF 16–20 years old”+“hydrogen TF 21–25 years old”+“hydrogen TF 26–30 years old” Units: veh.

(169) hydrogen truck share = 0 * TANH (15 * policies towards trucks alternative fuels + 0) + 0 Units: Dmnl.

(170) hydrogen trucks adoption = truck fleet inflow * hydrogen truck share Units: veh/Year.

(171) ideal barge fleet = waterway transport activity/“tkm/barge” Units: veh.

(172) ideal train fleet = rail transport activity/“tkm/train” Units: veh.

(173) ideal truck fleet = road transport activity/“tkm/truck” Units: veh.

(174) initial freight transport activity = 1.745e + 12 Units: ton * km.

(175) INITIAL TIME = 2020 Units: Year The initial time for the simulation.

(176) old barge fleet = INTEG (-old barge scrappage rate, 2709) Units: veh.

(177) old barge scrappage rate = old barge fleet * barges scrappage rate/year Units: veh/Year.

(178) policies towards alternative modes = RAMP(0.0666667, 2020, 2035) Units: Dmnl.

(179) policies towards barges alternative fuels = RAMP (0.033, 2020, 2050) Units: Dmnl.

(180) policies towards speeding up fleet renewal = RAMP (0.2, 2020, 2025) Units: Dmnl.

(181) policies towards trains alternative fuels = RAMP (0.033, 2020, 2050) Units: Dmnl.

(182) policies towards trucks alternative fuels = RAMP (0.0666667, 2020, 2035) Units: Dmnl.

(183) rail CO2 emissions = INTEG (rail diesel emissions + rail electricity emissions), 7e + 06) Units: ton.

(184) rail diesel emissions = train diesel consumption * “rail diesel KgCO2/L” * “ton/kg”/year Units: ton/Year.

(185) “rail diesel KgCO2/L”= 2.697 Units: kg/l.

(186) rail electricity emissions = train electricity consumption * “rail electricity KgCO2/Wh” * “ton/kg”/year Units: ton/Year.

(187) “rail electricity KgCO2/Wh”= 0 Units: kg/Wh.

(188) rail share = 0 * TANH (15 * policies towards alternative modes + 0) + 0.22 Units: Dmnl.

(189) rail transport activity = yearly freight transport activity * rail share) Units: ton * km.

(190) “road biodiesel KgCO2/L”= 2.431 Units: kg/l.

(191) road biomethane CO2 emission factor = 0.24 Units: kg/m^3.

(192) road biomethane emissions = truck biomethane consumption * road biomethane CO2 emission factor * “ton/kg”/year Units: ton/Year.

(193) “road CNG CO2 emission factor”= 2.101 Units: kg/m^3.

194) “road CNG emissions”= “truck CNG consumption” * “road CNG CO2 emission factor” * “ton/kg”/year Units: ton/Year.

(195) road CO2 emissions = INTEG (road hydrogen emissions + road biomethane emissions+“road CNG emissions” +“road diesel + biodiesel emissions”+road electricity emissions), 6.72e + 07) Units: ton.

(196) “road diesel KgCO2/L”= 2.697 Units: kg/l.

(197) “road diesel + biodiesel CO2 emission factor”= “road biodiesel KgCO2/L” * “% biodiesel in diesel”)+“road diesel KgCO2/L” * (1-“% biodiesel in diesel”) Units: kg/l.

(198) “road diesel + biodiesel emissions”= “truck diesel + biodiesel consumption” * “road diesel + biodiesel CO2 emission factor” * “ton/kg”/year Units: ton/Year.

(199) road electricity CO2 emission factor = 0 Units: kg/kWh.

(200) road electricity emissions = truck electricity consumption * road electricity CO2 emission factor * “ton/kg”/year Units: ton/Year.

(201) road hydrogen CO2 emission factor = 0 Units: kg/kg.

(202) road hydrogen emissions = truck hydrogen consumption * road hydrogen CO2 emission factor * “ton/kg”/year Units: ton/Year.

(203) road share = 0 * TANH (15 * policies towards alternative modes + 0) + 0.63 Units: Dmnl.

(204) road transport activity= (yearly freight transport activity * road share) Units: ton * km.

(205) SAVEPER = 1 Units: Year [0,?] The frequency with which output is stored.

(206) “scrappage CNG 0-5” = ”CNG/biomethane trucks adoption“ * ”truck scrappage rate 0-5” Units: veh/Year.

(207) “scrappage CNG 11-15” = CNG 10 to 11 * ”truck scrappage rate 11-15” Units: veh/Year.

(208) “scrappage CNG 16-20” = CNG 15 to 16 * ”truck scrappage rate 16-20” Units: veh/Year.

(209) “scrappage CNG 21-25” = CNG 20 to 21 * ”truck scrappage rate 21-25” Units: veh/Year.

(210) “scrappage CNG 26-30” = CNG 25 to 26 * ”truck scrappage rate 26-30” Units: veh/Year.

(211) “scrappage CNG 6-10” = CNG 5 to 6 * ”truck scrappage rate 6-10” Units: veh/Year.

(212) “scrappage DB 0-5” = biodiesel trucks adoption * ”truck scrappage rate 0-5” Units: veh/Year.

(213) “scrappage DB 11-15” = DB 10 to 11 * ”truck scrappage rate 11-15” Units: veh/Year.

(214) “scrappage DB 16-20” = DB 15 to 16 * ”truck scrappage rate 16-20” Units: veh/Year.

