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EVALUATION OF THE IMPACTS OF THE INCREASED AXLE LOAD ON A HIGH AXLE LOAD FREIGHT RAILWAY SYSTEM – MRS LOGÍSTICA CASE STUDY

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Final Project presented to ITL – Transport and Logistics Institute, CNT – National Transport Confederation, as part of the requirements for completion of the International Certification in Management of Rail and Metro Rail Systems course.

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January 14th 2024

ACKNOWLEDGEMENTS

The authors of this work would like to thank MRS Logística for the opportunity to participate in the high-quality course given by DB in partnership with CNT, ITL, SEST / SENAT.

We hope to contribute to the society and the railroad community with the lessons learned.

ABSTRACT

Due to the need to increase the efficiency and to expand the cargo transportation in Brazilian railways, mainly because of the early renewals of concessions and new regulatory obligations, several new challenges have been imposed on the freight railway system. In this scenario, the proposed work will address the increase in axle load as a main contributing factor to this leverage from a case study applied to MRS Logística, where the impacts of this initiative on infrastructure, superstructure, rolling stock, whether locomotives or wagons, and operation will be evaluated. Finally, the opportunities to mitigate the negative impacts will be identified and the possible gains associated with its implementation will be evaluated, concluding with the presentation of its technical and financial feasibility.

Keywords: Railway; freight railway; heavy haul; axle load; wagon.

RESUMO

Com o estímulo ao aumento da eficiência e ampliação do transporte de cargas nas ferrovias brasileiras, principalmente a partir das renovações antecipadas das concessões e as novas obrigações regulatórias, diversos desafios vêm sendo impostos ao sistema ferroviário. Nesse contexto, no trabalho proposto, abordaremos o aumento de carga por eixo como um fator principal contribuidor para essa alavancagem a partir de um estudo de caso aplicado à MRS Logística, avaliando os impactos dessa iniciativa na infraestrutura, na superestrutura, no material rodante, sejam locomotivas ou vagões, e na operação. Por fim, serão identificadas oportunidades de ações mitigadoras para os impactos negativos e mensurados os possíveis ganhos associados à sua implementação, concluindo sobre a sua viabilidade técnica e financeira.

Palavras-chave: Ferrovia; ferrovia de carga; heavy haul; carga por eixo; vagão.

LIST OF ABBREVIATIONS

ABNT – Associação Brasileira de Normas Técnicas (Brazilian Technical Standards Association)

ANTF – Associação Nacional dos Transportadores Ferroviários (National Association of Railway Transporters)

AREMA – American Railway Engineering and Maintenance-of-Way Association

HH – Heavy Haul

HAL – Heavy Axle Load

IPEA – Instituto de Pesquisa Econômica Aplicada (Institute for Applied Economic Research)

NBR – Norma Brasileira (The Brazilian Standard)

RFFSA – Rede Ferroviária Federal S.A. (Federal Railway Network S.A.)

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1 INTRODUCTION

Rail freight transport plays a fundamental role in the logistics of regions that produce large volumes of goods that need to be transported over long distances. Considering the importance of commodity exports for the current Brazilian economic model, the railway modal plays an important role in enabling its development, given that the main cargoes moved by train are grains, iron ore, cement, containers, steel products, among others.

The economic characteristics of rail transport in Brazil are high fixed costs, represented by the leasing of the network and terminals, and a high volume of fixed capital with the purchase of rolling stock. However, variable costs such as labour, fuel and energy are relatively low, making it suitable for transporting goods with low added value and high specific weight and volume (IPEA, 2013).

Brazil's freight railways reached their peak around 1962 (Figure 1), following the creation in 1957 of RFFSA - Rede Ferroviária Federal S.A., with the aim of integrating the railway network belonging to the union under the same administration (Nabais, 2014). Subsequently, the growing costs and inefficiency of the sector led to pressure for regulatory reforms, following an international trend towards privatization, which culminated in the start of major railway concessions to the private sector in 1996-1998, under 30-year contracts.

Figure 1: Extension of the Brazilian railway network

Over the years of the concessions, there has been a lot of progress in the sector. ANTF's current data (2023) shows a 98% increase in cargo handling on the railways compared to the period when the concessions began, an average annual increase of 2.76%, according to Figure 2. In terms of productivity, the sector has shown successive growth rates, always above GDP, with an annual average of 4.1% and 170.5% when compared to the period when the concessions began. Railways account for 21.5% of the Brazilian freight transport matrix, according to data from the PNL 2035, compared to 67.6% for road transport.

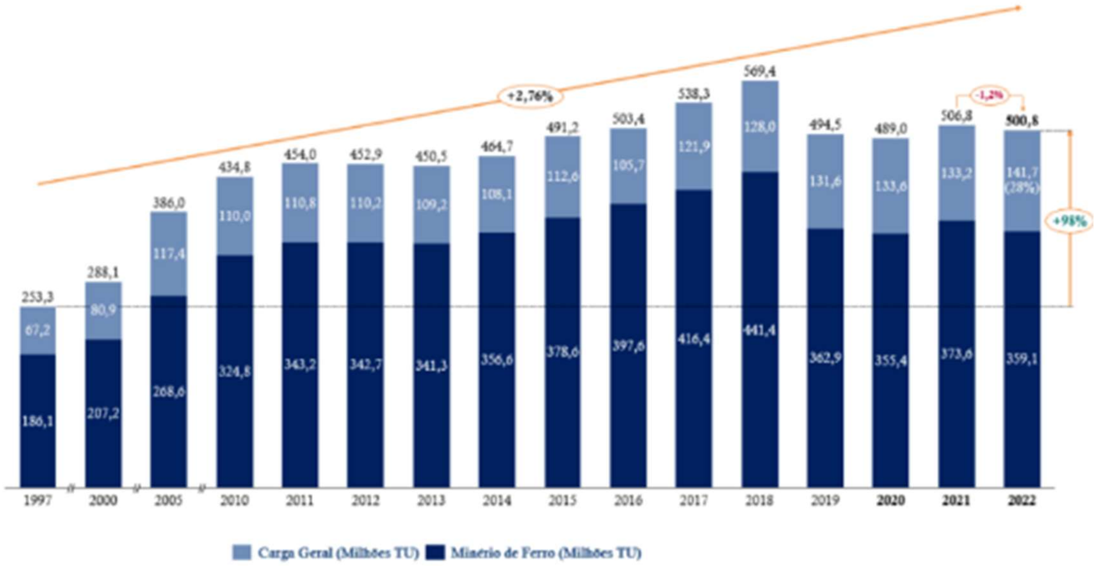


Figure 2: Evolution of freight transported by railways (ANTF, 2023)

Recently, there has been a lot of media coverage of the importance given by governments to railway concessions, whether new or renewed, in order to boost the country's economy, especially in the post-pandemic period. Considering that existing concession contracts are nearing their end, the Ministry of Transport and railway operators have sought to bring forward contract renewals for another 30 years, imposing strict investment targets and increasing transport efficiency.

In this sense, a number of challenges have been imposed on the Brazilian railway system, such as: increasing axle load, increasing operational density, increasing authorised average speeds, increasing the size of railway trains, reducing deadlines and costs associated with asset maintenance (Junqueira *et al.*, 2017) and expanding the railway network. In light of this, concessionaires and rail logistics companies have been evaluating strategies to increase efficiency and expand freight transport, boosting financial returns and complying with regulatory parameters.

In this context, this paper evaluates the positive and negative impacts of increasing axle loads on the railway system, discussing the main gains and possible risk mitigation measures. To this end, due to the particularities of each railway and the diversity between Brazilian railway operators, a case study was carried out of MRS Logística, which is a logistics operator that manages a 1643 km long railway network in the states of Minas Gerais, Rio de Janeiro and São Paulo.

2 CASE STUDY – MRS LOGÍSTICA

Due to the complexity surrounding the railway system, where each railway has significant characteristics that differ from one another and which are important to address because they directly interfere with each organisation's strategy, this work will look at the case study of MRS Logística, a railway operator that holds the concession for an important part of the Brazilian railway network, and which is currently among the largest freight railways in the world.

2.1 Context

MRS Logística, created in 1996, is a railway operator that manages a concession railway network of 1643 km along the states of Minas Gerais, Rio de Janeiro and São Paulo, a region that concentrates around half of Brazil's GDP. Its current output is around four times higher than that recorded in the 1990s when the concession contracts began. Almost 20% of everything Brazil exports and a third of all the cargo transported by trains in the country passes along MRS tracks (MRS, 2023).

Figure 3: Railway network under MRS Logística concession (Source: <https://www.mrs.com.br/empresa/ferrovia-frota/>)

Its strategic location allows for greater diversification of production, with the main cargos represented by containers, steel products, cement, bauxite, agricultural products, coke, coal and iron ore (these last three represent 59.8% of all cargo transported by MRS).

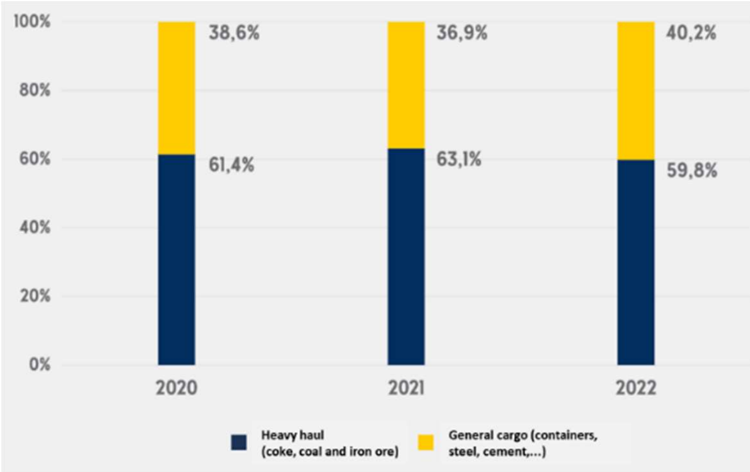


Figure 4: MRS freight distribution (Source: MRS Sustainability Report, 2023).

MRS currently owns around 20% of the national railway fleet, operating with an axle weight of 32.5 tf/axle. It should be noted that on the stretch where trains loaded with iron ore predominate, the railway network is prepared to receive 36 tf/axle, but issues associated with the dispersion of wagon loading limit its target to the lower value mentioned.

MRS's operational gauge is broad, with 1.60 metres between rails. On some more specific stretches, such as the banks around the Port of Santos, the Burnier branch and the Açominas branch, the railway track is built in mixed gauge, adding a metric gauge of 1.0 metre.

2.1.1 New regulatory obligations - Concession renewal

The initial concession of MRS was established in 1996 and was set to expire in 2026. To promote the development of the national railway sector, the Federal Government chose to conduct early renewals, with part of the grant being converted into infrastructure investments, implemented by the concessionaires.

In July 2022, MRS had its operating concession contract extended by an additional 30 years beyond the original contract, lasting until 2056. With the extended investment horizon for railway improvements, MRS aims to double the volume of general cargo and increase container transport by seven times over the new contract period.

The investment plan outlined in the new contract is supported by three pillars:

- Expansion of capacity to meet established performance parameters.
- Structuring investments of public interest, such as the elimination of conflicts with railways in urban areas.
- Projects to improve urban mobility and minimize urban conflicts, including features like footbridges, road viaducts, automatic barriers, among others.

As part of the early concession renewal, the plan includes disbursement of approximately BRL 11.0 billion (approximately USD 2.2 billion) for the renovation or expansion of the rail network, acquisition of new assets, and financial expenditures for other complementary obligations.

After the concession renewal, MRS adopted a new direction: to fully comply with over 500 obligations aimed at ensuring the quality of services provided by the company, maintaining assets in perfect operational condition, and improving the level of service for end-users.

According to the “MRS 2022 Sustainability Report”, the commitments made by the company in the concession renewal mainly encompass the following initiatives:

- Segregation of lines for freight trains (MRS) and passenger trains (CPTM) in the metropolitan region of São Paulo, expanding the capacity of both systems and increasing the operational window for the railway mode, currently constrained by time-sharing on tracks. MRS will construct a dedicated freight track, significantly contributing to the urban mobility of 12 municipalities and enhancing the company's operations in the biggest city of Latin America. This is the largest project in the renewal plan, with an estimated investment of BRL 6.5 billion (approximately USD 1.3 billion).
- Expansion of railway access capacity to the Port of Santos by more than 100%, ensuring capacity not only for MRS trains but also for other railways accessing the port.
- Revitalization and modernization of railway access to the Port of Rio.
- Investments in viaducts, footbridges, fences (security walls), level crossings, flow directors, and extraordinary solutions to enhance safety and reduce interference between the city and the railway in communities across 51 municipalities in the coming years.
- Acquisition of new locomotives and wagons to meet increased demand: over 60 locomotives and 2,000 wagons by the end of the concession contract, with more than 30 locomotives planned for the next 6 years. The expectation is that the volume of general cargo transported by MRS will increase by more than 50% due to the new investments, which will require the fleet expansion.
- Purchase of equipment for railway track maintenance: for the implementation of major track interventions project, for instance, 26 pieces of equipment and 81 wagons were procured to support the project's execution that started in 2022 and is planned to last until 2033.
- Expansion of railway yards in the three states where MRS operates, allowing the circulation of larger and more productive trains, such as in Vale do Paraíba, where crossing yards will be relocated outside urban centers and expanded to accommodate general cargo trains of up to 1,500 meters.

2.2 Impacts on the railroad infrastructure

MRS manages approximately 12,000 infrastructure assets along its network, an average of 7 assets per kilometre of railroad. The main figures are:

- 632 railway bridges;
- 90 road bridges;
- 59 pedestrian footbridges;
- 142 tunnels;
- 4,700 culverts;
- 5,814 cuts and embankments;
- 153 slope stabilization with high-tensile steel wire nets;
- 400 slope stabilization with anchored retaining walls.

To manage the infrastructure, guarantee its availability and operational reliability, MRS has a robust inspection and instrumentation plan, which feeds an asset management system and supports the technical team in defining maintenance strategies.

With regard to the increase in axle load, we highlight the railway bridges and cut and embankment substructures along the railroad, which are the main infrastructure components impacted and which must be assessed under this condition.

