Proceedings of the Sixth International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 7, Paper 2.6
Civil-Comp Press, Edinburgh, United Kingdom, 2024
ISSN: 2753-3239, doi: 10.4203/ccc.7.2.6

Challenges for Heavy Haul Rail Transportation in Brazil: A Safety and Environmental Perspective

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Abstract

This paper presents the characteristics of freight railroads in Brazil since their creation, reviewing the history of their implementation, the reasons and differences that arose from the different historical moments and their objectives. For the three main heavy haul railroads, this work shows some of the main current challenges in terms of operational safety and reducing environmental effects. To overcome these challenges, these companies use high-tech equipment, such as automated rail crossing inspection portals, vehicle component inspection systems, intelligent data analysis tools and community awareness programs. Among the actions they take to reduce the environmental impact of their operations are programs to replace their energy matrix, with new electric locomotives, and the development of sustainable fuels to replace diesel in hybrid locomotives. All these actions are in line with the significant increase planned for the Brazilian rail network, which should become more efficient and sustainable.

Keywords: railway safety, sustainability, environmental actions, heavy haul railway transportation, automatic inspection of vehicles, AI for data analysis.

1. Introduction

Transportation modes are constantly evolving and the rail freight sector is no exception. On the global stage, trends in rail freight transportation are emerging with the promise of a future focused on technological innovation, logistical efficiency and sustainability, driving economic and social development in an environmentally responsible manner. Brazil currently has around 30,000 km of railroads and still has a lot to grow and modernize compared to nations with an area of the same size, such as the United States, with almost 300,000 km; China, with more than 120,000 km; Russia, with around 90,000 km and Canada, with 80,000 km.

Given the growing pressure to optimise operating costs and reduce carbon emissions, many countries are expanding investments in actions aimed at modernizing rail infrastructure and digitizing freight management systems. In this context, innovation in the use of automation has the potential to revolutionize the rail sector, with the prospect of optimizing operations and increasing safety and efficiency in the modal. This global trend demonstrates the dynamism and transformative potential of rail freight transportation and, by embracing innovation, the sector is preparing a more resilient and prosperous future.

1.1.Objectives

This article aims to present the history of the railroad in Brazil, its current characteristics and the challenges that the main Brazilian railroads will face to increase their operational efficiency, with a focus on safety and the environment, as well as the solutions they have employed to meet these challenges. Selected challenges are presented for three of the main Brazilian railroad operators, MRS, VALE and RUMO, all of which operate railroads under concession.

1.2. Railways in Brazil - Historic facts

Primarily, as can be seen below, the Brazilian rail network was built to serve the primary goods export market, to link the production/exploitation areas to the ports. This characterizes an isolated, independent and non-integrated form of action.

The first attempt to establish a railroad in Brazil took place in 1835 [1], when Diogo Antônio Feijó, Regent at the time, enacted a law with a series of advantages to encourage the construction and operation of railroads linking the formerly capital of the Empire, Rio de Janeiro, to the capitals of the Provinces of São Paulo, Rio Grande do Sul, Minas Gerais and Bahia. However, at the time, there was no interest in the innovative undertaking, which would be groundbreaking for the country.

After frustrating attempts to stimulate the construction and operation of railroads, it wasn't until 1852 that Irineu Evangelista de Souza, the future Baron of Mauá, built the link between the Port of Mauá (Guanabara Bay) and Raiz da Serra (Petrópolis), two regions in the Province of Rio de Janeiro. Thus, in 1854, Brazil's first railroad was officially inaugurated, with a length of 14.5 km and a gauge of 1.63 m.

After the inauguration of the Mauá Railway on April 30, 1854, by Dom Pedro II, several railroads were built between 1858 and 1872, such as the Recife - São Francisco

Railway (PE) in 1858, the Santos - Jundiaí Railway (SP) in 1867 and the Companhia Paulista Railway (SP) in 1872, all on a 1.60 m gauge. Still, in the 19th century, other railroads were built in metric gauge, including the Companhia Sorocabana (SP) in 1875, the Central da Bahia (BA) in 1876, the Corcovado Railway (RJ) in 1884 and the Porto Alegre - Novo Hamburgo Railway (RS) in 1884.

Between the end of the 19th century and the beginning of the 20th, driven by the large production of coffee, Brazil's main export product at the time, there was a great expansion of the railroad system, with the construction of lines that connected cities, ports and producing regions, becoming symbols of the country's progress and modernization.

In 1922, Brazil had a rail network approximately 29,000 km long, 2,000 steam locomotives and 30,000 wagons in operation. After the world crisis of 1929, Brazil experienced the diversification of its agricultural production, the strengthening and development of its industrial park and the migration of a large population from the interior of the country to the large urban centres. The combination of these factors, together with the advent of the automobile age and the construction of highways, contributed to creating an unfavourable scenario for the expansion of the freight rail system, since there was no economic interest in expanding the railroads to regions with lower population density.

At the beginning of the second half of the 20th century, the Federal Government decided to unify the 18 railroads belonging to the Federal Railway system, which at the time totalled approximately 37,000 km of lines throughout the country. According to Barat [2], the creation of the Federal Railway Network (RFFSA) in the 1960s had the main objective of bringing the railroads together and trying to form a connected network. However, there was no restructuring of the way the freight transportation system worked, and the company's operations were restricted to the transportation of solid and liquid bulk with low added value.

At the end of the 20th century [3], Brazil was going through a period of profound structural reforms, prompted by the search for greater efficiency and competitiveness in the economy. In this scenario, the state model of railroad management, characterized by inefficiencies, growing deficits, lack of investment and a policy that set clear objectives, was seen as an obstacle to the development of the railway system. Faced with these facts and aware of the importance of the need for investment in the sector, the government decided in 1992 to include RFFSA in the National Privatization Program - PND.