(215) “scrappage DB 21-25” = DB 20 to 21 * ”truck scrappage rate 21-25” Units: veh/Year.

(216) “scrappage DB 26-30” = DB 25 to 26 * ”truck scrappage rate 26-30” Units: veh/Year.

(217) “scrappage DB 6-10” = DB 5 to 6 * ”truck scrappage rate 6-10” Units: veh/Year.

(218) “scrappage DBBF 0-5” = biodiesel barge adoption * ”barge scrappage rate 0-5” Units: veh/Year.

(219) “scrappage DBBF 11-15” = DBBF 10 to 11 * ”barge scrappage rate 11-15” Units: veh/Year.

(220) “scrappage DBBF 16-20” = DBBF 15 to 16 * ”barge scrappage rate 16-20” Units: veh/Year.

(221) “scrappage DBBF 21-25” = DBBF 20 to 21 * ”barge scrappage rate 21-25” Units: veh/Year.

(222) “scrappage DBBF 26-30” = DBBF 25 to 26 * ”barge scrappage rate 26-30” Units: veh/Year.

(223) “scrappage DBBF 6-10” = DBBF 5 to 6 * ”barge scrappage rate 6-10” Units: veh/Year.

(224) “scrappage DBTR 0-5” = biodiesel trains adoption * ”train scrappage rate 0-5” Units: veh/Year.

(225) “scrappage DBTR 11-15” = DBTR 10 to 11 * ”train scrappage rate 11-15” Units: veh/Year.

(226) “scrappage DBTR 16-20” = DBTR 15 to 16 * ”train scrappage rate 16-20” Units: veh/Year.

(227) “scrappage DBTR 21-25” = DBTR 20 to 21 * ”train scrappage rate 21-25” Units: veh/Year.

(228) “scrappage DBTR 26-30” = DBTR 25 to 26 * ”train scrappage rate 26-30” Units: veh/Year.

(229) “scrappage DBTR 6-10” = DBTR 5 to 6 * ”train scrappage rate 6-10” Units: veh/Year.

(230) “scrappage electric 0-5” = electric trucks adoption * ”truck scrappage rate 0-5” Units: veh/Year.

(231) “scrappage electric 11-15” = E 10 to 11 * ”truck scrappage rate 11-15” Units: veh/Year.

(232) “scrappage electric 16-20” = E 15 to 16 * ”truck scrappage rate 16-20” Units: veh/Year.

(233) “scrappage electric 21-25” = E 20 to 21 * ”truck scrappage rate 21-25” Units: veh/Year.

(234) “scrappage electric 26-30” = E 25 to 26 * ”truck scrappage rate 26-30” Units: veh/Year.

(235) “scrappage electric 6-10” = E 5 to 6 * ”truck scrappage rate 6-10” Units: veh/Year.

(236) “scrappage electric barge 0-5” = electric barges adoption * ”barge scrappage rate 0-5” Units: veh/Year.

(237) “scrappage electric barge 11-15” = EBF 10 to 11 * ”barge scrappage rate 11-15” Units: veh/Year.

(238) “scrappage electric barge 16-20” = EBF 15 to 16 * ”barge scrappage rate 16-20” Units: veh/Year.

(239) “scrappage electric barge 21-25” = EBF 20 to 21 * ”barge scrappage rate 21-25” Units: veh/Year.

(240) “scrappage electric barge 26-30” = EBF 25 to 26 * ”barge scrappage rate 26-30” Units: veh/Year.

(241) “scrappage electric barge 6-10” = EBF 5 to 6 * ”barge scrappage rate 6-10” Units: veh/Year.

(242) “scrappage electric train 0-5” = electric trains adoption * ”train scrappage rate 0-5” Units: veh/Year.

(243) “scrappage electric train 11-15” = ETR 10 to 11 * ”train scrappage rate 11-15” Units: veh/Year.

(244) “scrappage electric train 16-20” = ETR 15 to 16 * ”train scrappage rate 16-20” Units: veh/Year.

(245) “scrappage electric train 21-25” = ETR 20 to 21 * ”train scrappage rate 21-25” Units: veh/Year.

(246) “scrappage electric train 26-30” = ETR 25 to 26 * ”train scrappage rate 26-30” Units: veh/Year.

(247) “scrappage electric train 6-10” = ETR 5 to 6 * ”train scrappage rate 6-10” Units: veh/Year.

(248) “scrappage HTF 0-5” = hydrogen trucks adoption * ”truck scrappage rate 0-5” Units: veh/Year.

(249) “scrappage HTF 11-15” = HTF 10 to 11 * ”truck scrappage rate 11-15” Units: veh/Year.

(250) “scrappage HTF 16-20” = HTF 15 to 16 * ”truck scrappage rate 16-20” Units: veh/Year.

(251) “scrappage HTF 21-25” = HTF 20 to 21 * ”truck scrappage rate 21-25” Units: veh/Year.

(252) “scrappage HTF 26-30” = HTF 25 to 26 * ”truck scrappage rate 26-30” Units: veh/Year.

(253) “scrappage HTF 6-10” = HTF 5 to 6 * ”truck scrappage rate 6-10” Units: veh/Year.

(254) “scrappage rate 1960-1969” = ”train fleet 1960-1969” * “trains scrappage rate 1960-1969”/year Units: veh/Year.

(255) “scrappage rate 1970-1979” = ”train fleet 1970-1979” * “trains scrappage rate 1970-1979”/year Units: veh/Year.