2.2.1 Railway bridges

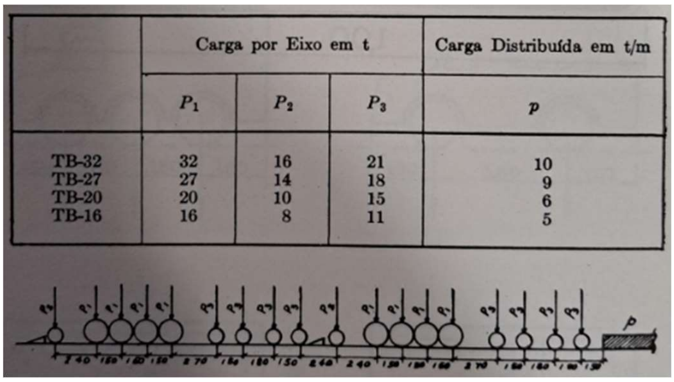
The MRS railroad, with the exception of the Steel Railway and a stretch in the São Paulo metropolitan region, is quite old, as can be seen in Figure 5. Over the years, especially during the period of public management, there has been little investment in maintaining the railroad infrastructure. Recently, during the private concession period, great importance has been attached to infrastructure, especially railway bridges, in order to guarantee operational reliability and safety.

Figure 5: Age of MRS railroad

Figure 6: Rivated steel bridge from 1910s and prestressed concrete bridge from 1980s respectively (Source: MRS)

Due to the age of the railroad, there is a considerable diversity of bridge types and structural systems along the railroad, such as riveted and welded steel bridges, rock block bridges, reinforced concrete bridges and prestressed concrete bridges. In addition, for the same reason, different standards have been adopted for the design and structural verification of bridges, the main ones being described below:

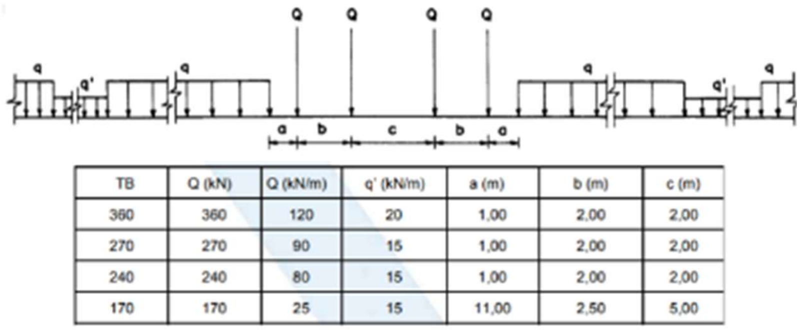
- NB7 (1943) Live Loads on Railway Bridges, which defined four Brazilian traffic load models: TB-32, TB-27, TB-20 and TB-16. In general, the TB-32 was to be used on new bridges on broad gauge main lines and the TB-20 on metre gauge. Specific conditions allowed the use of the other load models. The standard also made it possible to design the reinforcement of existing works by reducing the respective loads by 20 per cent.



	Carga por Eixo em t			Carga Distribuída em t/m
	P_1	P_2	P_3	p
TB-32	32	16	21	10
TB-27	27	14	18	9
TB-20	20	10	15	6
TB-16	16	8	11	5

Figure 7: Brazilian traffic load model from NB7 (1943)

- ABNT NBR 7189 (1985) Live Loads for Structural Design of Railway Works, which also defined four classes of Brazilian traffic load models: TB-360, TB-270, TB-240 and TB-170. The TB-360 was used for railways transporting iron ore, the TB-270 for railways transporting general cargo, the TB-240 for structural verification of existing works and the TB-170 for passenger transport. Due to its obsolescence, this standard fell into disuse and was cancelled in 2015.



TB	Q (kN)	Q (kN/m)	q' (kN/m)	a (m)	b (m)	c (m)
360	360	120	20	1,00	2,00	2,00
270	270	90	15	1,00	2,00	2,00
240	240	80	15	1,00	2,00	2,00
170	170	25	15	11,00	2,50	5,00

Figure 8: Brazilian traffic load model from ABNT NBR 7189 (1985)

Since then, Brazil has not had an active technical standard for this purpose. Railway operators have used their own studies or international references such as AREMA (American Railway Engineering and Maintenance-of-Way Association) and EUROCODE (European standards) to check existing bridges and design new ones.

Since 2022, the ABNT CEE-231 Special Committee has been carrying out studies to re-evaluate the Brazilian standard railway train in order to draw up a new standard for actions in the structural design of metro and railway works. The study is based on actual vehicle weighing data on the main Brazilian railway corridors and applied concepts from reliability theory and the ultimate limit state, especially fatigue (Lyra et al., 2022). Projections of increased axle loads on the railways are also being taken into account so that the upgrading of railway networks has technical and regulatory backing and establishes guidelines for the integration of the Brazilian railway network.

In this context, it is ideal for axle load increases to meet technical requirements and, in the absence or omission of technical standards, for special studies to be carried out for this purpose. In the case of railway bridges, due to their high cost of reinforcement or replacement and operational impacts, adequate assessments of their effective performance throughout their useful life must be carried out in order to decide on the best technical solution for recapacitation, guaranteeing financial efficiency and operational safety.

Assessments of the current condition and efficiency of interventions to structurally reinforce railway bridges require prior knowledge of their performance and the stresses accumulated during their life, gathering information that allows adequate inference of their performance and resistance (Junqueira, 2019). To this end, it is important to:

(i) Recording existing information and documents, such as: executive projects; as-built projects; calculation memories; history of inspections and interventions on the structure; and history of loads and operational trains.

(ii) Geometric survey of the structure in its current condition.

(iii) Characterisation of the mechanical properties of the materials.

(iv) Detailed inspections of all elements of the structure, carrying out non-destructive tests and mapping all anomalies (damage and pathological manifestations).

(v) Structural verification of the current condition and for the new loading condition, assessing the necessary reinforcements or the reduction of its residual useful life.

In special cases where there is some doubt or structural insecurity, or structures of greater importance from a strategic point of view, or structures that are more representative or repeatable along the railway, theoretical-experimental evaluations using instrumentation and dynamic analyses can be used to verify their structural performance under current and future conditions of increased axle load.

Junqueira (2019) proposed a theoretical-experimental assessment procedure (Figure 9) for railway bridges that has been applied and improved at MRS since 2015. The procedure initially consists of an assessment of existing documentation and knowledge, a geometric survey, material characterisation and inspection. Based on this information, a theoretical numerical model is drawn up and an instrumentation plan is defined. Sensors are installed on the structure and the passage of trains is monitored.

The theoretical model is calibrated with the deformations and displacements measured experimentally in order to effectively represent the structure in its service condition. Based on this calibrated model, the structural capacity is checked, the residual fatigue life is determined, the elements to be reinforced are identified and parameters are extracted that can support the prioritisation of interventions in these structures. Since then, experimental parameters for monitoring MRS bridges, such as the natural frequency as a function of span, have been used by other Brazilian railways.

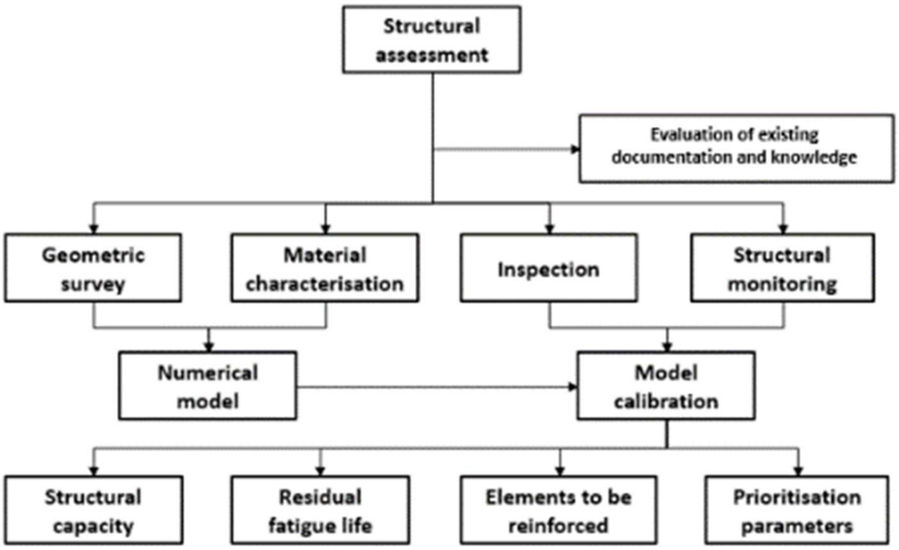


Figure 9: Theoretical-experimental assessment procedure applied at MRS (Junqueira, 2019)

In the case of Brazilian railway bridges, the increase in axle loads, operating density, the consequent increase in loading cycles and operating speeds recorded in recent years justify greater concern about the fatigue limit state. The phenomenon of fatigue consists of the loss of resistance from the process of material rupture caused by cyclical loading stresses without having reached its static resistance limit. This rupture can be sudden and without warning (Marques, 2006). Fatigue is the main cause of railway bridge collapse.

There are several theories for determining the residual fatigue life of railway bridges, the most widely used of which use the time series of static stresses and those resulting from trains passing over the bridges. The amplitudes of stress variations and the number of cycles are compared with the material's fatigue resistance by means of S-N curves (Stress range - Number of cycles), as shown in Figure 10.

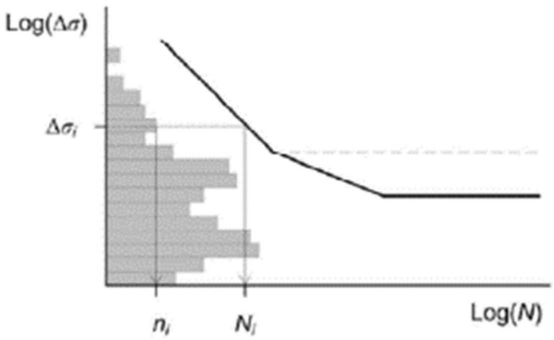


Figure 10: S-N graph for calculating damage accumulation (Kuhn et al., 2008)

According to the Palmgreen-Miner theory, the fatigue phenomenon is considered to be a process of damage accumulation up to a certain tolerable limit. This limit is represented by the line segments shown in the S-N graph in Figure 10. Thus, in a simplified way, for a better understanding, Miner's damage expression can be used:

$$DM = \sum_{i=1}^{n^{o}\,ciclos} \frac{n_i}{N_i} \leq 1$$

Where *DM* is the Miner damage, n_i is the number of cycles occurring for a stress range of magnitude $\Delta\sigma_i$, and N_i is the number of cycles corresponding to the fatigue resistance of a stress range of magnitude $\Delta\sigma_i$. In practice, the amplitudes resulting from the passage of vehicles are variable, making it necessary to use Rainflow algorithms to count the cycles. According to the formula, when the Miner damage *DM* is equal to 1, fatigue failure has occurred.

In this context, the implementation of axle load increases must be carefully studied, because in the case of railway bridges, structural retrofitting can result in high investments and operational impacts. The risk of asset failure, accidents and greater operational impacts are aggravated if the structural performance of railway bridges is not carefully assessed. Strategies for replacing and reinforcing bridges, or even monitoring the reduction in their residual life, can be adopted to dilute or reduce the total expected costs and deadlines.

2.2.2 Rail substructure

The rail substructure (Figure 11) is characterised as the surface of the ground prepared to support the elements of the superstructure (rails, sleepers, ballast and sub-ballast) of the permanent way, as well as the lateral spaces needed to install the drainage and signalling systems, among others (Rosa & Ribeiro, 2016). For the purposes of this work, we will consider the substructure to be made up of the existing linear earthworks of cutting and embankments, the purpose of which is to allow for a correct and uniform distribution of the efforts and impacts of the superstructure.

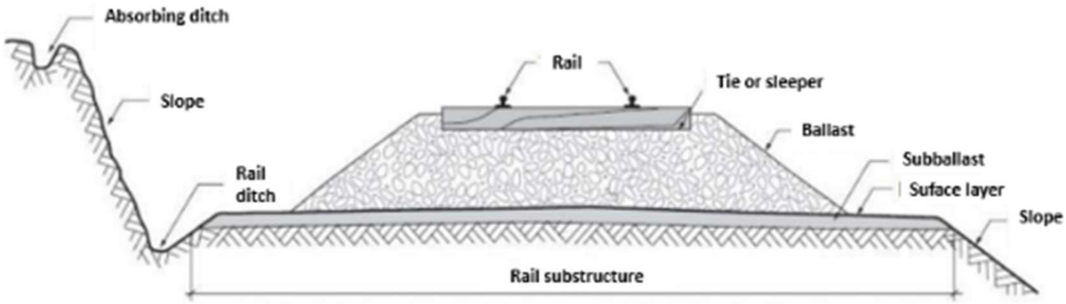


Figure 11: Track cross-section (Adapted from Nabais, 2014)

Most of the MRS railroad network is made up of century-old substructures where it is not possible to identify the sub-ballast layer, the ballast being laid on materials resulting from the mixture of old ballast and fines from ballast breakage or underpenetration of adjacent layers of soil, or directly on the sub-base, which can be an embankment material, rock, colluvium or residual alteration soil. On railroad built more recently, such as the Ferrovia do Aço, built between the 1970s and 1980s, you would expect to find a structure with ballast and sub-ballast, with the sub-ballast resting on the subgrade. In general, the maximum slope of the MRS railway platform is around 1.0%, and can reach 2.4% in the mountainous region of the state of Rio de Janeiro and 10.0% in the state of São Paulo.

Recently, in 2023, MRS began the process of renewing the permanent way with the aim of increasing the capacity of the railway and reducing the costs and operational impacts of the maintenance process. This project is in the initial stages of implementation, covering the scope:

- Total ballast undercutting with the return of drainage and elastic capacity;

- Replacing the matrix of wooden and steel sleepers to prestressed concrete sleepers;
- Expansion of the railway substructure with recovery of access for maintenance teams;
- Elimination of splint joints by electric welding with a specialised truck, reducing dynamic impacts on the track;
- Adjustment of substructure interferences (obstacles, signalling cables, etc.).

Figure 12: MRS ballast undercutter and track renewal machine in operation (Source: MRS)

In this context, the capacity of the rail substructure has been assessed to enable it to withstand both the stresses of the new superstructure characteristics, such as improving the drainage condition, removing the layer of clogged material below the ballast and increasing the weight of the sleepers. Substructure reinforcement solutions are being applied for this purpose.