The process of auctioning the railroads in the PND was a historic milestone for the Brazilian railroad sector, marking the beginning of a new era of private management and investment in infrastructure, in which companies won concessions to operate the railroads for a certain period, upon payment of a grant and investments in modernization and operation.

Currently, the regulation and supervision of Brazil's federal rail concessions are carried out by the National Land Transport Agency (ANTT), a federal authority created in 2001, which has, among other duties, the competence to guarantee the quality, safety and efficiency of the federal rail transport in the country.

ANTT is responsible for managing and overseeing fourteen Concession Contracts, namely: (i) Carajás Railroad - EFC; (ii) Paraná Oeste Railroad - FERROESTE; (iii) Vitória a Minas Railroad - EFVM; (iv) Centro-Atlântica Railroad - FCA; (v) Tereza Cristina Railroad - FTC; (vi) Transnordestina Logística Railroad - FTL; (vii) MRS Logística; (viii) Transnordestina Logística - TLSA; (ix) Ferrovia de Integração Oeste-Leste - FIOL; (x) Ferrovia Norte Sul - FNS; (xi) Rumo Malha Norte - RMN; (xii) Rumo Malha Oeste - RMO; (xiii) Rumo Malha Paulista - RMP; and (xiv) Rumo Malha Sul - RMS. It also manages and supervises two sub-concession contracts for sections of the FNS, namely: (i) Ferrovia Norte Sul Tramo Norte - FNSTN and (ii) Rumo Malha Central - RMC; and one sub-concession contract for the West-East Integration Railway - FIOL - Section 1.

Figure 1 shows a map of Brazil with the railroads under concession. This map does not show the southern extension of the North-South Railway and the FIOL and TLSA networks, as they are still under construction

Figure 1 - Rail Network under concession in Brazil [4].

1.3. Characteristics of Heavy Haul Brazilian Railways - Track Gauge

The Brazilian rail system has a complex panorama of gauges, with railroads operating at different widths. This diversity, the result of European influence in the construction of the first railroads. The inadequate planning in the construction of railroad lines at the beginning of the 20th century had a direct impact on the integration of transportation in the country to this day.

Deciding on the gauge for a railroad is an important strategic choice that takes into account several factors, such as the volume of cargo, since railroads with wider gauges can transport heavier loads and longer trains, which makes the transportation of large volumes of ore and grain more efficient; the cost of construction, since railroads with narrower gauges are cheaper to build and maintain, which is more advantageous for lines with less traffic or in regions with hilly terrain; and integration, since the standardization of the gauge facilitates interconnection between different railroads, optimizing transport logistics and avoiding transhipment costs. Table 1 shows the distribution of gauges and the lengths of Brazilian freight railroads that are subject to concession.

1.4.Brazilian Network Rail Expansion

Provisional Legal Act No. 1,065 of 2021 and subsequently Law No. 14,273 of 2021 introduced the possibility of building new sections of railway by authorization from the granting authority, a process that is more simplified than the traditional concession model. One of the highlights is that it facilitates the possibility of returning granted sections that are no longer of interest to the concessionaire, allowing other interested parties to obtain authorization to operate the rail transport service.

Also contributing to the expansion of the rail network, the agenda for the early extension of rail concession contracts was included in the Federal Government's Logistics Investment Program (PIL) in June 2015, with the main benefit for the government and society being the possibility of negotiating better contractual conditions with the concessionaires, such as shorter and more assertive deadlines for completing the work, investments in areas considered to be a priority and higher quality of service. From the concessionaire's point of view, early renewal brought legal certainty for making investments with predictable economic and financial returns over the long term.

Railway	Extension (km)	Railway gauge (m)
Estrada de Ferro Carajás - EFC	997	1,6
Estrada de Ferro Paraná Oeste - FERROESTE	249	1
Estrada de Ferro Vitória a Minas - EFVM	895	1
Ferrovia Centro-Atlântica - FCA	7.892	1,6
Ferrovia Tereza Cristina - FTC	162	1
Ferrovia Transnordestina Logística - FTL	4.294	1
MRS Logística	1.819	1,6
Transnordestina Logística S.A. - TLSA	1.728	1
Rumo Malha Norte - RMN	735	1,6
Rumo Malha Oeste - RMO	1.973	1,6
Rumo Malha Paulista - RMP	2.118	1,6
Rumo Malha Sul - RMS	7.223	1,6
Ferrovia Norte Sul Tramo Norte - FNSTN	750	1,6
Rumo Malha Central - RMC	1.535	1,6
FIOL - Trecho 1	537	1,6

Table 1 - Length and track gauges of the state's railways concession [5].

2. Safety Challenges

The main challenges facing Brazilian railroads in terms of safety are linked to their operational characteristics and the constant need to increase productivity, whether by increasing the capacity of cargo transported, increasing the speed of transport or even optimizing logistics. Maintaining or improving safety requires constant care, including anticipating problems that may arise because of the aforementioned interventions.

New technologies represent an important opportunity for finding solutions to the challenges faced. Innovative tools for the safety and control of operations, aided by more information and enabling more reliable decisions, represent the current trend for Brazilian companies. In their plans, they are betting on technologies that also benefit the communities in the places where they operate, while at the same time reducing their accident costs and making their operations compatible with actions linked to sustainability.

In this topic, Brazil's railroads describe their challenges and what measures they have taken to ensure global safety in their operations.