(256) “scrappage rate 1978-1983” = IF THEN ELSE (”speed up fleet renewal - policy control“=0, ”truck fleet 1978-1983” * “trucks scrappage rate 1978-1983”/year, (1 + policies towards speeding up fleet renewal) * ”truck fleet 1978-1983” * “trucks scrappage rate 1978-1983”/year) Units: veh/Year.

(257) “scrappage rate 1980-1989” = ”train fleet 1980-1989” * “trains scrappage rate 1980-1989”/year Units: veh/Year.

(258) “scrappage rate 1984-1989” = IF THEN ELSE (”speed up fleet renewal - policy control“=0, ”truck fleet 1984-1989” * “trucks scrappage rate 1984-1989”/year, (1 + policies towards speeding up fleet renewal) * ”truck fleet 1984-1989” * “trucks scrappage rate 1984-1989”/year) Units: veh/Year.

(259) “scrappage rate 1990-1995” = IF THEN ELSE (”speed up fleet renewal - policy control“=0, ”truck fleet 1990-1995” * “trucks scrappage rate 1990-1995”/year, (1 + policies towards speeding up fleet renewal) * ”truck fleet 1990-1995” * “trucks scrappage rate 1990-1995”/year) Units: veh/Year.

(260) “scrappage rate 1990-1999” = ”train fleet 1990-1999” * “trains scrappage rate 1990-1999”/year Units: veh/Year.

(261) “scrappage rate 1996-2001” = IF THEN ELSE (”speed up fleet renewal - policy control“=0, ”truck fleet 1996-2001” * “trucks scrappage rate 1996-2001”/year, (1 + policies towards speeding up fleet renewal) * ”truck fleet 1996-2001” * “trucks scrappage rate 1996-2001”/year) Units: veh/Year.

(262) “scrappage rate 2000-2009” = ”train fleet 2000-2009” * “trains scrappage rate 2000-2009”/year Units: veh/Year.

(263) “scrappage rate 2002-2007” = IF THEN ELSE (”speed up fleet renewal - policy control“=0, ”truck fleet 2002-2007” * “trucks scrappage rate 2002-2007”/year, (1 + policies towards speeding up fleet renewal) * ”truck fleet 2002-2007” * “trucks scrappage rate 2002-2007”/year) Units: veh/Year.

(264) “scrappage rate 2008-2013” = IF THEN ELSE (”speed up fleet renewal - policy control“=0, ”truck fleet 2008-2013” * “trucks scrappage rate 2008-2013”/year, (1 + policies towards speeding up fleet renewal) * ”truck fleet 2008-2013” * “trucks scrappage rate 2008-2013”/year) Units: veh/Year.

(265) “scrappage rate 2010-2019” = ”train fleet 2010-2019” * “trains scrappage rate 2010-2019”/year Units: veh/Year.

(266) “scrappage rate 2014-2019” = IF THEN ELSE (”speed up fleet renewal - policy control“=0, ”truck fleet 2014-2019” * “trucks scrappage rate 2014-2019”/year, (1 + policies towards speeding up fleet renewal) * ”truck fleet 2014-2019” * “trucks scrappage rate 2014-2019”/year) Units: veh/Year.

(267) “scrappage rate > 1959” = ”truck fleet > 1960” * “trains scrappage rate > 1959”/year Units: veh/Year.

(268) “speed up fleet renewal - policy control”= 1 Units: Dmnl.

(269) TIME STEP = 0.125 Units: Year [0,?] The time step for the simulation.

(270) “tkm/barge”= 1.13787e + 08 Units: (ton * km)/veh.

(271) “tkm/train”= 1.03586e + 08 Units: (ton * km)/veh.

(272) “tkm/truck”= 504,249 Units: (ton * km)/veh.

(273) “ton/kg”= 1/1000 Units: ton/kg.

(274) total barge fleet= “diesel + biodiesel barge fleet”+electric barge fleet + old barge fleet Units: veh.

(275) total freight emissions = rail CO2 emissions + road CO2 emissions + waterway CO2 emissions Units: ton.

(276) total old train fleet= “truck fleet > 1960”+”train fleet 1960-1969”+“train fleet 1970-1979”+”train fleet 1980-1989”+“train fleet 1990-1999”+”train fleet 2000-2009”+“train fleet 2010-2019” Units: veh.

(277) total old truck fleet= “truck fleet 1978-1983” +”truck fleet 1984-1989” +“truck fleet 1990-1995” +”truck fleet 1996-2001” +“truck fleet 2002-2007”+”truck fleet 2008-2013”+“truck fleet 2014-2019” Units: veh.

(278) total train fleet= “diesel + biodiesel train fleet”+electric train fleet + total old train fleet Units: veh.

(279) total truck fleet = total old truck fleet+“diesel + biodiesel truck fleet”+“CNG/biomethane truck fleet” +electric truck fleet + hydrogen truck fleet Units: veh.

(280) train diesel consumption = transport performed with diesel train * diesel train efficiency Units: l.

(281) train electricity consumption = transport performed with electric train * electric train efficiency Units: Wh.

(282) “train fleet 1960-1969” = INTEG (-”scrappage rate 1960-1969”, 284) Units: veh.

(283) “train fleet 1970-1979” = INTEG (-”scrappage rate 1970-1979”, 704) Units: veh.

(284) “train fleet 1980-1989” = INTEG (-”scrappage rate 1980-1989”, 721) Units: veh.