The increase in axle loads generates even greater overloads for the substructure and studies to assess its support capacity must be carried out beforehand. These studies consist of:

i. Analysis of existing geological information, through geological maps or academic productions on the region under study.
ii. Preliminary assessment of the conditions of the railroad section for current loads, mapping the location and extent of pockets, areas that have recently been lifted and measurements of the maximum height of the line.
iii. Once the problem areas have been identified, draw up a prospecting plan.
iv. Inspection with the aim of delimiting homogeneous sections in terms of geomorphology, geology, earthworks section, track geometry and visual analysis of the condition of the permanent way, such as the state of conservation of the ballast, type and state of conservation of the sleepers and condition of the drainage system.
v. Once the plan has been defined, the drilling of exploration wells to collect samples of the ballast, sub-ballast and subgrade and determine the thickness of the layers.
vi. Carrying out tests to characterize the layers.
vii. Geological-geotechnical mapping using the tests carried out.
viii. Defining the calculation cross-sections based on the data obtained and analysing the stress-strain produced by the efforts of the railway track components using the theoretical and experimental foundations of pavement mechanics.
ix. Obtaining stress and strain values and indicators for the track components and comparing them with the limit values determined in technical literature.
x. Determining the load capacity for predominantly elastic stresses, considering an adequate safety factor due to the heterogeneity of the material.
xi. Dimensioning and determining reinforcement interventions to adjust the substructure's support capacity.

Failure to adjust the substructure's support capacity can favour the occurrence of misalignment and unevenness of the superstructure (Figure 13), pumping of fines to the surface forming pockets and accelerated deterioration of the ballast.

Figure 13: Deformation in the superstructure caused by low substructure support capacity (Source: MRS)

In the same way as bridges, the bearing capacity of railroad substructure must be carefully assessed for increased axle loads and interventions to correct and increase capacity must be determined, since this tends to generate major operational impacts. In order to reduce these impacts, it is recommended that the interventions be planned to go ahead in conjunction with the permanent way renewal interdictions, optimising and giving synergy to the executive processes.

2.3 Impacts on the railway track

2.3.1 Current scenario

The railway track assets of MRS can be summarized by the figures below:

- 2,468 km of track + yards and terminals;
- Over 1,800 turnouts;
- Over 4.0 million sleepers;
- Over 320,000 tons of rails;
- Over 20,000 electro-electronic assets (including signaling, power, telecom and wayside equipment).

As mentioned in the previous railway infrastructure chapter, most of the MRS railroad network is made up of century-old substructures where it is not possible to identify the sub-ballast layer and the ballast being laid on materials resulting from the mixture of old ballast and fines of adjacent layers of soil, which strongly affects the condition of the railway track components. And even in the corridors built more recently, such as Ferrovia do Aço, (dated from 1970s and 1980s), the continuous maintenance of the railway track is a need to allow the increase of the operation speed, train lengths and axle load that have been carried out since 2010s for the heavy haul.

In this scenario, the increase of the axle load becomes a challenge. The topics below will present the current scenario for the maintenance strategies and the process of track renovation that has recently been launched and its relationship with the main track components: rail, sleepers, ballast and turnouts.

2.3.1.1 Maintenance strategy

The management of the railway track assets, similar to what has already been explained in the previous chapter regarding the infrastructure assets, is carried out by MRS through specific inspection and instrumentation plans. These plans feed into an asset management system that supports the technical team to defining maintenance strategies and deciding on the deployment of new technologies.

Actions directed towards the maintenance of the railway track are coordinated among three working groups that encompass:

- **Asset reliability**: responsible for assessing asset failures and defining improvement actions to support the definition of maintenance strategies.
- **Advanced maintenance engineering**: responsible for executing analyses to determine reliability targets and maintenance times, supporting predictive and preventive maintenance strategies.
- **Maintenance strategy**: responsible for the on-site inspections and diagnosis of track conditions using control cars and the definition of medium and long-term maintenance strategies (triggers for the execution of maintenance services).

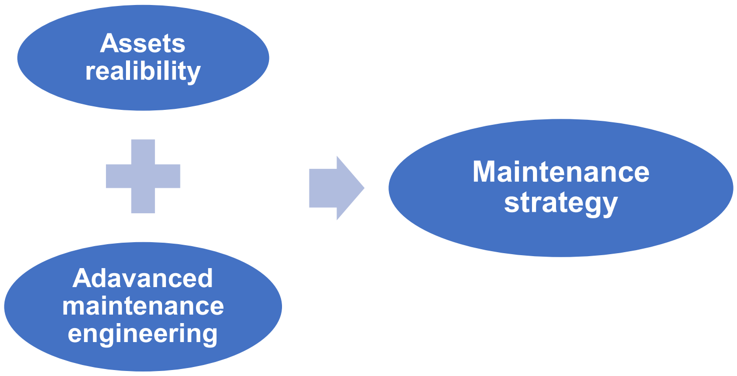


Figure 14: Maintenance strategy (Source: Author)

The graphics below represent the current situation at MRS, where a significant part of the railway network is passing through rehabilitation actions in accordance with the maintenance plan. But also, an expressive part of the heavy haul lines started in 2023 the full renovation process due to the poor ballast condition.

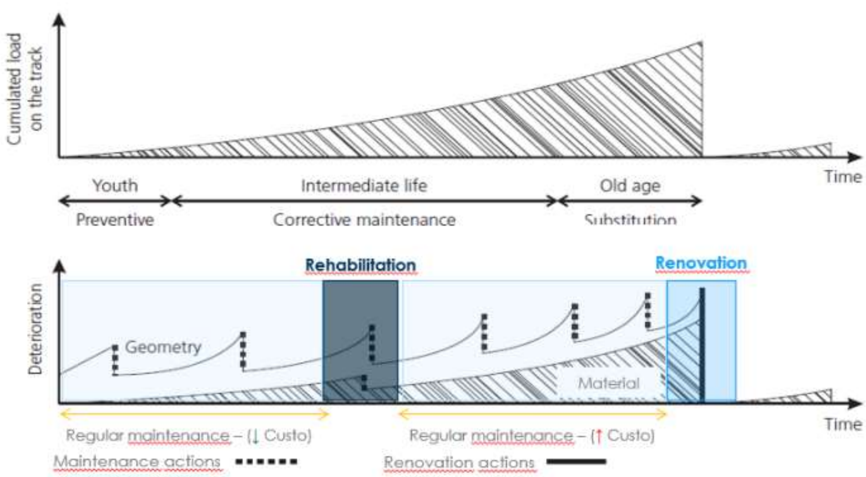


Figure 15: Railway track maintenance management (Source: MRS Maintenance Report, 2023)

To this study, the current condition of the assets and the maintenance strategies will be focused on the rails, sleepers, ballast and turnouts. In addition, the regulatory obligations that must be fulfilled under the contract of the concession renewal will also be highlighted for each of these components.

2.3.1.1.1 Rails

The current maintenance strategy aims to apply rail maintenance based on specific characteristics of each section, including axle load, balancing cost factors in the medium/long term and planned projects, with a focus on reliability, operational safety, and grinding and lubrication processes. The development of processes to expand predictive and preventive actions is ongoing, with a focus on:

Predictive actions:

It considers addressing worn rails and those with concentrations of surface defects/fatigue, depending on the section and its peculiarities. The pillars of rail management are concentrated in:

- Grinding: Maintaining continuous grinding cycles is one of the most important pillars of maintenance in heavy haul lines and proves to be an essential procedure to extend the component's lifespan, as shown in Figure 16.

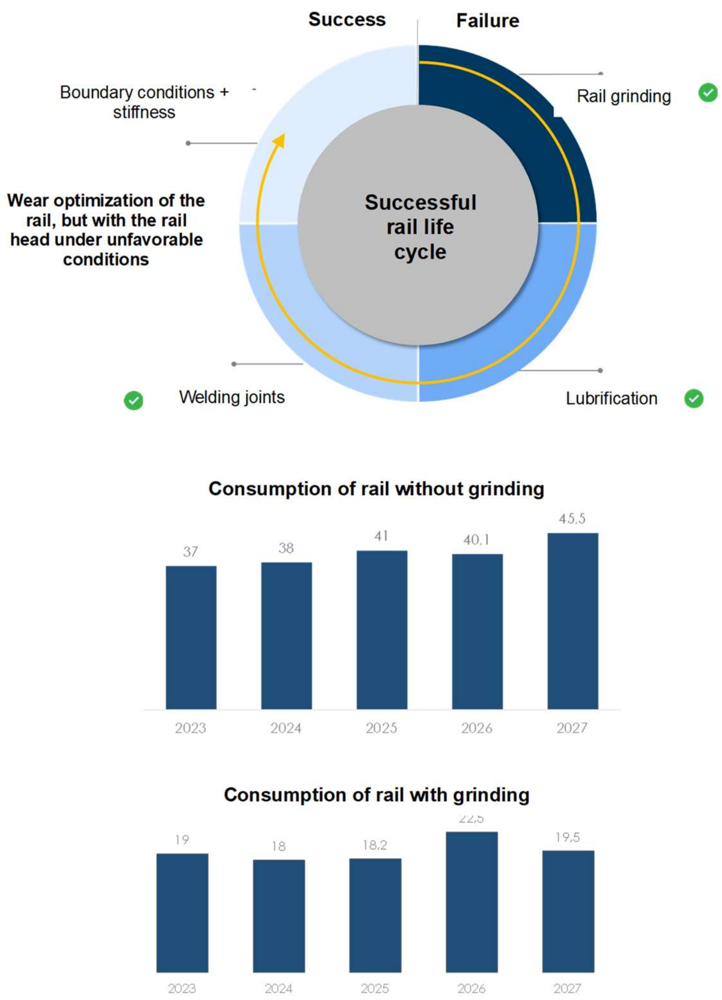


Figure 16: Rail maintenance life cycle and projection of the effects of rail grinding (Source: adapted from MRS, 2023)

- Lubrication.
- Improvement of the welding process.
- Track condition (diagnosis): reduction of fractures combined with an improvement in grinding process, evolution of the rail matrix, and strong focus on boundary conditions (plate condition, drainage, ballast contamination, etc.).

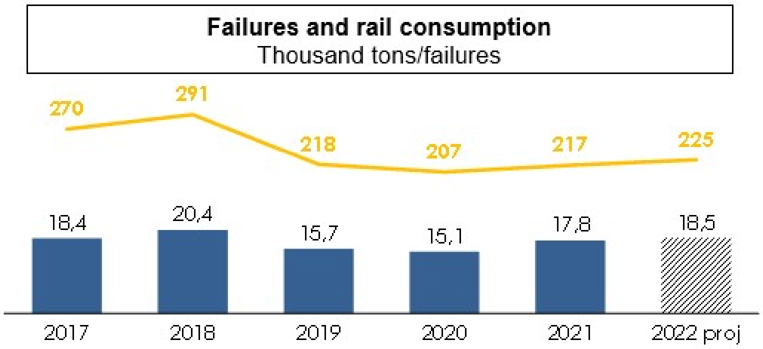


Figure 17: Correlation between failures and rail consumption (Source: adapted from MRS, 2023)

Preventive actions:

The preventive actions are mainly focused on two specific items:

- Preventive replacement of rail segments in critical locations.
- Focus on the rail head condition.

Ferrovia do Aço (the most demanded heavy haul corridor of MRS) represents quite well the importance of the maintenance strategy and how the boundary conditions strongly affect the performance of the railway track and its reliability and availabilty. This corridor presents a high incidence of fractures originating from the rail head, with the following aggravating factors:

Contaminated ballast: almost 100% of the ballast is classified as contaminated, and 65% highly contaminated. These numbers and the lack of effectiveness of the regular maintenance led the company to decide for the full renovation of the corridor (more details on Chapter 2.3.1.2 Railway track renovation).Railway track renovation

1) Challenges in ultrasonic detection of defects on the rail head (signal propagation):

   The signal is not able to cover all the rail profile, so cracks in the rail body are still not fully identified by this method.

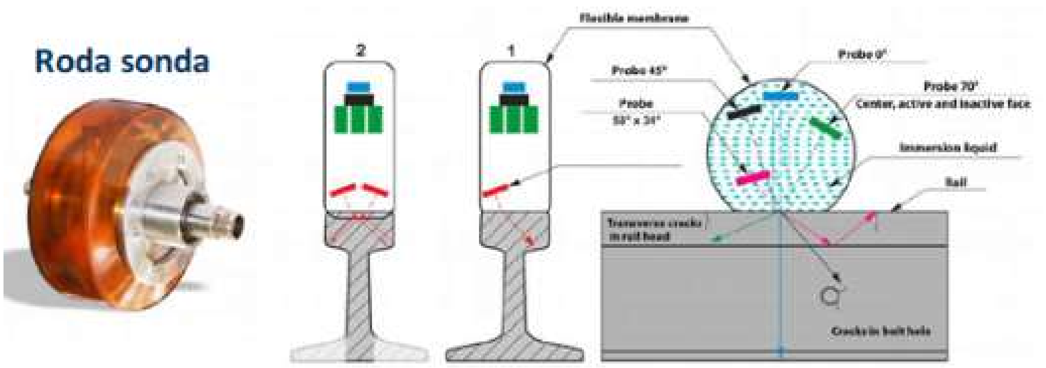


Figure 18: Ultrasonic inspection (Source: MRS Maintenance Report, 2023)

2) Issues related to boundary conditions:

   The high degradation of the support plates is also a frequent issue that has been corrected with the application of elastic rail pads.

Figure 19: Examples of degradated support plate and impacts for rail and sleeper (Source: MRS Maintenance Report, 2023)

Also the corridors in São Paulo and Vale do Paraíba present track issues that demand continuous preventive maintenance. These corridors present high incidence of defects in the rail head and rail breaks, which generate impacts in the other components of the track as they are all connected. The most common defect is the excess of surface defects on rails, which result in other impacts such as:

- Impacts on the rail joints, support plate and sleeper.
- Increased demand for tamping.
- The increase in the difficulty in maintaining cyclical maintenance, increasing the need for corrective interventions that are more costly and that demand operational interruptions to be executed.

Figure 20: Examples of critical rail failures (Source: MRS Maintenance Report, 2023)

2.3.1.1.2 Sleepers

The maintenance strategy aims to apply the sleeper with the best life cycle cost for the track, considering its specificities, balancing cost factors in the medium/long term, and planned projects, with a focus on reliability and always prioritizing operational safety.

The macro strategy seeks to reduce dependence on wooden sleepers and comply with the minimum specifications of the new obligations set by the Federal Government in the concession renewal, aiming to:

- Increase of the track life cycle.

- Gradually replace the wooden sleepers with prestressed concrete and steel sleepers.

Preventive actions (until 2022):

- Regular maintenance in line with the project of full renovation.
- Adoption of steel sleepers.
- Introduction of extensive data management.