2.1. MRS Safety Challenges and Actions

MRS's monthly average of accidents involving communities, such as hit-and-runs, collisions and vandalism, is in line with the standards of the main railroads in Europe and North America. However, establishing a culture of safety in the communities along the railway line remains a significant challenge for the company, since it operates on several heavily populated areas. Specifically, the rates of pedestrian accidents and collisions have not shown as much improvement as other indicators, possibly due to factors such as [6] [7]:

- People's rush.
- Distraction caused using electronic devices.
- Underestimation of the risks involved.
- Alcohol and drug use.

To mitigate these incidents, MRS is concentrating its efforts on eliminating interference in urban centres, using technology to monitor people's interaction with the railway, partnering with municipalities and carrying out awareness campaigns, having invested significant resources in projects with this objective [6] [7].

MRS incorporated Artificial Intelligence (AI) to increase personal and rail safety. One example of the use of this technology is to reduce accidents at level crossings. A system made up of cameras, audible alerts and specialized software has been tested, enabling real-time alerts about obstructions at these elements. The technology enables rapid response, including preventive measures such as the rapid dispatch of rail escort teams for local assistance or the temporary interruption of rail traffic until the obstruction is removed. During 2023, this solution was validated for implementation at more level crossings, which are still in the testing phase [6]. Figure 2 shows a photo of the test site where this technology was tested.

Figure 2 - Railroad Crossing site for tests with automatic detection of hazards [6].

Another example of the use of technology is linked to the "Video Analytics" project (automatic analysis of video content). MRS is testing the solution to detect fatigue in train drivers and track maintenance equipment operators, to improve personal and rail safety.

In addition to the challenges mentioned above, MRS is focused on increasing the efficiency of our assets. Among the initiatives is the formation of trains with a greater number of wagons, such as the 272-car composition, and increasing the average speed of trains. However, this also entails significant challenges related to rail safety. To address these, advanced AI technologies are being implemented to monitor and supervise rail components and interactions with the track [6].

Along with applying AI to monitor level crossings, MRS has been exploring its potential to monitor the useful life of our asset components, such as wagon brake shoes and permanent way inspection via drones. Recently, MRS conducted a study on the use of AI in the inspection and measurement of wagon brake shoes using "Video Analytics", to obtain accurate measurements that increase asset availability and reduce train downtime during field inspections. With drones, aerial images are captured to help assess the condition of the permanent way. This data is processed with the support of an AI that helps detect anomalies.

2.2. RUMO Safety Challenges and Actions

RUMO Logística is the largest railway operator in Brazil, playing a crucial role in the transportation of cargo throughout the country. However, rail operations face several challenges, particularly in the areas of safety and the environment. This section presents these challenges and discusses the main initiatives adopted by RUMO to mitigate environmental impacts and guarantee operational safety. The analysis includes data from sustainability reports, case studies and other reliable sources.

- **Safety Challenges in Railway Operation**

RUMO's railway operation presents safety challenges that include accident prevention, infrastructure maintenance and ensuring safe working conditions for employees. According to the 2023 Sustainability Report, the company achieved a 27.2% reduction in the rate of rail accidents, following the criteria of the Federal

Railroad Administration (FRA) for determining the rate of accidents with derailments and damage exceeding US$11,500 (2023 Sustainability Report).

- **Security Actions Implemented by RUMO**

i. Video-Based Inspection

The adoption of video-based inspection systems has brought significant improvements in the identification of damage to wagon components, avoiding the need to stop trains. This innovative method has reduced inspection time by 30%, from 90 seconds to 60 seconds per wagon, as well as substantially increasing the accuracy of fault detection [8].

Implementation process

During the experimental phase, two sets of nine cameras were installed on each line of a rail logistics operator at the port entrance, as can be seen in Figure 3. These systems use image recognition algorithms based on machine learning to monitor safety-critical components, while workers carry out video-assisted visual inspections according to the workflow shown in Figure 4.

Figure 3 - Schematic figure with the positions of the cameras in the inspection gateway [9].

Inspection results

Since the system was activated, 2029 damaged components have been identified, of which 1715 were detected by the video-assisted inspection, as shown in Figure 5. A further 312 damaged components were not detected by the video inspection and were identified by the team in the company yard, indicating that only 15% of the visible damage was not captured by the cameras [9]. During this period, two specific items showed multiple failures, indicating a widespread problem in the fleet and prompting the analysis and decision to modify the manufacturing process of one of these items.

Figure 4 - Workflow diagram for automatic inspections using the gateway [9].

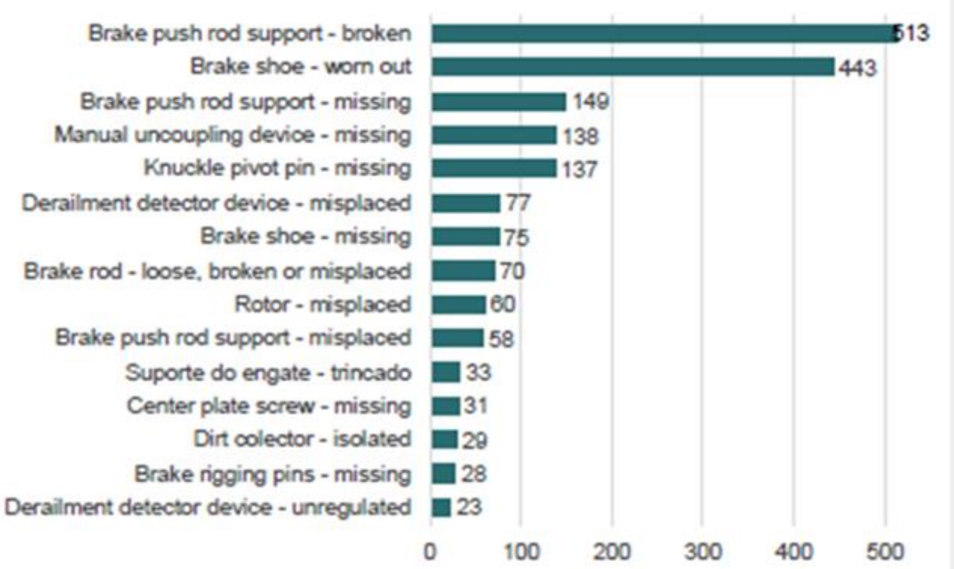

Figure 5 - Pareto diagram listing the damages detected using the gateway [9].