(285) “train fleet 1990-1999” = INTEG (-”scrappage rate 1990-1999”, 181) Units: veh.

(286) “train fleet 2000-2009” = INTEG (-”scrappage rate 2000-2009”, 462) Units: veh.

(287) “train fleet 2010-2019” = INTEG (-”scrappage rate 2010-2019”, 425) Units: veh.

(288) train fleet from 2020 onwards = INTEG (train fleet inflow, 0) Units: veh.

(289) train fleet inflow = IF THEN ELSE (total train fleet < ideal train fleet, ideal train fleet-total train fleet)/year, 0) Units: veh/Year.

(290) “train scrappage rate 0-5” = 1- (EXP (25.4501–3)/7.97197) + EXP (2 * 25.4501–3)/7.97197))/ (EXP(25.4501/7.97197) + EXP(2 * 25.4501–3)/7.97197)) Units: Dmnl.

(291) “train scrappage rate 11-15” = 1- (EXP(25.4501–13)/7.97197) + EXP(2 * 25.4501–13)/7.97197))/(EXP(25.4501/7.97197) + EXP(2 * 25.4501–13)/7.97197)) Units: Dmnl.

(292) “train scrappage rate 16-20” = 1- (EXP(25.4501–18)/7.97197) + EXP(2 * 25.4501–18)/7.97197))/(EXP(25.4501/7.97197) + EXP(2 * 25.4501–18)/7.97197)) Units: Dmnl.

(293) “train scrappage rate 21-25” = 1- (EXP(25.4501–23)/7.97197) + EXP(2 * 25.4501–23)/7.97197))/(EXP(25.4501/7.97197) + EXP(2 * 25.4501–23)/7.97197)) Units: Dmnl.

(294) “train scrappage rate 26-30” = 1- (EXP(25.4501–28)/7.97197) + EXP(2 * 25.4501–28)/7.97197))/(EXP(25.4501/7.97197) + EXP(2 * 25.4501–28)/7.97197)) Units: Dmnl.

(295) “train scrappage rate 6-10” = 1- (EXP(25.4501–8)/7.97197) + EXP(2 * 25.4501–8)/7.97197))/(EXP(25.4501/7.97197) + EXP(2 * 25.4501–8)/7.97197)) Units: Dmnl.

(296) “trains scrappage rate 1960-1969” = 1-(EXP(25.4501-(”average train age 1960-1969”/year))/7.97197) + EXP(2 * 25.4501-“average train age 1960-1969”/year))/7.97197))/(EXP(25. 4501/7.97197) + EXP(2 * 25.4501-(”average train age 1960-1969”/year))/7.97197)) Units: Dmnl.

(297) “trains scrappage rate 1970-1979”=1-(EXP(25.4501-(”average train age 1970-1979”/year))/7.97197) + EXP(2 * 25.4501-(“average train age 1970-1979”/year))/7.97197))/(EXP (25.4501/ 7.97197) + EXP(2 * 25.4501-(”average train age 1970-1979”/year))/7.97197)) Units: Dmnl.

(298) “trains scrappage rate 1980-1989” =1-(EXP(25.4501-(”average train age 1980-1989”/year))/7.97197) + EXP(2 * 25.4501-

(“average train age 1980-1989”/year))/7.97197))/(EXP(25.4501/7.97197) + EXP(2 * 25.4501-(”average train age 1980-1989”/year))/7.97197)) Units: Dmnl.

(299) “trains scrappage rate 1990-1999” = 1- (EXP(25.4501-(”average train age 1990-1999”/year))/7.97197) + EXP(2 * 25.4501-(“average train age 1990-1999”/year))/7.97197))/(EXP (25. 4501/7.97197) + EXP(2 * 25.4501-(”average train age 1990-1999”/year))/7.97197)) Units: Dmnl.

(300) “trains scrappage rate 2000-2009” = 1- (EXP(25.4501-(”average train age 2000-2009”/year))/7.97197) + EXP(2 * 25.4501-“average train age 2000-2009”/year))/7.97197))/(EXP (25. 4501/7.97197) + EXP(2 * 25.4501-(”average train age 2000-2009”/year))/7.97197)) Units: Dmnl.

(301) “trains scrappage rate 2010-2019”=1-(EXP(25.4501-(“average train age 2010-2019”/year))/ 7.97197) + EXP(2 * 25.4501-(“average train age 2010-2019”/year))/7.97197))/(EXP (25.4501/ 7.97197) + EXP(2 * 25.4501-(“average train age 2010-2019”/year))/7.97197)) Units: Dmnl.

(302) “trains scrappage rate > 1959” = 1-(EXP(25.4501-(”average train age > 1959”/year))/7.97197) + EXP(2 * 25.4501-(“average train age > 1959”/year))/7.97197))/(EXP(25.4501/7.97197) + EXP(2 * 25.4501-(”average train age > 1959”/year))/7.97197)) Units: Dmnl.

(303) “transport performed with CNG/biomethane truck”= road transport activity * “% CNG/biomethane truck” Units: ton * km.

(304) transport performed with diesel barge = waterway transport activity * “% diesel + biodiesel barge” Units: ton * km.

(305) transport performed with diesel train = rail transport activity * “% diesel + biodiesel train” Units: ton * km.

(306) “transport performed with diesel + biodiesel truck”= road transport activity * “% diesel + biodiesel truck” Units: ton * km.

(307) transport performed with electric barge = waterway transport activity * “% electric barge” Units: ton * km.