Prescritive actions (from 2023):

- Adoption of prestressed concrete sleepers.
- The data management is intensified aiming to cover all components, equipment's, 'and maintenance processes in order to make them more predictable.

The defined strategy for the medium term is centered on three goals:

- Increase of the life cycle.
- Reduction of the dependency of wood sleepers:
  - Short life cycle of approximately 3.5 years.
  - Dependency of external supply (mainly from USA).
  - Need of higher volumes to maintain the unserviceable sleeper rate in a manageable range.
- Fulfillment of the regulatory obligations of the concession renewal:
  - No acceptance of any unserviceable sleeper in turnouts, tunnels, viaducts, and segments that transport hazardous products.
  - Acceptance of unserviceable sleeper must complain with:

Tableau 1: Regulatoy obligation - Acceptance of unserviceable sleeper (Source: adapted from Caderno de Obrigações MRS, 2022)

Type of rail	Maximum % unserviceable sleeper			
	Tangent	R >= 350	250<R<350	R <= 250
TR 68	20%	20%	15%	10%
Hazardous cargo	10%	10%	5%	3%

  - The technical parameters for sleepers are related to their preservation and gauge limits.

The current MRS standard ensures the railway safety, as the verification through inspections ensures that the sleepers are within technical and safety parameters and do not pose risks to operations, combined with constant monitoring (on-site and with equipment) to ensure the stability of the track.

Figure 21: MRS scenario / ANTT parameter / Example of unserviceable sleeper

2.3.1.1.3 Ballast

As presented before, most of the MRS railroad network is made up of century-old substructures where it is not possible to identify the sub-ballast layer, the ballast being laid on materials resulting from the mixture of old ballast and fines from ballast breakage or underpenetration of adjacent layers of soil.

The regulatory obligations of the concession renewal determine minimum parameters for:

- Dimensions of the ballast layer.
- No evidence of fines pumping from the sub-ballast or granular base, or visual non-compliance issues regarding granulometric and geometric aspects.

The procedures for ballast maintenance and recovery at MRS are presented below, with the current situation at the heavy haul corridor.

Figure 22: Ballast cleaning and recovery procedures

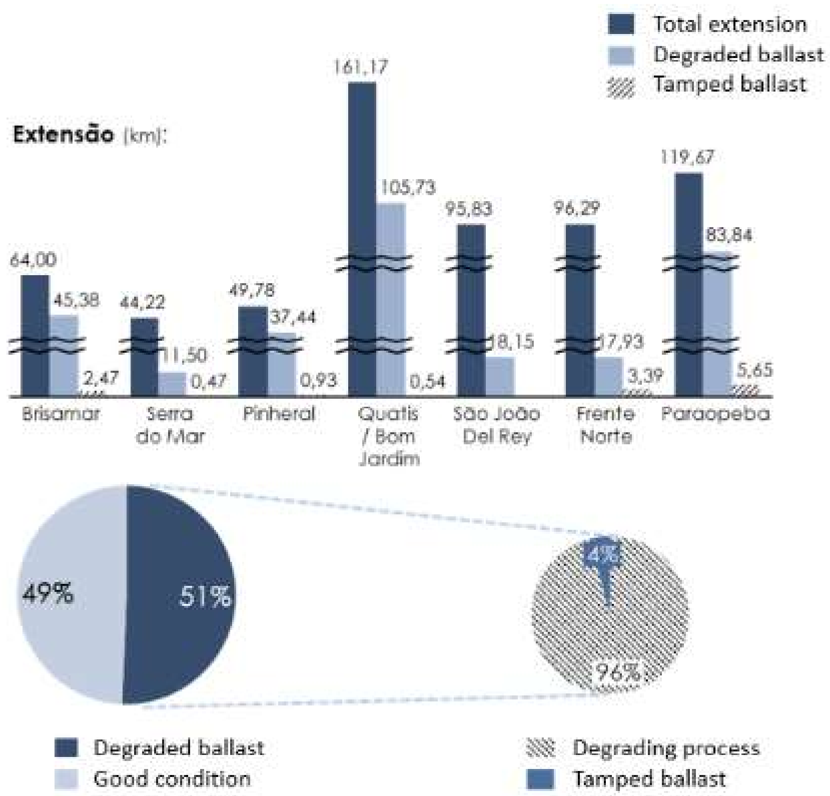


Figure 23: Ballast condition in the heavy haul corridors - to be renewed (Source: MRS Maintenance Report, 2023)

2.3.1.1.4 Turnouts

For the turnouts, the need for maintenance is similar to the rail that has already been presented as so as the challenge to increase the axle load. In addition, MRS is executing a plan to renew more than 420 track switches in the next 5 years because of life cycle parameter (equipment with more than 40 years) or due to equipment discontinuity.

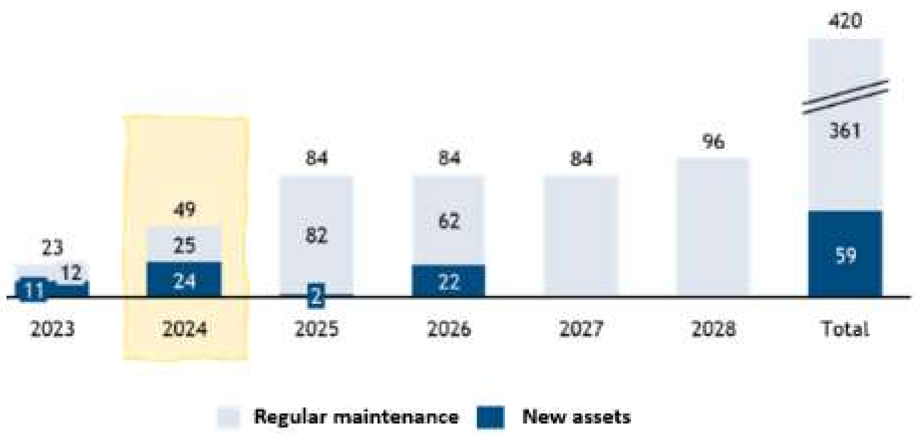


Figure 24: Renewal plan - track switches

2.3.1.2 Railway track renovation

In recent years, MRS has been seeking technical and economic feasibility for the implementation of a disinvestment and line renewal project due to the accelerated degradation of the railway track, a gradual increase in maintenance costs, and a scarcity of high-quality wooden sleepers in the market. By the end of 2019, the initiative aimed at railway track renewal projects was consolidated.

In this scenario, various tasks were undertaken to define the scope in MRS interface areas. This included simulation studies of operational impacts (capacity volume calculation) concerning the Line Renewal project, models of operational intervals to be adopted, necessary resources and equipment, definition of working trains and resources for acquisition, proposed layout for the construction of railway deviation for permanent way maintenance, and renewal/disinvestment project.

The first renewal cycle is expected to last 11 years and includes:

- Acquisition of 26 large equipment’s and 76 support wagons.
- Construction of 7 support and maintenance buildings.
- Renewal of over 560 km of tracks.
- Renewal of over 100 turnouts.
- Replacement of over 720,000 wooden sleepers with prestressed concrete sleepers.
- Elimination of splint joints by electric welding with a specialized truck, in order to reduce the dynamic impacts on the track.
- Complete replacement of ballast on renewed tracks.

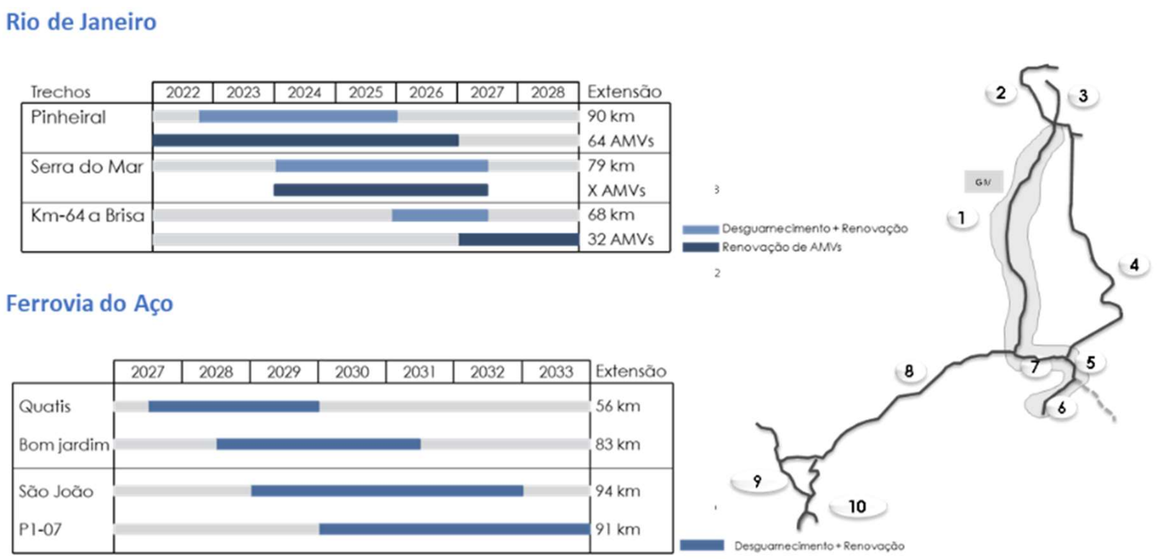


Figura 25: Segments to be fully renewed in the next 10 years (Source: MRS Maintenance Report, 2023)

It is important to mention that these interventions require operational intervals for service execution, with durations ranging from 10 to 24 hours, which obviously has a significant impact on operations in the sections under construction and, consequently, on the volume of cargo to be transported by the company.

2.3.2 Impacts of the increase of the axle load

The benefits and savings generated by the increase in axle load are unquestionable; however, as stated by Newman et al. (1990), from an engineering standpoint, there is no doubt that higher axle loads reduce the lifespan of permanent way components, increase the rate of line degradation and its structure, and escalate the cost of potential derailments, as evidenced in Figure 26.

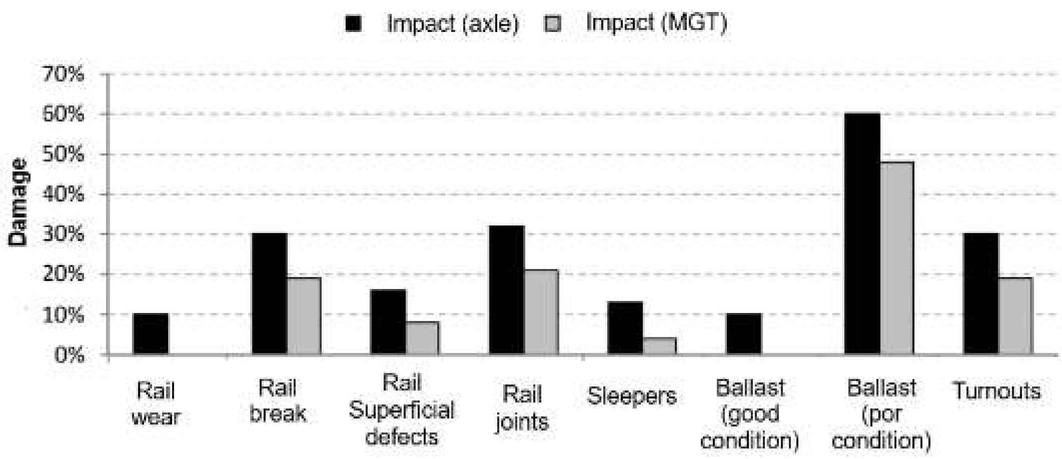


Figure 26: Impact of the increase of the axle load at MRS (Fonte: Adapted from FERREIRA, 2015)

It is also important to highlight that the reliability of the railway track is highly impacted by the increase in axle load. As a result, the maintenance process will be burdened by a greater number of corrective maintenance activities, a reduction in the time between preventive maintenance, and the need for intensified inspections and monitoring of the track. This applies to both control cars and on-site inspections, with the aim of mitigating the occurrence of critical failures and derailments.

2.4 Impacts on the rolling stock - Freight cars and locomotives

2.4.1 Rolling stock scenario at MRS

The MRS fleet encompasses approximately 22,000 railcars, with 50% allocated to Heavy Haul operations, comprising the GDT (130 tons) and GDU (150 tons) models. The table below illustrates the distribution of fleets within the overall scenario.

Table 2: Railcar Distribution Within the Fleet

Fleets	Quantity
Bulk Cargo	1.668
Heavy Haul (Dumper)	11.109
Hopper	807
Flat Car	2.371
Gondola	2.125
Boxcar	914
Cement	445
Track Fleet	332
Service	2.024
Total	21.795

In the locomotive segment, the company maintains an operational fleet of around 760 machines, with 40% of them falling under the premium category, represented by the AC44 and ES44 models. This diversity in the fleet underscores MRS's commitment to efficient operations tailored to the specific demands of railway transportation. Below is the table with the models and groups.

Table 3: Distribution and Models of Locomotives

Group	Model	Quantity
1	STADLER HE	7
2	GE-720HP	9
	GE-U5B	3
	GE-U6B	5
	HITACHI DI	2
3	GE-U20C	25
4	GE-U23C	21
	GM-SD18	1
	GM-SD38	30
5	GE-C26	62
6	GE-C30M1	18
	GM-SD40-2	32
7	GE-C30	40
	GM-SD40-3	14
8	GE-C36	131
9	GE-C44MIL	61
10	EMD-SD70AC	7
	GE-AC44MIL	285
	WT-ES44MIL	13
Total		766

MRS conducts preventive and corrective maintenance of its fleet in its own workshops and in partnership with third parties, covering light, intermediate, and heavy scopes. These processes involve a thorough assessment, replacement, and testing of all subsystems of the assets, ensuring that they are returned to operation with maximum reliability after the interventions are completed. This rigorous approach demonstrates MRS's commitment to the preservation and efficiency of its fleet.

Figura 27: Location of Railcar and Locomotive Maintenance Workshops (Source: MRS)

2.4.1.1 Railcar models

2.4.1.1.1 Heavy haul

To meet the demands of Heavy Haul railway operations, MRS relies on two predominant types of railcar models, primarily gondolas. These railcars are unloaded using the rail car dumper and are mostly configured as dual units, enhancing the load capacity and efficiency in transporting heavy materials.