Video-based wagon inspection reduces inspection times, increases productivity and reduces safety risks for yard personnel. In addition, it is useful for gathering information about the condition of the fleet, supporting maintenance planning and identifying hidden problems or patterns in the condition of components. However, the implementation process takes time, and many details need to be resolved as problems arise.

ii. Broken Rail Detection Project (DTQ)

The Broken Track Detection Project (DTQ) represents a significant advance in railway maintenance and safety. This project integrates an Artificial Intelligence (AI) system that has demonstrated a remarkable ability to improve assertiveness in identifying track problems. Before the system was implemented, assertiveness levels in detecting broken rails were 95%. With the introduction of AI, these levels increased to 98%, representing a considerable advance in the safety and efficiency of rail operations.

Initial Project Phase

The first phase of the DTQ project began in 2018, with the installation of several devices along the tracks, capable of detecting their condition in real-time. These devices use advanced sensors to continuously monitor the condition of the tracks, capturing essential data on structural integrity and possible failures. The information collected is transmitted in real-time to the Network Operations Centre (NOC), where it is analysed by AI systems [8].

How the AI system works

The AI system used in the DTQ project is based on machine learning algorithms trained to recognize patterns associated with rail faults. These algorithms analyse the data received from the sensors, identifying anomalies that may indicate the presence of broken rails or other irregularities. The system's ability to learn and adapt to new data allows for continuous improvement in detection accuracy.

Benefits and Impacts

Accurate, real-time detection of track faults enables a rapid response, minimizing the risk of accidents and interruptions to the rail service. In addition, efficiency in preventive maintenance is significantly increased, since problems can be identified and corrected before they become critical. Implementing the system also has a positive impact on operational planning, allowing train routes to be optimized and downtimes to be reduced.

iii. SafeTruck: Wagon Balance Monitoring Project

The SafeTruck project is an innovative initiative aimed at monitoring the sway of wagons to prevent accidents caused by failures in the damping system. This project involves several areas, including Research and Development, Wagon Engineering, Wagon Maintenance, Maintenance Intelligence Centre and Maintenance Planning and Control, demonstrating a multidisciplinary approach in the search for effective solutions to complex problems in railway operation.

How the SafeTruck System works

The sway monitoring system, known as SafeTruck, uses a laser measuring device to capture the occupancy of the wagon and record reference points as shown in Figure 6, creating a curve representing the oscillatory movement (roll) of the wagon box. The measurement is carried out on sections of tangent track, just after known curves, ensuring that the excitation on the wagon comes only from the preceding curve, without any influence from track geometry defects. The laser measuring device captures amplitude, frequency and damping factor data from the wagons, inferring the modelling of the suspension system, known as a viscous damping system. The efficiency of the friction damping (friction wedges) of the wagon suspension system is determined by the value of ζ, which allows the system's response to track disturbances to be assessed [10].

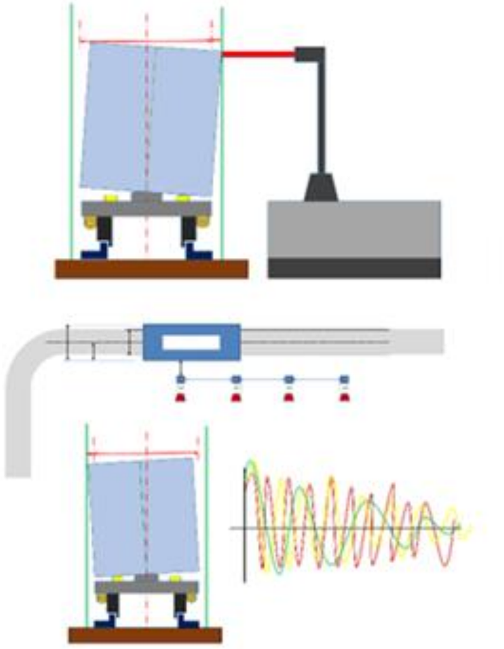

Figure 6 - Wagon Sway Monitoring System Layout [10]

Results and Analysis

During the test phase, three different journeys of a specific wagon were analysed. The data collected by the SafeTruck system revealed a 41% greater average variation in movement amplitude in the wagon studied compared to wagons with good performance, indicating problems in the damping system. This analysis of the curves was carried out as shown in Figure 7, in which the ζ values are decisive for identifying the quality of the damping and recommending the wagon for treatment. The field analysis revealed wear on the friction wedges and problems with the springs, confirming the effectiveness of the SafeTruck system in identifying wagons with poor damping performance.

Conclusion

The SafeTruck system has proved to be a valuable tool for preventing rail accidents, providing a detailed and accurate analysis of the performance of the wagons' damping systems. Through the preventive detection of faults, such as worn friction wedges and spring problems, it is possible to direct wagons for maintenance before serious faults occur, reducing the risk of derailments and improving operational safety.