(308) transport performed with electric train = rail transport activity * “% electric train” Units: ton * km.

(309) transport performed with electric truck = road transport activity * “% electric truck” Units: ton * km.

(310) transport performed with hydrogen truck = road transport activity * “% hydrogen truck” Units: ton * km.

(311) truck biomethane consumption= “transport performed with CNG/biomethane truck” * biomethane truck efficiency * 0.3 Units: m^3.

(312) “truck CNG consumption”= “transport performed with CNG/biomethane truck” * “CNG truck efficiency” * 0.7 Units: m^3.

(313) “truck diesel + biodiesel consumption”= “transport performed with diesel + biodiesel truck” * “diesel + biodiesel truck efficiency” Units: l.

(314) truck electricity consumption = transport performed with electric truck * electric truck efficiency Units: kWh.

(315) “truck fleet 1978-1983” = INTEG (-”scrappage rate 1978-1983”, 486) Units: veh.

(316) “truck fleet 1984-1989” = INTEG (-”scrappage rate 1984-1989”, 4869) Units: veh.

(317) “truck fleet 1990-1995” = INTEG (-”scrappage rate 1990-1995”, 41784) Units: veh.

(318) “truck fleet 1996-2001” = INTEG (-”scrappage rate 1996-2001”, 217737) Units: veh.

(319) “truck fleet 2002-2007” = INTEG (-”scrappage rate 2002-2007”, 412363) Units: veh.

(320) “truck fleet 2008-2013” = INTEG (-”scrappage rate 2008-2013”, 770755) Units: veh.

(321) “truck fleet 2014-2019” = INTEG (-”scrappage rate 2014-2019”, 453988) Units: veh.

(322) “truck fleet > 1960” = INTEG (-”scrappage rate > 1959”, 171) Units: veh.

(323) truck fleet inflow = IF THEN ELSE (total truck fleet < ideal truck fleet, (ideal truck fleet-total truck fleet)/year, 0) Units: veh/Year.

(324) truck hydrogen consumption = transport performed with hydrogen truck * hydrogen truck efficiency Units: kg.

(325) truck sale from 2020 onwards = INTEG (truck fleet inflow, 0) Units: veh.

(326) “truck scrappage rate 0-5” = 1-(1/(1 + EXP(0.1 * (3–17))) + 1/(1 + EXP(0.1 * (3 + 17)))) Units: Dmnl.

(327) “truck scrappage rate 11-15”= 1-(1/(1 + EXP(0.1 * (13–17))) + 1/(1 + EXP(0.1 * (13 + 17)))) Units: Dmnl.

(328) “truck scrappage rate 16-20” = 1-(1/(1 + EXP(0.1 * (18–17))) + 1/(1 + EXP(0.1 * (18 + 17)))) Units: Dmnl.

(329) “truck scrappage rate 21-25” = 1-(1/(1 + EXP(0.1 * (23–17))) + 1/(1 + EXP(0.1 * (23 + 17)))) Units: Dmnl.

(330) “truck scrappage rate 26-30” = 1-(1/(1 + EXP(0.1 * (28–17))) + 1/(1 + EXP(0.1 * (28 + 17)))) Units: Dmnl.

(331) “truck scrappage rate 6-10” = 1-(1/(1 + EXP(0.1 * (8–17))) + 1/(1 + EXP(0.1 * (8 + 17)))) Units: Dmnl.

(332) “trucks scrappage rate 1978-1983” = 1- (1/(1 + EXP(0.1 * (”average truck age 1978-1983”/year-17))) + 1/(1 + EXP(0.1 * (“average truck age 1978-1983”/year + 17)))) Units: Dmnl.

(333) “trucks scrappage rate 1984-1989” = 1-(1/(1 + EXP(0.1 * (”average truck age 1984-1989”/year-17))) + 1/(1 + EXP(0.1 * (“average truck age 1984-1989”/year + 17)))) Units: Dmnl.

(334) “trucks scrappage rate 1990-1995” = 1-(1/(1 + EXP(0.1 * (”average truck age 1990-1995”/year-17))) + 1/(1 + EXP(0.1 * (“average truck age 1990-1995”/year + 17)))) Units: Dmnl.

(335) “trucks scrappage rate 1996-2001” = 1-(1/(1 + EXP(0.1 * (”average truck age 1996-2001”/year-17))) + 1/(1 + EXP(0.1 * (“average truck age 1996-2001”/year + 17)))) Units: Dmnl.

(336) “trucks scrappage rate 2002-2007” = 1-(1/(1 + EXP(0.1 * (”average truck age 2002-2007”/year-17))) + 1/(1 + EXP(0.1 * (“average truck age 2002-2007”/year + 17)))) Units: Dmnl.

(337) “trucks scrappage rate 2008-2013” = 1-(1/(1 + EXP(0.1 * (”average truck age 2008-2013”/year-17))) + 1/(1 + EXP(0.1 * (“average truck age 2008-2013”/year + 17)))) Units: Dmnl.

(338) “trucks scrappage rate 2014-2019” = 1-(1/(1 + EXP(0.1 * (”average truck age 2014-2019”/year-17))) + 1/(1 + EXP(0.1 * (“average truck age 2014-2019”/year + 17)))) Units: Dmnl.

(339) waterway CO2 emissions = INTEG(waterway diesel emissions + waterway electricity emissions), 5.5e + 06) Units: ton.