The GDT model, more widely distributed and making up a significant portion of the Heavy Haul fleet, accounts for approximately 85% of the entire Heavy Haul fleet. These railcars typically have a tare weight of 19 tons, a maximum gross weight of 130 tons, and a volume of 50 cubic meters. They feature wheelsets equipped with K-class cartridge type railway bearings and 36” micro-alloy steel wheels with a hardness between 380 and 415 BHN. The bogie must meet the key concepts of wheel-rail interaction, with high resistance to misalignment ("warp") and lateral oscillation ("hunting"), along with increased freedom of rotation for the wheelset (radial clearance). Normally, the forces on the couplings reach up to 150 tons.

Figure 28: GDT Inox Railcar (Source: MRS)

The GDU railcar, designed for Heavy Haul operations, has an average tare weight of approximately 22 tons, with a maximum gross weight of 150 tons and a volumetric capacity of 50 cubic meters. Equipped with bogies featuring 38” wheels and G-class bearings, these railcars share the radial technology of the bogies with the GDT model, as well as the forces on the couplings. This technological standardization ensures consistency and operational efficiency between the GDT and GDU models in the rail fleet.

Figure 29: Typical GDU Railcar (Source: MRS)

2.4.1.1.2 General cargo

For the efficient transport of general cargo, MRS maintains a diversified fleet of railcars, adapted according to the specific requirements of the type of cargo to be transported. This variety includes models such as Hopper, Flatcar, Boxcar, Tank, among others. Each of these models is designed to meet different logistical demands. The gross load capacities of these railcars range between 80 and 130 tons.

Below are some railcar models that are part of the MRS fleet:

Figure 30: PET, HPT, and FHS Railcars (Source: MRS)

2.4.1.2 Locomotive models

MRS relies on a variety of locomotive models for its railway operations, each designed with specific technical features to meet the demands of rail transportation. When examining the company's most recent locomotive model, we highlight relevant information as presented in the table below:

Table 3: Technical Specifications of the ES44-AC Locomotive

Características	Especificação
Model	ES44-Aci
Total Lenght	22,3 meters
Total Width	4,67 meters
Nominal Power at full effort and 1050 rpm	4.365 HP
Cylinders	12
New Wheels	42"
Maximum Speed	112 km/h
Controlled Maximum Speed	76 km/h

Continuous Tractive Effort	75.300 kgf
Maximum Tractive Effort	90.700 kgf
Maximum Braking Effort	53.000 kgf
Brake Technology	CCBII
Powered Wheelsets	6
Fuel Tank Capacity	18.900 liters
Gross Weight	197,9 tons
Friction Enhancer	Sand
Bogies	3 axles

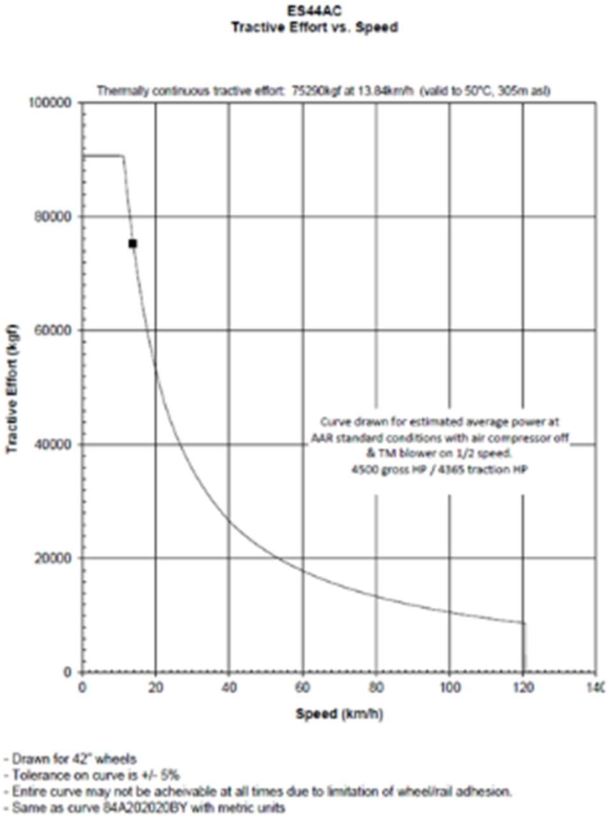


Figure 31: Tractive Effort Curve of the ES44-AC Locomotive

Figure 32: ES44-ACi Locomotive (Source: MRS)

2.4.2 Approach to increased load – Rolling stock

To optimize cargo transport, considering both locomotives and railcars, several strategies can be implemented, including:

- Acquisition of more railway assets.
- Increase in train length.
- Enhancement of fleet availability.
- Exceeding railcar load limits.

Here is a preliminary analysis of the impacts associated with these items, aiming to assess their technical, financial, and operational feasibility.

2.4.2.1 Assets acquisition

In this case, the impact on the company is significantly financial, as the cost of acquiring assets in the railway sector is notably high, often exceeding the multimillion-dollar mark. To carry out such acquisitions, a thorough analysis of the transportation demand is conducted, determining the economic viability of the purchase. From a long-term perspective, the maintenance of these assets comes into play, requiring a careful evaluation of the capacity of workshops, whether internal or external, that provide these services. This evaluation is essential for the effective planning and meeting the demands related to these assets over time.

2.4.2.2 Increase in train length

When considering the expansion of the train size, there naturally arises the need to increase the tractive effort available in the traction locomotives. In this context, the impact of opting for more powerful locomotives, with better traction performance, reflects on the clearance restrictions, as, in certain cases, more robust locomotives may have larger dimensions. Therefore, it becomes imperative to conduct a detailed assessment of the allowed dimensions to ensure the feasibility of circulation.

Another relevant point to be considered lies in the arrangement and operational mode of locomotives, especially when adopting the distributed traction method, which will require the use of more locomotives to form the desired type of train.

This analysis should also take into account the maximum allowed efforts of the traction components to prevent detrimental effects such as fractures, excessive wear, or other low-reliability effects.

2.4.2.3 Increase in fleet availability – Maintenance backlog approach

Expanding fleet availability represents a significant and impactful risk in the maintenance process, as it can lead to the postponement of triggers for scheduled maintenance in a given period. This deferral, in turn, contributes to the increase in the backlog of railcars / locomotive with overdue maintenance, creating a trend of rising occurrences of reliability indicators and, consequently, ineffective fleet management in terms of quality and scope compliance as a whole.

2.4.2.4 Exceeding railcar load limits

2.4.2.4.1 Bearing wear

The bearings mounted on the wheelsets, when subjected to overload, begin to have their service life reduced as they are being stressed beyond the factors calculated for the manufacturing design. There are some failure modes that, when visible in high concentration, indicate bearing overload.

Micro spalling of the cup and cone is an indication of bearing overload because with more dynamic load on the bearings, the lubrication film is extinguished at times, increasing friction and metal-to-metal contact, which is extremely detrimental.

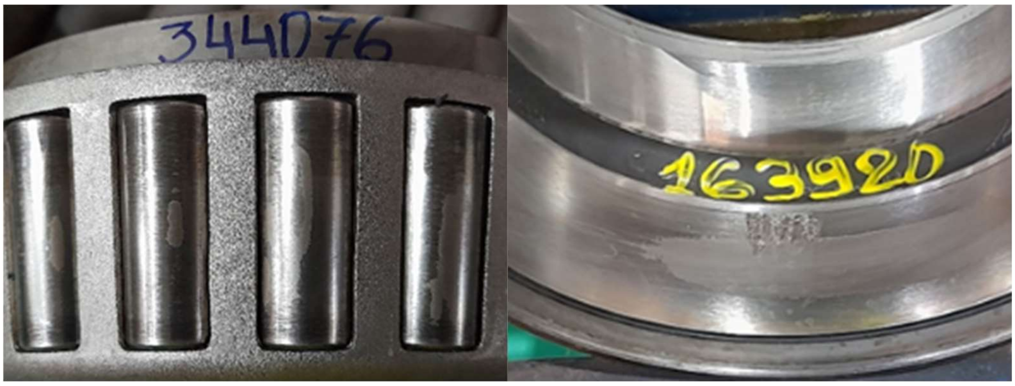


Figure 33: Micro spalling of the cone and cup (Source: MRS)

Figure 34: Severe cup spalling (Source: MRS)

Another indication is the face wear failure mode on bearing cones, especially in Short and AP-II models, as the axle sleeve flexes more than designed, causing the inner face of the cone to friction against the thrust ring.

Figure 35: Face wear on the bearing cone, class K

The theoretical life of railway bearings is calculated by the method called L10 and takes into account, to a greater extent, the operating speed and the load applied in operation. Below is a simulation curve of the theoretical life of class K bearings, applied to railcars with a gross weight of 130 tons, for some scenarios of average speeds.

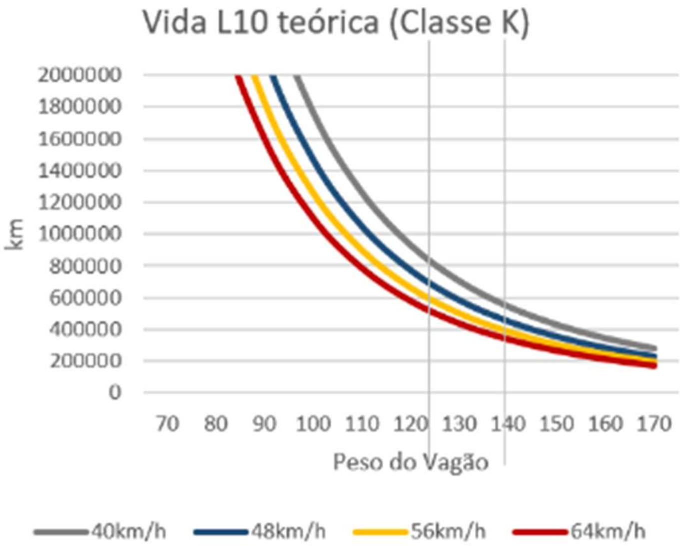


Figure 36: Theoretical life graph of class K bearing – Speed Curve

2.4.2.4.2 Wheel failures

Excessive load can lead to anomalies in wheels that impact operational performance and may result in train stoppage.

An increase in contact fatigue (RCF) on wheel treads can be an indicator that the wheels are subjected to positive variations in the load supported by the wheels.

Figure 37: Contact Fatigue (RCF) (Source: MRS)

Another failure mode that may be linked to excess load is the shattered rim, where a fraction of the wheel becomes detached. This occurs due to the concentration of loads at the external points of the wheel tread, causing it to be unable to support the load and fail.

Figure 38: Shattered Rim Cases (Source: MRS)

Premature wheel wear may also occur, necessitating wheel reprofiling sooner than planned. This has financial impacts due to the unnecessary loss of wheels and operational impacts as the railcar is unavailable for operation, being immobilized in the workshop for wheel replacement.

Figure 39: Excessive wheel wear (Source: MRS)

2.4.2.4.3 Coupling Impacts

Analyzing the axial impact absorption system of the train, an increase in load can have undesirable effects on the structural characteristics of the components. As a basic premise, the function of the shock absorption system is to transmit and attenuate stresses to the railcar structure.

Greater demands imply higher fatigue stresses, resulting in accelerated wear and crack nucleation that can lead to component fractures, causing the train to break apart. These are significant impacts on operations that require time to restore the conditions for circulation.

For the increase in train size, as described in the above section, there is the same concern about the health and load absorption capacity of couplings and shock appliances.

Figure 40: Fractures in the coupling system (Source: MRS)

3 RISK ANALYSIS

The elevation of axle load in heavy haul railways poses a significant challenge, necessitating a thorough analysis of associated risks and the implementation of effective mitigation measures. Operating trains with exceptionally heavy loads per axle can impact various facets, ranging from wear and tear on railway infrastructure to environmental and regulatory concerns. This study aims to comprehensively examine the inherent risks in this practice, emphasizing critical areas such as rail wear, stress on structures, potential issues with scales and silos, while also addressing procedural risks including documentation, adherence to conduct standards, and the imperative need for alignment with stakeholders. By delving into both operational and procedural dimensions, this research seeks to provide insights that ensure operational safety, sustainability, and compliance with established standards.

Expanding on the introductory paragraph, the following section aims to visually present the diverse risks associated with increased axle weight in heavy haul railways. Enclosed in the forthcoming figure, this "Diagram of Risks Associated with Increased Axle Weight in Heavy Haul Railways" serves as an illustrative guide, providing a centralized overview of the identified risks categorized into five crucial dimensions: Maintenance Strategy, Operational Impacts, Regulatory and Environmental Risks, and Implementation Process Risk. The figure enhances clarity by visually mapping the intricate interconnections among these risk factors, offering stakeholders a tangible reference for in-depth analysis and discussion. This graphic underscores the importance of a holistic understanding of the challenges posed by increased axle weight in heavy haul railways, setting the stage for comprehensive exploration and strategic considerations in the subsequent sections.

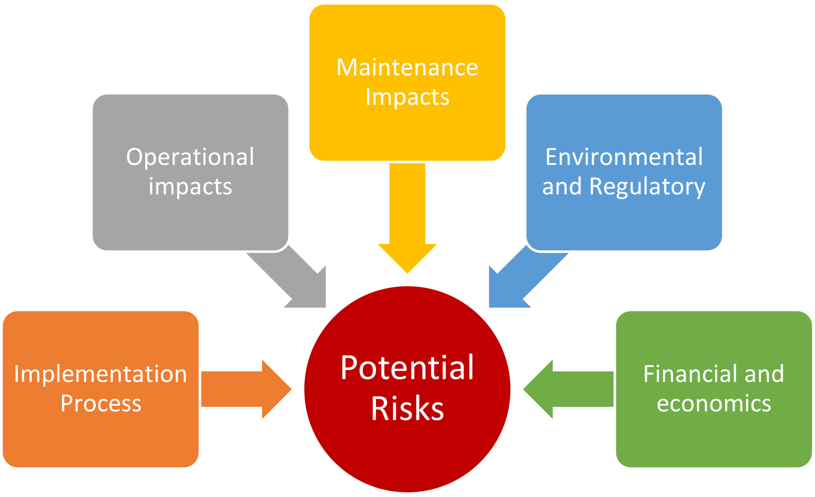


Figure 41: Diagram of Risks Associated with Increased Axle Weight in Heavy Haul Railways (Source: MRS)

Continuing with the detailed approach, each of the crucial dimensions highlighted in the diagram will be explored more extensively, providing an in-depth analysis of the specific risks associated with increased axle weight in heavy haul railways, along with discussions on mitigating actions.