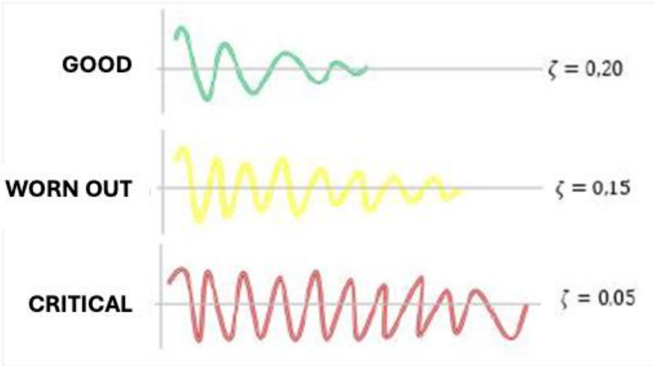

Figure 7 - Classification of Damping Curves as used in the SafeTruck System.

2.3. VALE Safety Challenges and Actions

VALE, like all other *heavy haul* operators, faces major challenges related to operational safety. An event in any railway process, from the origin of the transported product to its circulation and final delivery, as well as all the infrastructure that supports the operation of the three processes mentioned, can have very unfavourable consequences for the environment. Such actions can generate long-lasting or, in some cases, irreparable events and can represent changes in people's lives, which are priceless assets.

The topic of environmental safety involves people directly involved in railway processes, as well as their communities. It is therefore a priority when assessing programs to increase productivity or implement new projects. In the event of exposure to risks to people and the environment, containment measures and emergency response plans must be implemented to neutralize or reduce the impacts.

For railroads, the two main fronts that enable them to increase productivity are: (a) reducing the operating cycle, which is measured by the interval between two deliveries or unloading, considering the use of the same rolling stock and train set, and (b) increasing the axle load. There is a third possibility: increasing the size of the train set. However, the first two are based on the principle of maximizing the existing rail infrastructure, without increasing the number of yards, acquiring locomotives and wagons or altering the blocking sections, which are not covered in this article.

The combined use of the possibilities mentioned above is common in many programs to increase production capacity. Briefly exploring speed increases, the context would be similar to that of a car travelling on a highway: it is not recommended for the user to use the same speed and drive the car in the same way when empty or with a certain load. Each vehicle and each road have a certain characteristic, depending on its route (drag profile) and its particular design. Both require a specific maintenance strategy. Of course, since all processes need to be prioritized or revisited constantly, some preventive or predictive maintenance items can be postponed. New processes and controls can also be developed to ensure that unwanted effects do not occur.

For railroads, driving a train with empty vehicles requires different procedures from driving a loaded one. The increase in speed requires a review of braking distances, greater control of the maintenance of both the railroad and the wagons and locomotives, revisiting the railroad profile and applying new technologies to develop new components - especially railroad bogies. In addition, the application of new materials and the use of decision-making tools during train movements are very important.

With the increase in train speed, the maintenance strategy needs to be revisited. Higher speeds mean greater cycling of equipment and components, with greater wear on wheels and rails. Instrumentation of the railroad as a whole becomes mandatory to understand the behaviour of sleepers, ballast and fastenings.

Since the items that make up a railroad are treated as independent assets and represent a multitude of items in maintenance control, the use of artificial intelligence (AI) tools has become increasingly widespread. To this end, development partnerships have been created between railway operators, traditional suppliers and research and development institutions, with a focus on understanding the operational consequences of increasing speed. The first results are already being seen by the railroads that are pioneering this initiative.

Another option that is often explored is increasing the axle load. For example, for a concept train with 300 wagons, an increase of 1 (one) ton per axle represents 4 (four) tons more per wagon and a total of 1200 (one thousand two hundred) tons per train of 300 wagons circulating on the rail network. However, the initiative to increase the axle load for railroads in operation, which were built with a relatively low axle load compared to the standard of new railroads built recently for heavy haul operation, presents some challenges such as:

- General wagon redesign.

- Redefining the locomotive model.

- Remodelling of routes.

- Updating loading and unloading systems.

- Compatibility of all structural assets (tunnels, bridges, …) and drainage systems.

As with studies on increasing the speed of railroads, increasing the axle load requires a review of various procedures for driving empty and loaded trains. Currently, railroads are increasingly adopting tools to analyse driving and suggest operations (driving optimizers).

Safety requirements need to be revisited. These include stopping distances and the recommended locations for stopping and restarting the movement of the train after a total stop, whether programmed or not. Once the axle load issue has been resolved on the railroad, attention must be paid to the equipment used to load and unload the wagons (silos and car dumpers). These must withstand the new load and be capable of delivering greater loading and unloading capacity.

Both the initiatives to increase speed and axle load consider the exposure to risks for the company and the railroad's surroundings (communities). Many railroads were born in regions where there were no neighbourhoods or isolated residents. Over the years, the scenario has changed considerably, and large cities have formed along the railroads, generating liabilities for the railroad companies and forcing them to implement specific operating procedures for running in cities. Most of these trains need to be slowed down, which has a direct impact on transportation efficiency.

It is important to note that the creation of populated areas along the railroad demands crossings for pedestrians and vehicles (level crossing), a condition that also requires a speed reduction.

Actions to raise public awareness are widely publicized and implemented, but their effects are not immediate. In addition, vandalism events represent significant losses in productivity.

VALE has a different characteristic from other operators in Brazil since the railroad is shared for the transportation of iron ore, general cargo and passengers. The latter type of transportation has priority for circulation and for crossing with other trains (general cargo and ore). As a result, the other trains have to slow down or even stop completely for the passenger train to run.

To increase productivity, railroads face the problem of scalability, which is often not attractive to new suppliers and the few that are interested demand high costs for supplying solutions and equipment even as an alternative supplier.

