CNT - Confederação Nacional dos Transportes

DB - Deutsche Bahn

ITL - Instituto de Transporte e Logística

International Certification in Management of Rail and Metro Rail Systems

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Rail profiling for improved operations

Final Project

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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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ABSTRACT

The permanent way plays a very important role in the proper function of a rail system, this issue is even more critical in passenger services given that confort, speed, and safety are key elements in client satisfaction and are very dependent on the quality of the permanent way. Maintaining proper quality requires assessment of the track and is expensive and time consuming, companies are constantly seeking more agile and cost-effective ways to assess the condition of their track so they can act accordingly to any issues that may cause problems with day to day operations. Metro DF is committed to its clients satisfaction and safety, doing routine checks on its track and conducting corrective and preventive maintenance. However, we are now committed to put a greater emphasis on preventive and predictive maintenance. For this change in our strategy, we will develop a new concept, using our own rolling stock as a tool to provide an daily assessment of the condition of the track, allowing us to improve the usage of our personnel and resources and act on track issues as soon as they occur and monitor their progress while saving costs. Using the well-established vibration analysis technique, we expect to develop a well rounded analytical model to provide a good tool for permanent way assessment.

Keywords: Permanent way, Metro DF, Track assessment, Preventive maintenance, Vibration analysis.

RESUMO

A via permanente desempenha um papel crucial no funcionamento adequado de um sistema ferroviário, sendo essa questão ainda mais crítica em serviços de passageiros, visto que o conforto, a velocidade e a segurança são elementos-chave na satisfação do cliente e são muito dependentes da qualidade da via permanente. Manter uma qualidade adequada requer a avaliação da via, o que é caro e consome tempo. As empresas estão constantemente buscando maneiras mais ágeis e econômicas de avaliar a condição de suas vias para agir de acordo com quaisquer problemas que possam afetar as operações diárias. O Metrô-DF está comprometido com a satisfação e segurança de seus clientes, realizando verificações de rotina em sua via e conduzindo manutenção corretiva e preventiva. No entanto, agora estamos empenhados em dar maior ênfase à manutenção preventiva e preditiva. Para essa mudança em nossa estratégia, desenvolveremos um novo conceito, utilizando nosso próprio material rodante como uma ferramenta para fornecer uma avaliação diária da condição da via, permitindo-nos melhorar o uso de nosso pessoal e recursos, agir imediatamente em problemas na via, monitorar seu progresso e economizar custos. Utilizando a técnica estabelecida de análise de vibração, esperamos desenvolver um modelo analítico abrangente para fornecer uma boa ferramenta para a avaliação da via permanente.

Palavras-chave: Via permanente, Metrô-DF, Avaliação da via, Manutenção preventiva, Análise de vibração.

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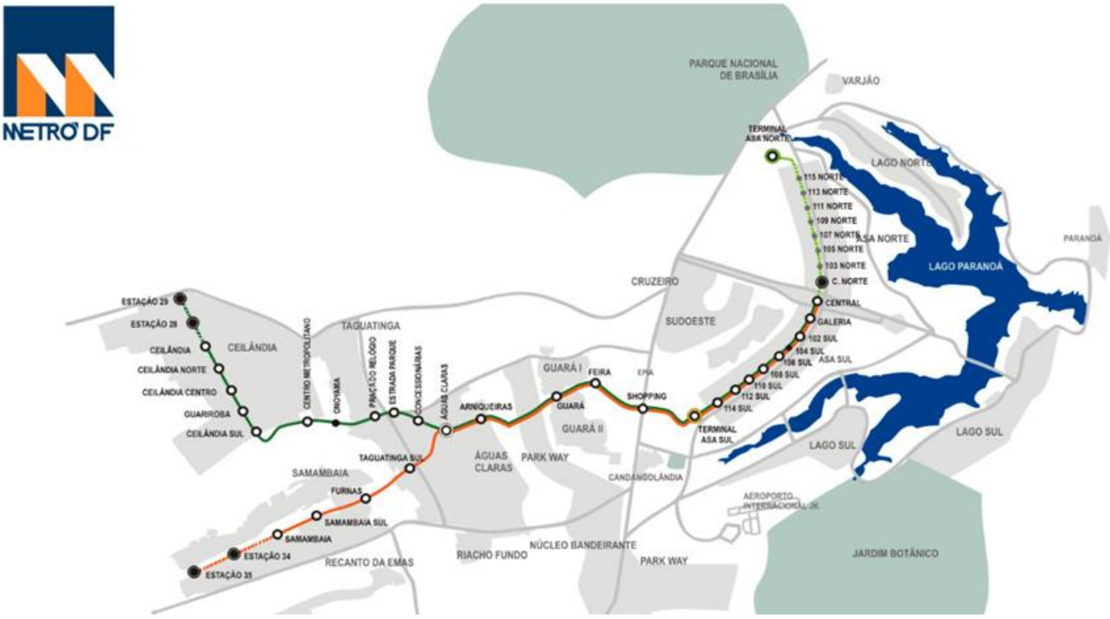
1. INTRODUCTION

METRO-DF was founded in 1991, with the creation of an Executive Working Group and the preparation of the first studies on the environmental impact of the project. Today it is established as a Public Company governed by Private Law, in the form of a joint stock company. Its competencies include:

- Plan, design, build, operate and maintain the Public rail transport system in the Federal District, as well as commercially exploit brands, patents, technology and specialized technical services, linked to or arising from its productive activity.
- Organize, monitor, manage and explore the areas bordering the roads and subway stations, absorbing resources from commercial and real estate developed there.