(340) waterway diesel emissions = barge diesel consumption * “waterway diesel KgCO2/L” * “ton/kg”/year Units: ton/Year.

(341) “waterway diesel KgCO2/L”= 2.697 Units: kg/l.

(342) waterway electricity emissions = barge electricity consumption * “waterway electricity KgCO2/Wh” * “ton/kg”/year Units: ton/Year.

(343) “waterway electricity KgCO2/Wh”= 0 Units: kg/Wh.

(344) waterway share = 0 * TANH (15 * policies towards alternative modes + 0) + 0.15 Units: Dmnl.

(345) waterway transport activity= (yearly freight transport activity * waterway share) Units: ton * km.

(346) year = 1 Units: Year.

(347) yearly freight transport activity = INTEG (yearly freight transport activity inflow, initial freight transport activity) Units: ton * km.

(348) yearly freight transport activity change = 0.0343 Units: 1/Year.

(349) yearly freight transport activity inflow = yearly freight transport activity * yearly freight transport activity change Units: ton * km/Year.

B. Policy equations

Appendix B presents the policy equations used for each scenario simulation in the proposed model. Table B.1 shows the model equations for policies toward alternative modes; Table B.2 presents the equations for policies toward alternative fuels; and Table B.3 presents the equations for policies toward increasing the percentage of biodiesel in the diesel blend.

Table B1

Equations for modal share and policies toward alternative modes.[*]

Modes	BAU	Low	Medium	High
Roadway	0 * Tanh(15x + 0) + 0.63	−0.04 * Tanh(15x − 7.5) + 0.59	−0.12 * Tanh(15x − 7.5) + 0.51	−0.16 * Tanh(15x − 7.5) + 0.48
Railway	0 * Tanh(15x + 0) + 0.22	0.05 * Tanh(15x − 7.5) + 0.26	0.10 * Tanh(15x − 7.5) + 0.32	0.13 * Tanh(15x − 7.5) + 0.34
Waterway	0 * Tanh(15x + 0) + 0.15	−0.01 * Tanh(15x − 7.5) + 0.14	0.01 * Tanh(15x − 7.5) + 0.16	0.02 * Tanh(15x − 7.5) + 0.17

[*] Where x in the equations represents the variable “policies toward alternative modes”.

Table B2

Equations for fuel share and policies toward alternative fuels.[*]

Modes	Fuels	BAU	Low	Medium	High
Roadway	Diesel/biodiesel	0 * Tanh(15x + 0) + 1	−0.07 * Tanh (15x − 7.5) + 0.93	−0.16 * Tanh (15x − 7.5) + 0.84	−0.5 * Tanh (15x − 7.5) + 0.5
	Natural gas/ biomethane	0 * Tanh (15x + 0) + 0	0.035 * Tanh (15x − 7.5) + 0.035	0.05 * Tanh (15x − 7.5) + 0.05	0.25 * Tanh (15x − 7.5) + 0.25
	Electricity	0 * Tanh (15x + 0) + 0	0.035 * Tanh (15x − 7.5) + 0.035	0.075 * Tanh (15x − 7.5) + 0.075	0.2 * Tanh(15x − 7.5) + 0.2
	Hydrogen	0 * Tanh (15x + 0) + 0	0 * Tanh (15x + 0) + 0	0.035 * Tanh (15x − 7.5) + 0.035	0.05 * Tanh (15x − 7.5) + 0.05
Railway	Diesel	0 * Tanh(15x + 0) + 1	0 * Tanh(15x + 0) + 1	−0.25 * Tanh (15x − 7.5) + 0.75	−0.5 * Tanh (15x − 7.5) + 0.5
	Electricity	0 * Tanh (15x + 0) + 0	0 * Tanh(15x + 0) + 0	0.25 * Tanh (15x − 7.5) + 0.25	0.5 * Tanh (15x − 7.5) + 0.5
Waterway	Diesel	0 * Tanh (15 * x + 0) + 0.28	0.11 * Tanh (15 * x − 15) + 0.39	0.01 * Tanh (15 * x − 15) + 0.29	−0.14 * Tanh (15 * x − 15) + 0.14
	Fuel oil	0 * Tanh (15 * x + 0) + 0.72	−0.11 * Tanh (15 * x − 15) + 0.61	−0.26 * Tanh (15 * x − 15) + 0.46	−0.4 * Tanh (15 * x − 15) + 0.36
	Electricity	0 * Tanh(15 * x + 0) + 0	0 * Tanh(15 * x + 0) + 0	0.25 * Tanh (15 * x − 15) + 0.25	0.5 * Tanh(15 * x − 15) + 0.5

[*] Where x in the equations represents the variable “policies toward alternative fuels”.

Table B3

Equations for policies toward increasing the percentage of biodiesel in diesel blend.[*]

Fuels	BAU	Low	Medium
Diesel	0 * Tanh(15x + 0) + 0.88	−0.03 * Tanh(15x − 7.5) + 0.85	−0.09 * Tanh(15x − 7.5) + 0.79
Biodiesel	0 * Tanh(15x + 0) + 0.12	0.03 * Tanh(15x − 7.5) + 0.15	0.09 * Tanh(15x − 7.5) + 0.21

[*] Where x in the equations represents the variable “policies toward alternative fuels”.

C. Tests performed for the proposed model

Appendix C presents the tests performed for the proposed SD model: boundary adequacy, structure assessment, dimensional consistency, integration error, extreme conditions, and behavior reproduction tests.