3. Environmental Challenges

3.1. MRS Environmental Challenges and Actions

MRS was the first Brazilian railroad to be licensed by the Brazilian Institute of the Environment and Renewable Natural Resources - IBAMA, because of the company's commitment to the environment. To illustrate the company's commitment to the environment, more than 116,000 square meters of degraded areas have been restored along the railway network. In addition, MRS also carries out innovative projects, such as using solar energy to illuminate shunting yards and using polymer sleepers to replace wooden sleepers whenever possible [6] [11].

As far as solid waste is concerned, MRS manages and treats its effluents properly, making it possible to reuse the water for washing locomotives. The disposal of household waste and rubble around the rail network is still a major challenge for the company. As well as posing a safety risk, garbage deposited around the railroad can attract animals and affect the drainage system, increasing the risk of flooding, which can impact nearby residential areas [11].

Intending to improve operational efficiency, MRS is implementing the ore train model with 272 wagons, double the current standard train of 136 wagons. The results of this new train model by the end of 2023 have shown great improvements on some sections, surpassing the performance of the standard train [6].

Energy efficiency at MRS is monitored through the global indicator of litres per thousand TBK (referring to the number of litres consumed to transport one thousand gross tons over one kilometre). This global indicator reflects the combined efficiency of the three cargo groups in which the company operates: ore, agricultural and general cargo [11].

In 2023, the company's overall energy efficiency index was 2.488 L/kTKB, showing an improvement compared to the previous year [6]. Figure 8 shows the evolution of MRS' L/kTKB since 2011.

This significant reduction in the evolution of L/kTKB and diesel consumption is linked to initiatives such as:

- driving management.
- the adoption of distributed traction in trains.
- constant monitoring to increase permitted speeds.
- implementation of AESS (automatic engine start and stop system).
- use of more modern rolling stock.

Figure 8 - Evolution of fuel consumption of MRS since 2011 - L/kTKB [6].

3.2. RUMO Environmental Challenges and Actions

RUMO's rail operations have a direct impact on the environment, especially in terms of greenhouse gas emissions and waste management. Greenhouse gas emissions are one of the main environmental problems associated with rail transportation, due to the intensive use of fossil fuels [8]. In 2023, the company faced significant challenges in reducing these emissions and managing resources sustainably.

In addition to energy efficiency and emissions reduction studies and initiatives, RUMO also works on various fronts focused on best environmental practices, as presented below.

i. Hybrid Diesel and Battery Locomotives

The evaluation and implementation of hybrid locomotives that combine diesel engines with batteries has been one of RUMO's main initiatives to reduce fuel consumption and greenhouse gas emissions. These hybrid locomotives optimize energy efficiency and minimize the environmental impact of railway operations.

How Hybrid Locomotives Work

The hybrid diesel and battery locomotives operate using the energy generated by a 4500 HP diesel engine, in conjunction with different battery pack configurations. The battery recharging mechanisms include the principle of regenerative braking, where the energy generated during dynamic braking is used to recharge the batteries. They also include the use of the batteries at times of low thermodynamic efficiency of the diesel engine, such as during idling or the first notches of traction [10]. These dynamics are illustrated in Figure 9.

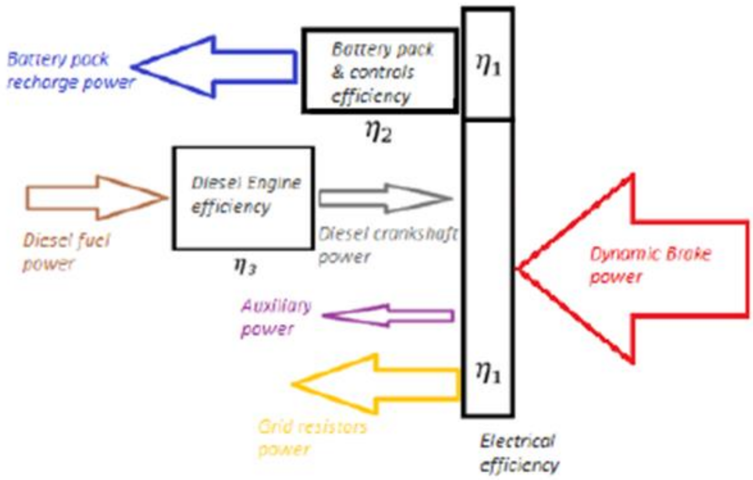

Figure 9 - Power scheme of a hybrid locomotive

Simulation Studies and Results

Simulation studies carried out by RUMO have shown that the use of hybrid locomotives can result in fuel savings of up to 14.7%. The simulations considered different battery pack specifications, including lithium iron phosphate (LiFePO4) batteries with a capacity of 800 kWh and nickel-manganese-cobalt (NMC) batteries with a capacity of 1150 kWh. The results indicated that, for the rail profile found on the railroad, fuel savings ranged from 14.70% to 10.18%, depending on the battery specifications and recharge rate [12].

Benefits and Financial Viability

In addition to fuel savings, hybrid locomotives offer significant benefits in terms of reducing greenhouse gas emissions. The financial viability of these locomotives was also assessed, considering the cost of the batteries and the utilization rate of the locomotives. Financial simulations suggest that, with a cost of 460 USD/kWh for

NMC technology and a minimum electricity generation rate of 265 MWh/month, it is possible to achieve positive financial viability, with a rate of return on investment, depending on the price of diesel in Brazil, from 5 to 8 reais per litre [12].