3.1 Implementation process risk

The risks associated with the implementation process span various aspects, including marketing, economic, and operational considerations. However, at this juncture, we will focus on the strategy employed from the initiation of adjustments to the complete restructuring of the company for the new axle weight scenario. It is essential to underscore that this is a long-term project, implying a prolonged period of hybrid operation. This necessitates heightened process control at all levels of the organization, given the coexistence of legacy practices and new procedures during the transition.

3.1.1 Implementation of the process risk for maintenance of infrastructure

Starting with the maintenance of infrastructure, throughout the entire migration period, there will be sections and OAE (Overall Asset Effectiveness) with varying capacities to support both the new and old axle weights. The impacts of this model on train operation and circulation will be addressed in the subsequent operational topic. Speaking specifically about infrastructure maintenance and OAE, we can identify the following risks:

- Elevation of control for future asset replacement.
- Resizing and adaptation of stocks for maintenance.
- Continuous system updates for communication with operations.
- Constant review of maintenance strategies by section.

3.1.1.1 Elevation of control for future asset replacement

In the context of migrating to new axle weight standards in heavy haul railways, this risk associated with increased control and management necessary for future asset replacements. This includes an elevation in monitoring, assessment, and planning requirements to ensure that existing assets align with the new load standards. This risk can manifest in various ways:

- **Asset Obsolescence:** As new standards are implemented, some assets may become obsolete or inadequate. Identifying and monitoring assets that will need replacement in the future will require heightened control to ensure ongoing compliance.
- **Asset Lifecycle**: Migration to new standards can accelerate the lifecycle of certain assets, demanding careful assessment to determine the optimal timing for replacements. This entails an elevation in asset lifecycle management.
- **Strategic Planning:** Increased control involves more sophisticated strategic planning for asset replacement, considering factors such as necessary investments, downtime, and seamless integration with new operational standards.

To mitigate this risk, it is crucial to implement effective asset monitoring systems, conduct regular assessments of asset condition, and develop clear replacement strategies. Additionally, maintaining open communication with suppliers and stakeholders throughout the migration process contributes to a smoother and more efficient transition.

3.1.1.2 Resizing and adaptation of stocks for maintenance

In the context of the heavy haul railway axle weight standard migration study, addressing the "Resizing and adaptation of stocks for maintenance" risk involves considering the challenges associated with adjusting and modifying inventories of parts and equipment essential for railway infrastructure maintenance. This risk involves specific challenges:

- **Outdated Inventory**: The introduction of new weight standards may render some previously stocked parts and equipment obsolete. Resizing involves updating the inventory to reflect the new requirements, avoiding the maintenance of unnecessary items.

- **Availability of Specific Parts**: With the coexistence of sections operating under old and new standards, there is a need to ensure the availability of specific parts for both. This requires careful resizing of maintenance stocks, considering the specificities of each standard.
- **Training and Technical Knowledge:** Adapting stocks also involves training maintenance teams to handle new parts and procedures specific to updated standards. Failure to adapt in this regard can result in operational inefficiencies and extended downtime.

To mitigate these risks, it is vital to conduct a comprehensive analysis of existing stocks, identifying redundant or obsolete parts. Additionally, implementing robust training programs for the maintenance team, ensuring they are adequately prepared to handle the demands of the new weight standards, will significantly contribute to a successful transition. Effective stock management, aligned with the maintenance requirements of each standard, is crucial for operational continuity during the migration process.

3.1.1.3 Continuous system updates for communication with operations

In the context of our discussion on migrating to new axle weight standards in heavy haul railways, the aspect of "Continuous system updates for communication with operations" underscores the importance of ongoing technological adjustments to maintain seamless communication between different operational facets.This involves:

- **Integration with New Standards:** As the axle weight standards evolve, continuous updates to communication systems are crucial to ensure seamless integration with new operational requirements. This is particularly vital during the coexistence of old and new standards.
- **Real-Time Data Exchange**: Continuous system updates enable real-time data exchange between maintenance operations and broader railway management systems. This facilitates informed decision-making and timely responses to emerging challenges.
- **Adaptability to Operational Changes:** The railway's operational landscape may undergo shifts during the migration period. Regular system updates allow for adaptability to changes in train schedules, load distributions, and other operational variables.
- **Enhanced Safety Protocols:** Communication systems play a critical role in ensuring safety protocols are consistently enforced. Continuous updates help in incorporating the latest safety measures and standards into the communication framework.
- **Efficiency in Resource Management:** Updated communication systems contribute to the efficient management of resources, including personnel, equipment, and infrastructure, leading to optimized operations throughout the migration process.

By prioritizing continuous system updates, railway operators can uphold a high level of communication efficiency, enhancing overall operational performance and responsiveness to evolving standards. This adaptability in communication systems is essential for the successful management of heavy haul railways during the transition to new axle weight standards.

3.1.1.4 Constant review of maintenance strategies by section

The concept of "Constant review of maintenance strategies by section" emphasizes the need for an ongoing assessment and adaptation of maintenance strategies tailored to each distinct railway section.

This practice involves:

- **Dynamic Operational Environment**: Recognizing that different sections of the railway may have unique characteristics and challenges, a constant review allows for the adjustment of maintenance strategies to suit the dynamic operational environment.
- **Compliance with Varied Standards**: As the migration involves a period of coexistence between old and new weight standards, maintenance strategies must be flexible enough to comply with both sets of requirements. A continuous review ensures alignment with evolving standards.
- **Optimizing Resource Allocation**: Regularly reassessing maintenance strategies allows for the optimization of resource allocation, ensuring that the right resources are deployed to address specific challenges in each railway section efficiently.
- **Adapting to Technological Changes**: The review process facilitates the integration of emerging technologies and best practices, enhancing the overall effectiveness and sustainability of maintenance strategies over time.

By incorporating a constant review mechanism, railway operators can proactively address emerging issues, enhance operational resilience, and maintain a high level of safety and efficiency throughout the migration process and beyond. This adaptability is crucial for navigating the complexities associated with the coexistence of different axle weight standards during the transitional phase.

3.1.2 Implementation of the process risk for rolling stock maintenance

Certainly, transitioning to the maintenance of rolling stock, particularly locomotives and railcars, during the project implementation process with a hybrid operation introduces various impacts and procedural risks. Given the coexistence of railcars with different capacities and the varied use of locomotives, challenges can be diverse. Let's explore the procedural risks in this scenario:

- **Divergent Maintenance Systems**: With the operation of railcars and locomotives with distinct capacities, there may be a need for divergent maintenance systems to address the specificities of each category. This requires a careful approach to ensure efficiency and compliance.
- **Ongoing Team Training**: The introduction of new assets and hybrid operation demands continuous training for the maintenance team. This includes familiarization with the specific technical characteristics of each railcar and locomotive type, ensuring proper maintenance practices.
- **Inventory of Parts and Tools**: Managing inventory becomes more complex with diverse rolling stock. Maintaining an efficient inventory of parts and tools to cater to different models is crucial to avoid delays in maintenance.
- **Harmonized Safety Standards**: Ensuring that safety standards are harmonized across different types of rolling stock is essential. A unified approach to safety procedures simplifies operations and reduces risks.
- **Condition Monitoring of Assets:** Implementing condition monitoring technologies becomes vital for proactive maintenance. This allows for early identification of potential failures and optimization of maintenance planning.

Addressing these procedural risks in rolling stock maintenance, the company will be better positioned to tackle the specific challenges of operating a heterogeneous fleet during the transition period. This contributes to operational efficiency and the ongoing safety of the operation.

3.1.3 Implementation of the process risk for operation

The impacts on railway operations during a hybrid phase throughout the project's initiation to completion, which may span many years, involves considering various aspects. In this context, factors such as the conductors' driving standards, average speed of the section, maneuvering procedures, railcar loading, and more are crucial. Let's explore the procedural impacts in the context of a hybrid operation:

Driving Standards: The hybrid operation necessitates a balance in driving standards for train conductors accustomed to both old and new axle weight standards. This requires ongoing training and clear communication to ensure a smooth transition in driving practices.

- **Average Speed Adjustments:** With the coexistence of railcars with different capacities, adjustments to the average speed on the rail section may be necessary. This accounts for variations in loading, ensuring safe and efficient operation without compromising on schedules.
- **Maneuvering Challenges:** Operating a hybrid system introduces maneuvering challenges, especially when transitioning between sections with varying weight standards. Train conductors must adapt to different handling characteristics, necessitating careful planning and coordination during maneuvers.
- **Loading Procedures:** The hybrid nature of the operation involves loading both old and new railcars. Adjustments in loading procedures are crucial to ensure optimal weight distribution, preventing imbalances that could impact train stability and safety.
- **Communication Protocols:** Clear communication protocols become paramount during the hybrid phase. Train conductors need to be well-informed about the specificities of each railcar type and the corresponding operational requirements to maintain efficient and safe operations.
- **Operational Flexibility:** The hybrid operation demands a high degree of operational flexibility. This includes the ability to adapt to unexpected challenges, changes in scheduling, and the evolving demands of a dynamic railway environment.

By addressing these operational impacts proactively, railway operators can navigate the complexities of a hybrid phase seamlessly. This involves a holistic approach, incorporating ongoing training, efficient communication, and adaptable operational procedures to ensure the success of the project over its extended timeline.

3.1.4 Conclusion

In summary, the implementation process of migrating to new axle weight standards in heavy haul railways encompasses a spectrum of risks and procedural considerations across marketing, economic, and operational dimensions. Focusing on the strategic aspect, the transition involves a comprehensive strategy from the initiation of adjustments to the complete restructuring of the company for the new axle weight scenario. This intricate, long-term project demands heightened process control at all organizational levels, especially during the prolonged period of hybrid operation, where legacy practices coexist with new procedures. The procedural risks in maintenance of infrastructure and rolling stock, coupled with the challenges in operational dynamics during the hybrid phase, underscore the need for meticulous planning, continuous adaptation, and strategic mitigation efforts. By prioritizing clear communication, ongoing training, and flexible operational procedures, railway operators can successfully navigate this intricate transition, ensuring the efficiency, safety, and long-term success of the project.

3.2 Operational impacts

In the post-implementation phase, we shift our focus to the risks associated with railway operations. Having previously addressed risks during the project, we now delve into considerations after all modifications have been completed. Examining aspects such as load distribution, driving standards, and operational elements is crucial in this context. Let's explore these post-implementation risks and their respective mitigating actions:

3.2.1 Load distribution in loading

- Risk: Challenges may persist in optimizing load distribution among railcars, affecting stability and operational efficiency.
- Mitigation: Implement real-time monitoring systems to promptly identify load imbalances. Conduct regular training sessions for loading personnel to enhance skills in optimizing load distribution.

3.2.2 Driving and operational standards

- Risk: Train conductors adapting to new driving standards may face ongoing challenges, impacting operational efficiency.
- Mitigation: Provide continuous training to the train conductors to ensure a seamless transition to new driving standards. Establish a feedback loop for train conductors to share insights on operational challenges, fostering a collaborative improvement environment.

3.2.3 General operational aspects

- Risk: Continuous maintenance is critical, with potential operational disruptions post-implementation.
- Mitigation: Implement predictive maintenance technologies to identify potential issues before they escalate. Develop a comprehensive fleet management strategy to optimize resource allocation and enhance operational efficiency.
- Risk: Managing a diverse fleet poses ongoing challenges in post-implementation operations.
- Mitigation: Develop a robust fleet management system incorporating real-time tracking and monitoring. Conduct regular reviews to ensure optimal resource utilization and identify opportunities for fleet optimization.
- Risk: Effective communication and coordination may face ongoing challenges.
- Mitigation: Implement advanced communication systems for real-time information exchange. Establish cross-functional coordination protocols and conduct periodic drills to ensure seamless collaboration among operational teams.

3.2.4 Regulatory and safety risks

- Risk: Changes in operational practices may lead to ongoing regulatory implications.
- Mitigation: Establish a dedicated regulatory compliance team to monitor changes and ensure continuous adherence. Conduct regular compliance audits to identify and address potential issues proactively.
- Risk: Continuous evaluation of safety protocols is essential for post-implementation operations.

- Mitigation: Implement a robust safety management system with regular safety audits. Invest in training programs to keep staff updated on safety protocols and emergency response procedures.

Addressing these post-implementation risks necessitates a proactive approach and ongoing commitment to operational excellence. By implementing these mitigating actions, railway operators can navigate the unique challenges of the post-implementation phase, ensuring the sustained efficiency, safety, and success of their operations.

3.3 Maintenance impacts

In the post-implementation phase of the axle weight standard migration project, robust maintenance strategies become pivotal for ensuring the longevity, safety, and efficiency of both railway infrastructure and rolling stock. This chapter explores the specific considerations and actions required for effective maintenance practices in the aftermath of the project implementation.

3.3.1 Infrastructure maintenance

Risk 1 - Ongoing Asset Management Challenges:
Even after the implementation, challenges in managing assets persist, requiring ongoing attention to prevent disruptions.

Mitigation:
Implement a comprehensive Computerized Maintenance Management System (CMMS) to facilitate real-time asset tracking and maintenance scheduling. Conduct regular asset condition assessments and invest in predictive maintenance technologies to foresee potential issues.

Risk 2 - Variability in Sectional Maintenance Requirements:
Different railway sections may have unique maintenance requirements, demanding adaptable strategies.

Mitigation:
Adopt a dynamic maintenance approach, tailoring strategies to the specific characteristics of each railway section. Implement continuous monitoring to identify evolving maintenance needs promptly.

Risk 3 - Post-Implementation Overheads:
Overheads related to the post-implementation phase may emerge, impacting the financial aspects of maintenance operations.

Mitigation:
Develop a comprehensive budgeting strategy that considers post-implementation overheads. Prioritize investments in preventive maintenance to reduce reactive maintenance costs over time.

3.3.2 Rolling stock maintenance

Risk 1 - Divergent Maintenance Systems:
Railcars and locomotives with different capacities may necessitate distinct maintenance systems.

Mitigation:

Implement a unified maintenance platform that accommodates the diverse rolling stock. Standardize maintenance procedures where possible and provide specialized training for maintaining various types of rolling stock.

Risk 2 - Ongoing Training Requirements:
Continuous training is essential for the maintenance team, ensuring proficiency with new assets and hybrid operation.

Mitigation:
Establish an ongoing training program that incorporates the latest maintenance practices and technologies. Facilitate cross-training to enhance the versatility of maintenance personnel.

Risk 3 - Inventory Management Complexities:
Diverse rolling stock introduces complexities in managing parts and tools inventory.