C.1. Boundary adequacy test

The model boundaries could be expanded with the inclusion of variables from the literature review and the interviews with experts, including, for example, details of the multiple factors considered by users when choosing one technological alternative over another. However, it was decided to address such factors in an aggregated approach through policy-related variables (policies toward alternative fuel vehicles, policies toward speeding up fleet renewal, and policies toward alternative modes), which objective is not to show how (cost reduction, provision of infrastructure, increased efficiency, etc.), but rather when targets will be achieved in different scenarios. Then, the boundary of the proposed model is considered adequate for its purpose.

C.2. Structure assessment test (physical conservation)

Structure assessment focuses on the conformance of the model to basic physical realities such as conservation laws (Sterman, 2000). In the process of formulating the model, the physical conservation test was performed by inspecting stock and flow diagrams, beside the equations.

C.3. Dimensional consistency test

The dimensional consistency test refers to the direct and systematic verification of all equations and variables to check their real meaning and unit adequacy (Sterman, 2000). This test was performed using the “units check” tool available on Vensim® Pro. The inconsistencies were solved during the model formulation.

C.4. Integration error test

For the proposed model, we used the Euler integration technique, whose assumption is that the rates (flow variables) remain constant between two time periods (time step *dt*). The assumption that the rates remain constant throughout the time interval *dt* is reasonable if the dynamics of the system are slow enough and *dt* is small enough. The definitions of “reasonable” and “small enough” depend on the accuracy required, which in turn depends on the purpose of the model.[2]

Given the purpose of the model to simulate the impacts of policies over decarbonization of the freight system, which can take years, the assumption of the Euler integration technique was considered appropriate. The choice of the time step *dt* was made by systematically cutting the value in half and checking the significance of the change over the results. Table C.1 shows the output values of the total CO_2 emissions from freight transport for the year 2050. The chosen time step was 0.125, since the variation of its result is under 0.5%, taken as a reasonable accuracy.

Table C1
Freight CO_2 emissions in 2050 for different time steps.

Year	Time Step (year)	Emission CO_2 ($tonCO_2$)	Variation (%)
2050	1	9.71×10^9	–
	0.5	9.86×10^9	1.55
	0.25	9.94×10^9	0.78
	0.125	9.97×10^9	0.39
	0.625	9.99×10^9	0.20

C.5. Extreme conditions test

Models must be robust under extreme conditions, which means that their behavior must be realistic under any imposed conditions. The extreme conditions test verifies if the model presents an appropriate behavior when the parameters are subjected to extreme values, such as zero or infinity, and can be performed by direct inspection of the model equations or by simulation (Sterman, 2000). The variables submitted to extreme values for this test, as well as the expected behavior for verification, are shown in Table C.2.

Table C2
Tested variables in extreme conditions test.

Submodel	Variable	Value	Expected behavior
Ideal fleet size	Yearly freighttransport activity	0 tkm	Optimal Vehicle fleet, Vehicle fleet inflow, Vehicle energy consumption, and Emissions will be null

(continued on next page)

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[2] For more information about numerical integration techniques, see Appendix A of STERMAN (2000, p. 903).

Table C2 (*continued*)

Submodel	Variable	Value	Expected behavior
Energy consumption and emissions	Yearly freight transport activity change	100%	Variable “control” will reach 1 much earlier, meaning that emissions would exceed its budget too fast
	Energy vehicleEfficiency	1 l/tkm	Energy consumption and emissions will be much higher
	Emissions factor	1000 $kgCO_2$/l	Emissions will be much higher and Variable “control” will reach 1 much earlier, meaning that emissions would exceed the budget too fast

All expected behaviors under the extreme conditions established were respected, which corroborates the structure reliability of the proposed model.

C.6. Behavior reproduction test

The behavior reproduction test assesses the model’s ability to reproduce the behavior of a system by using, for example, descriptive statistics to assess the point-by-point fit. The behavior reproduction test aims to uncover flaws in the structure or parameters of the model and assess whether they matter relative to the purpose (Sterman, 2000).

This test was carried out based on the BAU scenario, and on the variables “yearly freight transport activity”, “total freight emissions”, “total truck fleet”, and “truck fleet sales”, for which we have historical data series to compare the results with, as shown in Fig. C.1. For a more complete analysis, we used validation metrics of regression models, which help in the analysis of the prediction model in comparison to the database used. Such metrics are based on the calculation of the difference between the real data and the value obtained by the model based on the baseline scenario. The metrics used were the coefficient of determination (R^2), Mean Absolute Percentage Error (MAPE), Mean Absolute Deviation (MAD), and Root Mean Squared Error (RMSE), all shown in Table C.3.