<u>Results and Conclusions on Diesel-Battery Hybrid Locomotives</u>

The study on hybrid diesel and battery locomotives carried out by RUMO showed promising results in terms of energy efficiency and emissions reduction. The simulation carried out indicated fuel savings of up to 14.7% as shown in Figure 10, which could represent a significant reduction in diesel consumption and, consequently, CO2 emissions. In addition, the position of the locomotives in the loaded trains significantly influenced the generation of regenerative braking energy, further contributing to the efficiency of the system [12].

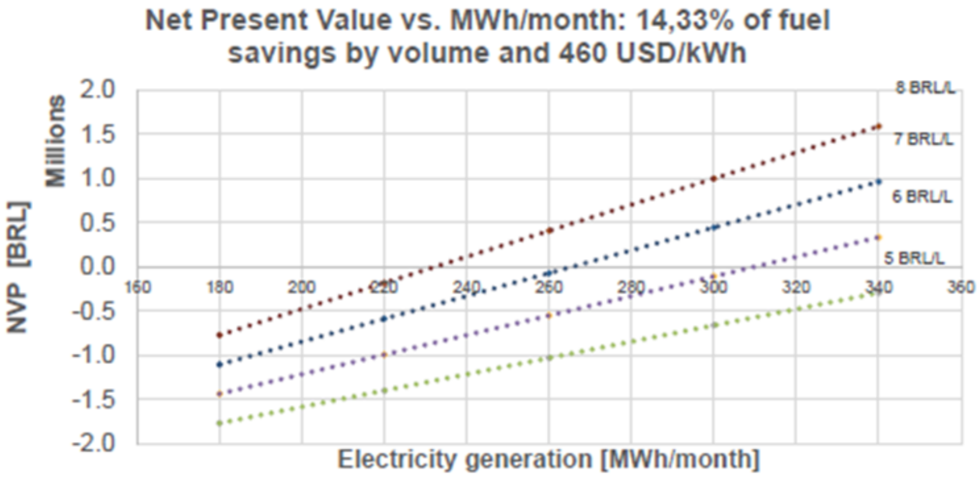

Figure 10 - Net Present Value compared with hybrid generation solution, for different scenarios for the fuel cost [12]

ii. Reducing Emissions

The modernization of locomotives to more efficient and less polluting models is a key strategy for RUMO. By 2023, the company had managed to reduce specific emissions by 0.25%, avoiding the emission of 6.6 million tons of CO2. These efforts are part of RUMO's ongoing commitment to improving its energy efficiency and reducing its carbon footprint [8].

iii. Waste Management

RUMO implements robust programs for recycling and proper disposal of materials. In 2023, 66% of the waste generated by railway operations was sent for recycling. The company also promotes the reduction, reuse and recycling of materials, seeking to minimize the amount of waste sent to landfills [8].

iv. Environmental Compensation

RUMO invests in reforestation projects and the recovery of degraded areas as a way of offsetting the environmental impacts of its operations. These projects not only help to sequester carbon but also promote biodiversity and the recovery of local ecosystems [8].

v. Environmental Education Program (PEA)

RUMO develops and implements structured teaching and learning activities on environmental education and railway safety, impacting students and local communities. The EAP aims to raise awareness of the importance of environmental conservation and promote sustainable practices among participants [8].

<u>Conclusion</u>

RUMO demonstrates an ongoing commitment to safety and environmental sustainability through innovative actions and significant investments. However, challenges persist and require an integrated approach to ensure the sustainability and safety of its rail operations. The implementation of advanced technologies, training programs and environmental initiatives are important steps to mitigate negative impacts and promote safer and more sustainable operations.

3.3. VALE Environmental Challenges and Actions

VALE's decarbonization challenges were defined in 2017, considering a temperature rise of 1.5°C on the planet. VALE aims to reduce emissions. The company's goal was divided into two phases: the first phase (2030) considers an absolute reduction of 33% in scopes I & II of CO_2 EQ, and the second, neutral emissions in 2050. A target has also been set for scope III. Figure 11 summarizes the distribution by scope.

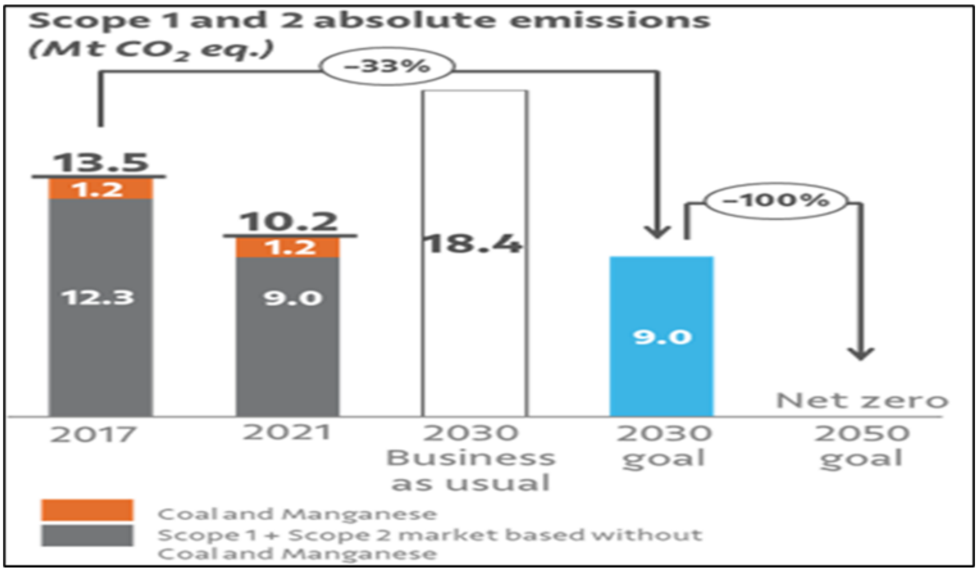

Figure 11 - Environmental Goal Stratification by Scope

After defining the goals, a technological roadmap was defined for each scope, where various initiatives were prioritized. Figure 12 shows some of the concrete actions, tested and/or implemented even as a pilot project, to understand the technology.