Mitigation:
Implement an advanced inventory management system that considers the varied requirements of different rolling stock types. Conduct regular audits to eliminate redundant or obsolete parts.

This chapter emphasizes the critical role of post-implementation maintenance in sustaining the operational efficiency and safety of heavy haul railways. By implementing adaptive strategies, embracing technological advancements, and prioritizing ongoing training, railway operators can navigate the complexities of maintaining both infrastructure and rolling stock effectively.

3.4 Environmental and regulatory risks

As we transition into the post-implementation phase of the axle weight standard migration project, Chapter 6 delves into the risks associated with the environment, regulatory compliance, and community relations. Acknowledging the importance of sustaining positive relationships with the environment, regulatory bodies, and neighboring communities is crucial for the continued success of heavy haul railway operations.

3.4.1 Environmental risks

Risk 1- Ecological Impact of Operations

Even after project implementation, the ecological impact of railway operations remains a concern, necessitating ongoing environmental risk management.

Mitigation:

Implement environmentally friendly technologies such as noise barriers and pollution control systems. Conduct regular environmental impact assessments to identify and address any potential ecological issues promptly.

Risk 2 - Waste Management Challenges:

The generation of waste during post-implementation operations can pose environmental risks if not managed effectively.

Mitigation:

Develop a robust waste management strategy that emphasizes recycling and responsible disposal. Engage in community awareness programs to promote responsible waste practices.

3.4.2 Regulatory risks

Risk 1- Evolving Regulatory Standards:

Changes in regulatory standards post-implementation can pose compliance challenges for railway operations.

Mitigation:

Establish a dedicated regulatory compliance team to monitor and adapt to changes in standards. Conduct regular audits to ensure ongoing compliance with evolving regulations.

Risk 2 - Legal Consequences:

Non-compliance with regulatory standards can lead to legal consequences, impacting the operational and financial aspects of the railway.

Mitigation:

Maintain transparent communication with regulatory bodies. Invest in legal counsel to stay abreast of changing regulations and proactively address compliance issues.

3.4.3 Community relations risks

Risk 1- Noise and Vibration Concerns:

Post-implementation, concerns from neighboring communities regarding noise and vibrations may persist.

Mitigation:

Implement noise reduction technologies and conduct regular community engagement sessions to address concerns. Develop community-friendly schedules for heavy operations.

Risk 2 - Land Use Disputes:

Conflicts related to land use, especially in proximity to railway operations, can arise and impact community relations.

Mitigation:

Establish transparent communication channels with local communities. Work collaboratively to address land use concerns and consider community input in operational planning.

This chapter underscores the ongoing commitment required to manage environmental, regulatory, and community-related risks in the post-implementation phase. By adopting sustainable practices, staying attuned to evolving regulations, and fostering positive community relationships, heavy haul railway operators can enhance their long-term viability and contribute positively to the areas they serve.

3.5 Economic and financial risks

As we embark on the exploration of economic and financial intricacies within the heavy haul railway project, it's imperative to recognize that these factors encapsulate the final layer of risks in our comprehensive analysis. This segment scrutinizes the economic landscape, financial stability, and potential challenges arising from dependencies on global markets, project cost deviations, fluctuating interest rates, production uncertainties, and the availability of crucial suppliers. By addressing these economic and financial considerations, we strive to fortify the resilience of the heavy haul railway project against diverse challenges, ensuring its sustainable success from construction through post-implementation operations.

3.5.1 Demand-related economic risks

Risk 1 - Economic Dependency on China

The project's economic success is tied to China's demand for minerals, exposing it to fluctuations in the Chinese economy.

Mitigation:

Diversify market dependencies by exploring alternative international markets for mineral exports. Maintain a dynamic business strategy adaptable to changes in global economic conditions.

3.5.2 Project cost deviation risks

Risk 1 - Large Deviations in Project Costs:

The construction phase may encounter significant cost overruns, impacting the overall financial viability of the project.

Mitigation:

Implement stringent project management protocols, conduct thorough cost estimations, and establish contingency funds. Engage in regular project audits to identify and address potential cost deviations promptly.

3.5.3 Financial market risks

Risk 1 - Interest Rate Fluctuations

Oscillations in interest rates can impact the cost of capital, influencing project financing and operational expenses.

Mitigation:

Adopt hedging strategies to mitigate risks associated with interest rate fluctuations. Maintain proactive communication with financial institutions to secure favorable financing terms.

3.5.4 Production-related risks

Risk 1 - Catastrophes in Ore Production:

Unforeseen events such as natural disasters or mining incidents can disrupt ore production, affecting revenue streams.

Mitigation:

Invest in robust risk assessment for mining operations. Implement contingency plans for production interruptions, including alternative sourcing strategies or emergency response protocols.

3.5.5 Supplier scarcity risks

Risk 1 - Scarcity of Suppliers for Project Execution:

Limited availability of suppliers for construction materials and spare parts poses a risk to project timelines.

Mitigation:

Diversify the supplier base to reduce dependency on a single source. Establish long-term partnerships with reliable suppliers and maintain strategic stockpiles of critical spare parts.

This chapter underscores the need for a comprehensive risk management approach to navigate the economic and financial intricacies of the heavy haul railway project. By implementing strategic mitigations, continuously monitoring economic conditions, and fostering resilient supplier relationships, the project can enhance its adaptability and financial sustainability throughout its lifespan.

4 COST BENEFIT ANALYSIS

4.1 Operations Context

MRS operations can be divided in two big groups, Heavy Haul, hereinafter HH, operations (mainly iron ore transport) that represents roughly 85% of the freight hauled by the company and general cargo operations (transport of agricultural commodities, steel products, containers, construction products, among others), and although the increase of axle load can be applied and bring positive results in both cases, next it will be focused on the HH operations due to its representation.

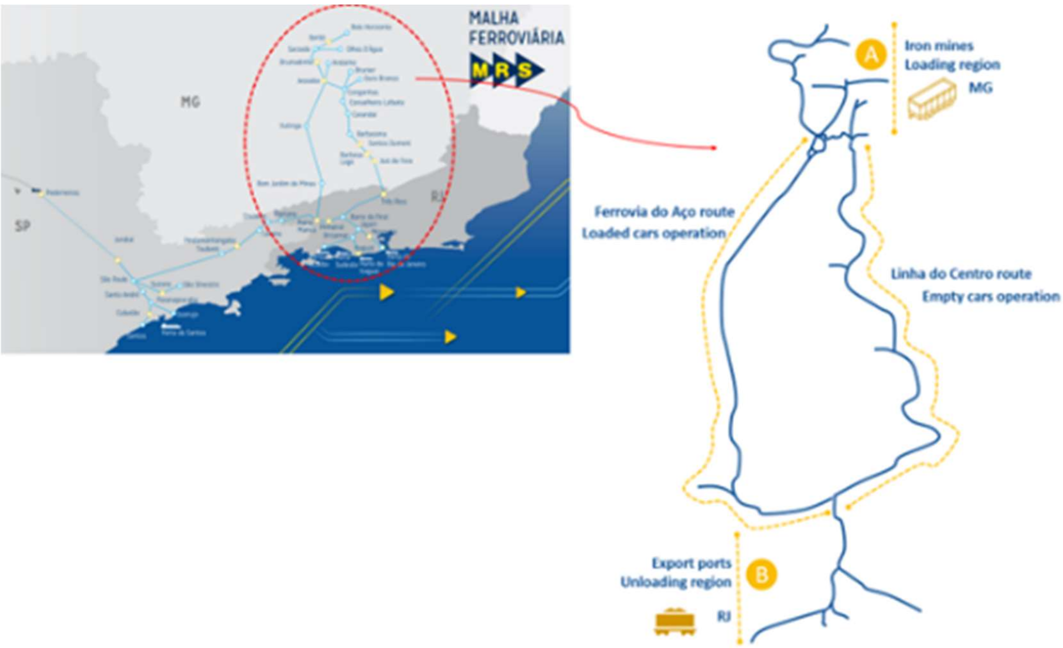


Figura 42: Diagram of MRS tracks and operations (Source: MRS website, 2024)

The HH operation as aforementioned is mainly iron ore transport, where the ore is loaded on terminals near the mines in Minas Gerais (MG) – region A on Figure 43 – and unloaded on export ports at the state of Rio de Janeiro (RJ) – region B on Figure 43.

It must be noted that two of the most important tracks segments, Ferrovia do Aço and Linha do Centro, are single tracks. Therefore, the majority of HH operations occur in single tracks with unidirectional circulation, in which trains with loaded cars use the Ferrovia do Aço route and trains with empty cars use the Linha do Centro route, creating an operation similar to a circle or carousel. The unidirectional circulation on those routes were implemented to increase track capacity by avoiding trains crossings and reducing the headway between trains.

Both loading region and unloading region have two-way circulation, where the loading region is mainly single tracks with loops rail crossings and the unloading region is mainly double tracks.

4.1.1 Train formation

One of the most common restraints in railroad operations is the block length, that often is used to determine the maximum train length, at MRS it was defined to optimize the length of unloading terminals. At MRS HH operations there is a standardized type of formation, in which the quantity of wagons, regardless of the type and capacity of them, and quantity and type of locomotives are predefined. In this scenario, the wagons used on HH operations are blocked in groups of 136 cars and the locomotives in groups of 2. To make the operation more efficient, the groups usually contain wagons with similar characteristics to each other.

Therefore, the regular HH operation at MRS occur with trains of 2 locomotives in front and 136 wagons, both on trains with loaded and unloaded. The standardization occurred to make the operations more flexible and agile, ensuring that almost every group of cars could be used in any loading or unloading terminal, and therefore enhancing operations productivity.

Recently, solutions have been developed to enable the use of 2 groups of 136 wagons on the same train to increase track capacity, but it has not yet been implemented in its entirety and is not very representative in current operations.

4.1.2 Loading process

Heavy Axle Load (HAL) operations and the increase of axle load are directly related to the loading process and to its control and variability, in which the closer to the limit of railway assets the better the loading must be, in order to obtain productivity gains without exceeding these limits, ensuring safety and adequate performance of the assets.

At MRS heavy haul operations there are more than 10 different loading terminals, that can be divided into two categories: loading by silo and loading by loader or truck. Of all the loading terminals, only 3 have silo loadings but these three represent 56% of the total export iron ore hauled by MRS in the last 10 years (from 2014 to 2023). The remaining terminals load the wagons using trucks or loaders.

Figure 43: Loader loading terminal

Figure 44: Silo loading terminal

Due to the level of control over the loading volume and positioning of the load, in addition to the need for constant movement to the ore piles, the use of loaders and trucks generates greater variability in the process and has worse efficiency in the loading process. Process enhancements and the use of technology, such as video analytics, can marginally improve loading variability and efficiency, but to achieve optimal results, investments in loading silos will likely be necessary.

The conformity of the loading process is essential to ensure that the wagons will be loaded to its maximum capacity and that there will not be any overweight or load eccentricity, since both problems can make the increase in axle load unfeasible.

- Car overload: can bring two types of problems, the first is the excess of stress on the assets, wagons, or infrastructure, that could lead to an increase in failures rates, maintenance cost or even a higher impact on track availability. This issue could be controlled with rail scales at the loading terminals, but it would generate loss of material (iron ore) and the second type of problem: operational impact and loss of time. If it is necessary to carry out load adjustment when overweight is found, the loading terminal will lose productivity and it may impact other trains depending on the position of the scale, local and procedure to carry out load.

- Load eccentricity: it can be a problem especially when the load is concentrated on one of the car axles, in which case even if the total car weight does not exceed the limit, one axle might exceed the limit, creating high impact on the wagon and in infrastructure assets. To correct this problem, a device for regulating the load could be used. Another way to avoid this situation is the use of a specific loading silo that controls and ensures precise loading.

At MRS, the car loading process showed a standard deviation of up to 6.9 tonnes in 2023. Indicating the need to address with customers and terminal operators the necessary treatment to improve the process to enable the increase in axle load in a controlled manner.

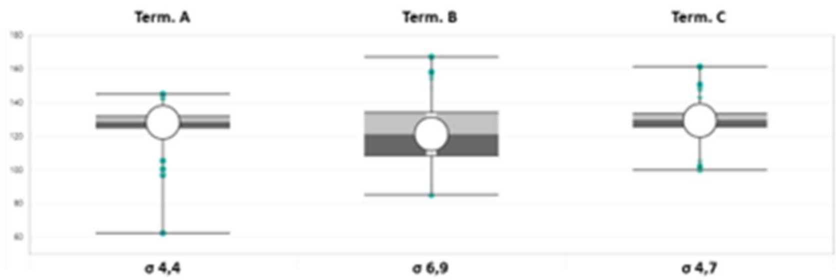


Figure 45: Car load boxplot on 3 different terminals from January to October of 2023

4.2 Operations impact with axle load increase

The operational capacity, or total transport volume of a railway in a given period of time, can be calculated considering the number of trains that can circulate on that railway, the maximum length of each train, the maximum weight of each train – and therefore of each wagon–, the transit time, the operational time for shunting, loading and unloading and the amount of resources (assets and crews) available to carry out the operation.

This way, the increase of axle load is a powerful way to increase operational capacity, in which it is possible to maintain the train length, avoiding high investment costs to change sidings, layout of yards or terminals.

In general, when increasing the axle load the railway is capable of hauling the same volume with less trips, which results in less total trains, which takes less wagons and locomotives ownership and lower need of crew. It must be added, however, that the number of locomotives might change if the train formation is already optimized, i.e., if there is no traction capacity excess, when increasing the axle load it must be added traction capacity to keep the same train length. This can be done by enhancing technology, adding locomotives, or changing the train formation, e.g., by using distributed power.

At MRS operations, for example, the standard locomotive formation allows trains up to approximately 18,000 gross tonnes, disregarding the weight of the locomotives. If MRS increases its axle load from 32.5 tonnes to 36 tonnes per axle, without adding traction power, it would require reducing the train size from 136 wagons to 125 wagons. This reduction still brings benefits to operations, such as reduction in wagon acquisition or ownership and savings in wagon maintenance, but it does not allow capturing all the gain such as crew reduction, fuel consumption reduction or increase in transport capacity. Therefore, to achieve the full potential in productivity and transport capacity it is necessary to address an increase in traction power as well.