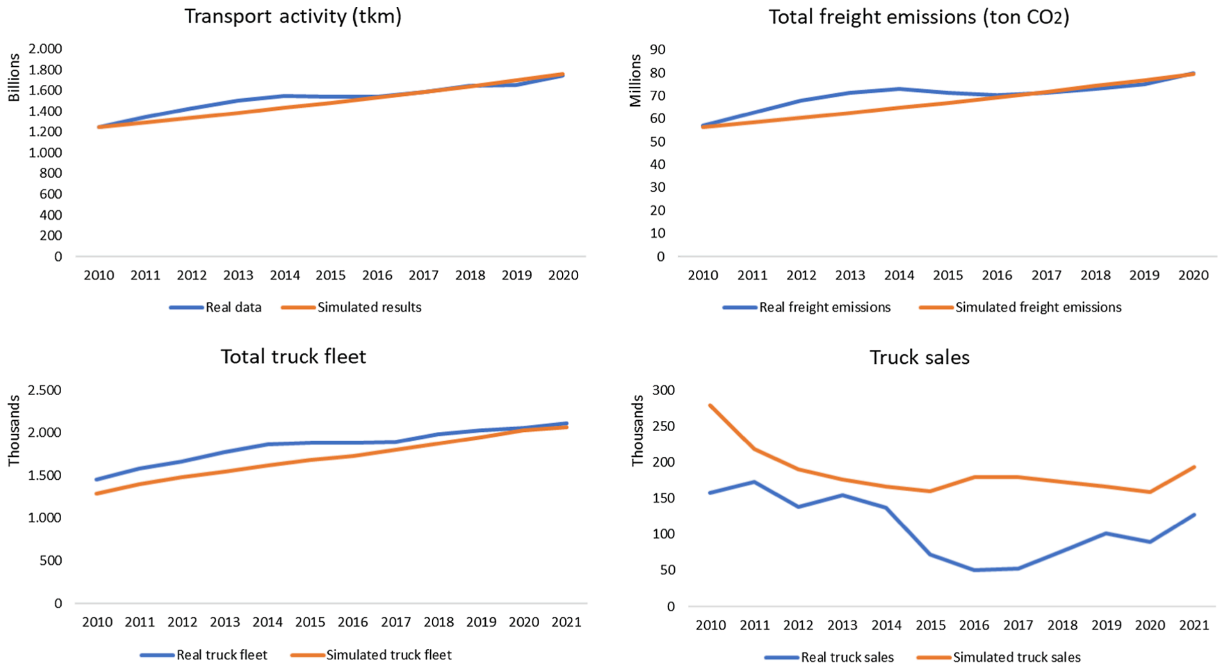

Fig. C1. Comparison between real data and simulated results for transport activity, total freight CO_2 emissions, total truck fleet, and truck sales.

Table C3
Measures of fit between data series and simulated results.

Variables	Coefficient of determination (R^2)	MAPE	MAD	RMSE
Freight transport activity	90%	3%	142.8 (10^9 tkm)	63.8 (10^9 tkm)
Total freight emissions	75%	5%	6.7 (10^6 ton)	4.6 (10^6 ton)
Total truck fleet	95%	8%	230,148 un	157,269 un
Truck sales	30%	93%	75,934 un	79,387 un

As can be observed in Table C.3, the results for freight transport activity, total freight emissions, and total truck fleet presented small error percentages, with a good percentage of R^2, which is considered acceptable for the model. The results of the variable truck sales, however, have not presented a good fit for the real data. By inspecting the graph in Fig. C.1, we can see an abrupt drop in truck sales in 2015 and 2016, which can be explained by the economic crisis experienced in Brazil in that period with negative GDP growth, also affecting the automotive sector. It means that external factors that impact this variable are not being considered within the model boundaries, yielding a large error between actual and simulated truck sales. After this period, the simulated curve tends to follow the same behavior as the real truck sales curve. Despite the economic scenario impacting vehicle sales, we decided not to include this factor in the model. We, however, point out that the sale of new vehicles is susceptible to the economic situation of the region or country under study.

D. Setups of scenarios

Table D.1 presents the setups of all 32 scenarios carried out in this study.

Table D1

Scenarios considering the impact level of changes and timeline for each policy.

	Scenarios	Alternative modes	Timeline alternative modes	Alternative fuels	Biodiesel use	Timeline alternative fuels and biodiesel
	BAU	None	–	None	None	–
Individual policies	Scenario 1	Low	2035	None	None	–
	Scenario 2	Medium	2035	None	None	–
	Scenario 3	High	2035	None	None	–
	Scenario 4	None	–	Low	None	2035
	Scenario 5	None	–	Medium	None	2035
	Scenario 6	None	–	High	None	2050
	Scenario 7	None	–	None	Low	2035
	Scenario 8	None	–	None	Medium	2035
Combined policies	Scenario 9	Low	2035	Low	None	2035
	Scenario 10	Low	2035	Medium	None	2035
	Scenario 11	Low	2035	High	None	2050
	Scenario 12	Medium	2035	Low	None	2035
	Scenario 13	Medium	2035	Medium	None	2035
	Scenario 14	Medium	2035	High	None	2050
	Scenario 15	High	2035	Low	None	2035
	Scenario 16	High	2035	Medium	None	2035
	Scenario 17	High	2035	High	None	2050
Combined policies + Accelerate scrappage rate	Scenario 18	Low	2035	Low	Medium	2035
	Scenario 19	Low	2035	Low	Medium	2035
	Scenario 20	Low	2035	Low	Medium	2035
	Scenario 21	Medium	2035	Medium	Medium	2035
	Scenario 22	Medium	2035	Medium	Medium	2035
	Scenario 23	Medium	2035	Medium	Medium	2035
	Scenario 24	High	2035	High	Medium	2050
	Scenario 25	High	2035	High	Medium	2050
	Scenario 26	High	2035	High	Medium	2050
Combined policies + Alternative policy timing	Scenario 27	Low	2025	Low	Medium	2025
	Scenario 28	Low	2050	Low	Medium	2050
	Scenario 29	Medium	2025	Medium	Medium	2025
	Scenario 30	Medium	2050	Medium	Medium	2050
	Scenario 31	High	2025	High	Medium	2025
	Scenario 32	High	2050	High	Medium	2050

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