In 2021, VALE put Brazil's first 100% battery-electric locomotive into operation at the Vitória-Minas railroad shunting yard in the city of Vitória, Espírito Santo. In 2022, a second locomotive was delivered for operation at the Carajás Railway shunting yard in the city of São Luis - MA. This second locomotive was developed and manufactured in partnership with CRRC (China) and is shown in Figure 13.

Continuing the search for decarbonization solutions, a batch of 3 (three) 100% battery electric locomotives, with greater capacity, is in the process of being developed and manufactured. After commissioning, they will make up the world's largest hybrid train (Batteries + Diesel), which will be implemented on the Carajás Railroad and is expected to start operating in 2027. This action is a decarbonization initiative focused on energy efficiency.

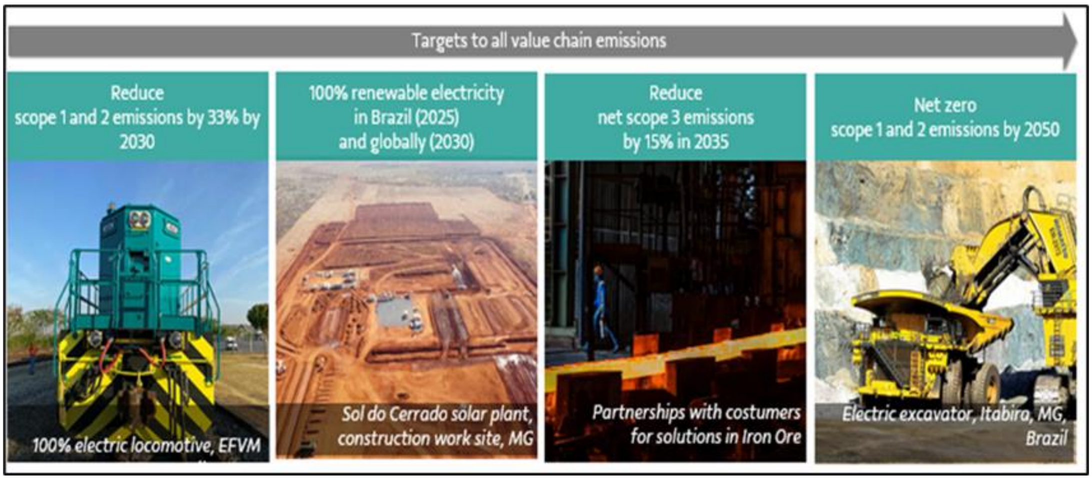

Figure 12- VALE's environmental targets for emissions

Figure 13 - CRRC Locomotive has been tested in VALE's railway yard

A major challenge for the application of batteries, in addition to the lack of information on efficiency and behaviour in heavy operations, is the high investment in recharging infrastructure and the unavailability time for recharging batteries, which is much longer than the supply time with fossil fuels.

Since the decarbonization target was set and the Decarbonization program was created, various studies have been carried out to achieve the target by 2030 and carbon neutrality by 2050, including electrification with the application of partial catenaries along the EFC and EFVM railroads. The conclusions indicate that, for partial or total decarbonization, each railroad will require an almost exclusive solution and changes in operational and maintenance concepts.

Currently, one of VALE's focuses in the global Decarbonization process is on the use of alternative fuels, which also require detailed assessments and changes in production processes.

4. Conclusions

The construction characteristics of Brazilian freight railroads have posed a challenge to their interoperability since their creation. Railroads have been built to different gauges and this often prevents operators from sharing sections of railway concessions. This difference in such a large country requires specific rail concession models, not for the transportation of a specific product, but for the operation of specific sections. The model favours the concentration of services in a smaller number of operators but allows for more significant investments since the entire railway is granted and all the management is done by the company holding the concession. As a result, Brazil has large operators, with long sections, which have gradually been remodelled and expanded, reducing the difference in the percentage of cargo transported by rail with the world's major nations.

Brazilian railway operators have included several actions in their development plans to help achieve the Sustainable Development Goals. The article shows some of these actions aimed at making the railroads less invasive where they operate, increasing the safety of their operations and contributing to the safety of the communities with which they interact in the transportation process. Steps are being taken to improve the maintenance of their vehicles and tracks, such as the implementation of the SafeTruck system and others, as well as to raise public awareness to eliminate accidents at level crossings. The use of intelligent tools for data analysis and decision-making has also been highlighted.

As far as the environment is concerned, the operators have taken steps to reduce emissions, developing with suppliers the most suitable vehicles for their trains, whether hybrids or fully electric. In addition, they have worked with the communities where they operate to change behaviours based on a culture that uses the railroad areas, including the tracks, as free spaces for building occupations and dumping construction waste. To do this, they work with awareness and education, showing the damage that such attitudes can cause.

This paper has presented just a few of the actions currently underway by the country's three main railway operating companies. What has been presented is strongly linked to the authors' areas of activity, but it gives an adequate, albeit simplified, overview of the current efforts underway to improve transportation in Brazil, which is a country with a lot to grow in rail lines and which has adequately faced the challenges that arise in its growth process.

Acknowledgements

The authors wish to acknowledge VALE S.A., RUMO Logistica, MRS Logistica and Railway Transport Superintendence (ANTT) for collaborating with this article. Also, to CNPq (grant number 303582/2023-5), which funded Prof. A. A. Santos research. Finally, to Pedro H. A. Correa, who improved the quality of the text in English.

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