Among the benefits of increasing axle load, the following stand out:

- Reduction on cars ownership and future acquisition
- Reduction on wagons maintenance costs
- Increase of network capacity
- Reduction of number of trains on track
- Reduction of impact on unexpected failures
- Savings on fuel consumption
- Reduction of operational and maintenance crews
- Reduction of unloading time

The increase of axle load on railroads might be divided into categories: marginal increment and change of level, in which marginal increment consists in small increments within the limits already established that are not used due to operational inefficiency and change of level consists in higher increases that requires a more detailed assessment, in addition to fleet adaptation or acquisition and possibly a change in train formation.

Marginal increments on axle load might provide significant savings for ongoing operations with process improvements. For example, at MRS current HH operations, by increasing 1% of car load it is possible to save a group of 136 available wagons, without exceeding the limits already established.

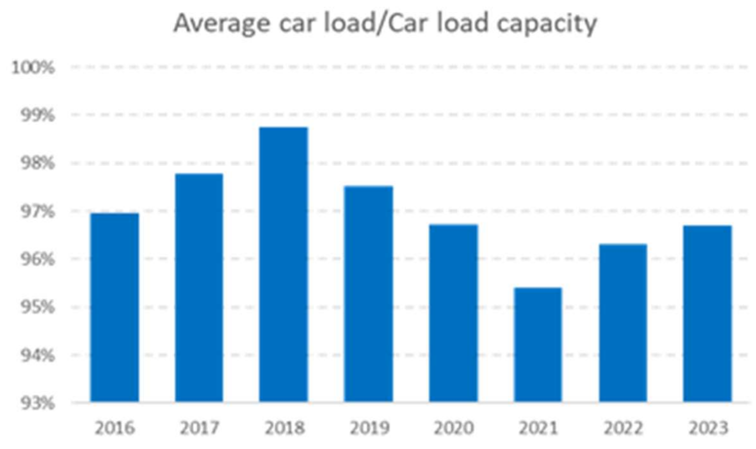


Figure 46: MRS average car load over current car load capacity

Despite being several factors that can influence the car load, such as type of product, product density, available fleet, standardization of car groups, fleet allocation, among others, it is possible to assert that there is room for improvement and enhancement in productivity.

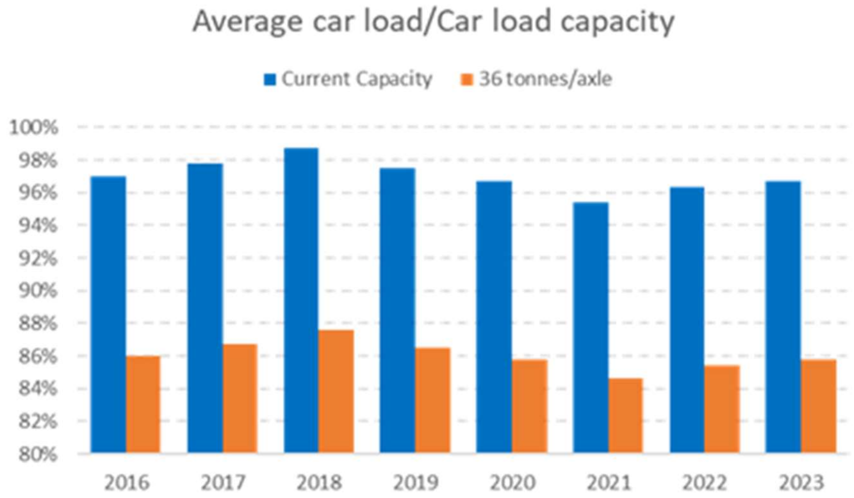


Figure 47: MRS average car load over potential capacity of 36 t/axle

As an example, if MRS would adjust its whole fleet to a capacity of 36 t/axle, its adherence would be lower 90%, displaying the change of level that might be done. It must be noted that in order to do so, several changes are needed, from fleet acquisition, maintenance adjustment to loading improvement.

4.3 Financial impact

As Martland (2013) stated, railroads have, for many years, been increasing siding length, improving locomotive technology, and using distributed power to enable the use of longer, heavier trains. This practice has been recurring due to the high return provided.

At North America, heavy axle load operations especially coal transport, show very positive results. According to Martland (2013), with the increase of axle load to cars of 286k pounds from cars of 263k pounds generated cumulative benefits 1994 to 2010 of approximately $6 billion USD, and annual benefits were $600 to $700 million USD in 2010. The main benefits come from operating expenses and reduced car acquisition, compensating for the cost increase in track maintenance.

Hargrove et. al. (1996) presented data and model to compare the effect of increasing axle load from 29.6 t/axle to 32.2 t/axle, in which there were costs reductions on operating expenses regarding crew (up to 10%), locomotive ownership (up to 10%), locomotive maintenance (up to 10%), car ownership (up to 8%), car maintenance (up to 5%), fuel (up to 8%) and track maintenance costs increase (up to 11%).

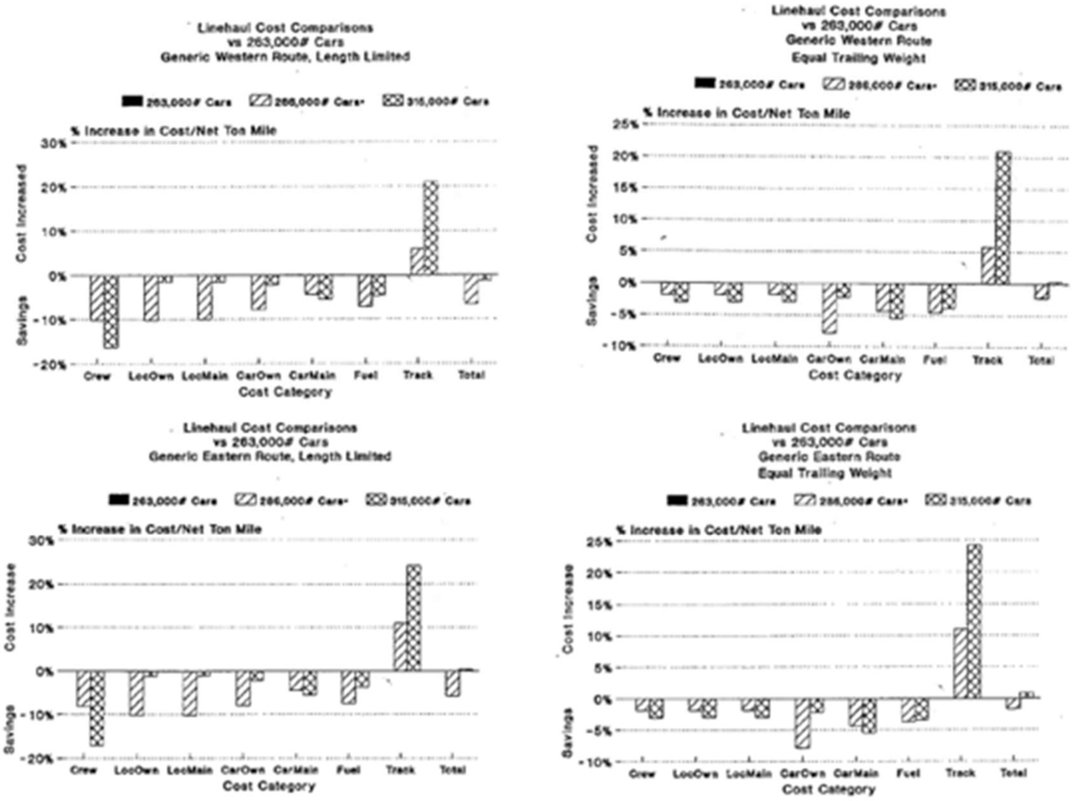


Figure 48: Cost comparison in axle load increase
Source: Hargrove et. al. (1996) adapted.

Although there is evidence of feasibility, providing up to 7% total cost reduction when comparing 286k pounds cars with 263k pounds cars, the study also shows that a higher increase in axle load, to 315k pounds cars might not provide cost reduction, especially due to the increased infrastructure costs.

At MRS HH operations a similar scenario might occur, where the costs to increase the axle load from 32.5 tonnes beyond 36 tonnes, would imply a major renewal and replacement of infrastructure assets, especially bridges, making it unfeasible.

Considering the current axle load limit (32.5 t/axle) and the current fleet, if the operation is completely optimized, in which every wagon is loaded to its maximum capacity it would be possible to save more than $500 million BRL or it could generate an increase of 4.7% iron ore transport capacity.

In a scenario where MRS is able to operate with each wagon in its full capacity, in which case 9% of cars would be loaded with 36t/axle, the savings would be up to $1,000 million BRL or it could generate an increase of 7% in iron ore transport capacity.

5 PROJECT PLAN / IMPLEMENTATION PLAN

Hargrove (1991) stated that freight railroad technology shows a pattern of increasing vehicle size with increasing axle loads as developments in materials and engineering knowledge have made their use technically feasible and economically desirable.

At MRS increasing axle load has been a practice and object of study over the time.

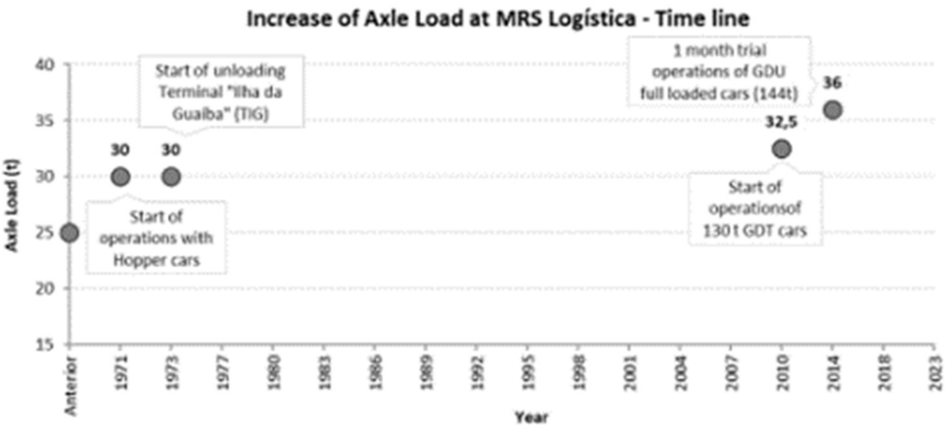


Figure 26: MRS axle load time line

Despite the viability and benefits provided, the axle load increase is not considered as *sine qua non* condition to ensure long-term operation, due to other capacity and expansion projects already foreseen in the strategic planning and concession renewal plan. However, this project meets the others to increase capacity, making it possible to postpone large expansion investments and reduce the acquisition of new assets, especially during the Ferrovia do Aço track renewal scheduled to start late this decade.

The implementation of axle load increase must follow the two categories aforementioned: marginal increment and change of level.

5.1 Marginal increment

The main objective in this category is to optimize the axle load considering the asset conditions already established. In this scenario most of the action plan consists of short-term actions, divided in two groups of actions: “Increase of Capacity Adherence and Variability Reduction” and “Increase uniformity of group of wagons”.

The “Increase of Capacity Adherence and Variability Reduction” divides itself into 3 main areas of study, being:

- Technologies to enhance loading process: Use of video analytics and sensors to monitor the wagon during loading process, use of video analytics to monitor the loaders on terminals without silo, development of equipment to assist with load conformity.
- Wagons allocation optimization: study of the resource allocation process to better take advantage of the characteristics of each terminal and each load, development of resource allocation optimization tools depending on the scenario.
- Development plan for loading crew: set of actions, trainings and assist to loading terminals crew to enhance capabilities and provide information to provide better loading process.

As for the “Increase uniformity of group of wagons” it is divided into 2 main areas of study:

- Adjustment of group of wagons: monitoring and adjustments to ensure the adequate set of cars according to their axle load capacity and operational characteristics.

Figure 27: Example of car types monitoring

- Assessment of Wagons Maintenance Strategy: set of actions to increase of availability of higher capacity cars and spare asset strategy to keep the uniformity of each group of wagons.

5.2 Change of level

The main objective in this category is to enhance the system capacity to enable increased axle load considering future investments and projects. In this scenario most of the action plan consists of long-term actions, divided in three groups of actions: “Loading process”, “Fleet planning” and “Infrastructure planning”.

- Loading process: studies for implementation of volumetric loading silos and replacement of old silos, assessment of terminals layout and infrastructure to enhance loading process, implementation of equipment to ensure load conformity.
- Fleet planning: development of new project and prototype of stainless steel GDU wagon, adjustment to the long-term wagon acquisition curve considering increased axle load, review of the asset replacement strategy considering the acquisition of higher capacity wagons and cutting of lower capacity wagons to supply parts, assessment of new train formations and their impact on increasing axle load, studies for enhancing traction power to enable the operation of higher axle load with long trains.
- Infrastructure planning: studies of bridges structure condition and evaluation of structural retrofitting investments, overlapping axle load increase schedule with track renewal schedule, assessment of necessary adjustments to drainage structures.

6 FINAL CONSIDERATIONS

The increase of axle certainly brings operational benefits and is constantly being studied by MRS and show great potential for reducing the need of future fleet acquisition along with other operational cost reductions, such as fuel and crew costs. However, the increase of axle load intensifies the degradation of assets due to increased efforts, generating higher track, infrastructural and wagons per unit maintenance costs.

Over time, MRS's infrastructure assets have already been recapacitated for the axle loads currently practiced and therefore are close to their installed capacity. For that reason, for new increases in axle load, a thorough and cautious study is necessary so that its implementation does not generate a greater risk of asset failures and operational impacts, making the project unfeasible. New recapacitations can result in monitoring, reinforcement and even replacement of assets, leading to large and long-term investment, both due to executive difficulty and the total expend.

As aforementioned along with infrastructure maintenance costs, track maintenance costs are the most impacted with the increase of axle load, due to higher stress on its components. With the conclusion of track renewal process at MRS that begun in 2022, the cost impact might be reduced.

As for the rolling stock, the axle load increase impacts in different ways. For rail cars, there is a higher degradation of its components, and it will probably require a review on fleet acquisition strategies. For locomotives, the impact may vary according to the train formation used, in which in order to create asset reduction studies must be conducted to generate higher traction capacity, such as distributed traction or new technologies.

At MRS current operations there are still opportunities to enhance productivity with a better utilization of the rail cars capacity, increasing the axle load executed but respecting conditions already established. In this scenario, there is potential to save more than $500 million BRL. In addition, MRS constantly work on projects to enhance operations productivity and generate operational savings, such as better usage of car fleet, loading and unloading time reduction, track renewal, maintenance windows and rain contingency plan impact reduction, among others.

The increase of axle load project, as other productivity projects, must be continuously studied to identify opportunities and generate better overall operation, specially in such cases where anticipated planning is essential due to operational complexity and high investments.

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