The company currently operates a network consisting of 42 km and 29 stations on two lines, line 1 in green color and line 2 in orange, with 32 trains available, 20 belonging to the Series 2000 and 12 to the Series 1000, manufactured in the mid1990s and in the years 2010/2011, respectively, by ALSTOM. Series 1000 trains require more detailed technical monitoring and a greater number of interventions, and Series 2000 trains require interventions with greater efficiency to avoid a decrease in the life cycle. System limitations allow for only 24 to be run on the tracks. Trains from the two lines share tracks, the system transported a total of 39,1 million passengers in the year 2022, with a daily ridership of approximately 160.000.

Image 1 - System map with planned expansions



Source: Metrô-DF.

Total revenue was R$ 186,4 million, 98% coming from fares, the R$ 181.8 million in fares represents a 57,9 % increase from 2021. For the year 2023 the investment perspective has increased as the budget ceiling was raised to R$ 197.4 million, a good prospect for upgrading our services. The new more agile ticketing systems, by credit/debit card used directly at the ticket gate present a good outlook for more passenger inflow and revenue.

Geometrical Track inspection is done using a control car, with data acquisition for correction of defects, ultrasound equipment is used to verify the rails for internal defects e rupture of the rails, we also carry out visual inspections on foot and receive operator reports.

METRÔ-DF seeks continuous improvement, innovation and sustainability. Among the actions concerning the sustainability and innovation, the following actions have been taken:

- Solar Generation Sustainability and Cost Reduction in Transport Subway
- Online Signaling System and METRO App.
- Modernization of the ticketing technology park: modernization of ticketing equipment and systems to guarantee safety of fare collection, full integration with other modes and migration to the MetroCard in addition to the implementation of QR Code,

The prospect of having a daily on the fly monitoring of the track condition would give our maintenance crews a better view of the track defects, where they occur, and how they progress. This approach would provide an important historic of the permanent way with substantial data available for the maintenance crews to work on the most critical problems before they occur, would also save significant amount of man hours of work as the constant monitoring would pinpoint where the crew should focus their attention.

Saving in costs and time would allow for a more overall efficient maintenance, as fixing issues on the tracks before they increase in gravity, will improve not only the lifecycle of the permanent way but as well as the rolling stock lifecycle and its availability, and provide more reliable, safer and more comfortable ride for our customers and therefore an increased satisfaction. Overall, our maintenance strategy will move from the corrective/preventive to a more predictive approach.

2. RESEARCH RESULTS

Currently, there are several inspection methods to assess the condition of the permanent way, depending on the level of sophistication and technology, as well as the data you wish to obtain, regarding the situation of the rails, sleepers, ballast, among others.

Visual inspection appears to be a simple and basic technique, which consists of traveling the entire railway line on foot, with a specialized vehicle or using the train itself, in which it is possible to visually identify the general condition of the tracks and possible problems, such as broken rails or surface problems, damaged sleepers, non-conforming ballast, etc.

There is also ultrasound inspection, through the use of high-frequency sound waves, which proves to be quite efficient in detecting internal irregularities in the tracks that are not visible to the naked eye, thus preventing them from evolving into a more critical condition. In a similar way, acoustic emission inspection can be mentioned, which can detect potential cracks in the rails, through the emission of sound waves produced by the materials under stress.

Thermography inspection can also be used to check temperature variations that may indicate anomalies, due to heating caused by excessive friction or braking problems, through the use of thermographic cameras.

A more robust inspection can be used using special vehicles equipped with monitoring technology and sensors to detect anomalies in the railway infrastructure. Defects can be detected in the rails, such as cracks, fissures, wear and surface irregularities that are not easily visible to the naked eye. Regarding sleepers, their structural integrity can be assessed, detecting damage, rot, breakages or structural problems. The ballast can also be analyzed, checking for compaction, possible contamination by foreign materials or erosion. The track geometry can also be carried out with the aid of a control vehicle, in order to check the alignment of the tracks, superelevation, inclination of the curves and other geometric characteristics.

It is noteworthy that each inspection and analysis method has its advantages and limitations, and in order to guarantee the safety and efficiency of the permanent way, they can be used together.

From the Metrô-DF standpoint, foot patrol analysis, ultrasound car and control car are currently being developed jointly. Due to the fact that the permanent way in question is only 42 km long, it is still possible that joint inspections can cover the most critical track problems, considering that 2 inspections are carried out per year in the control car and 2 inspections per year with the ultrasound assistance, being complemented with foot patrols at other intervals of the year.

However, carrying out the foot patrol in this area and given the number of employees hired in the sector, becomes a time-consuming activity with a short window of operation at night. This is because it is only possible to carry out this task during non-business hours, averaging 4 hours per night. Furthermore, because it is at night and with the use of flashlights, some problems on the permanent way that may exist may go unnoticed or possibly be detected only after a higher level of severity of the nonconformity. Considering the time between one inspection and another, problems can evolve into a more critical and more costly situation.

Furthermore, there is no historical archive containing all existing nonconformities and after the intervention of the permanent way maintenance team at Metrô-DF, despite the fact they would be valuable in analyzing trends, identifying patterns of recurring problems, developing maintenance strategies preventive and continuous improvement of maintenance schedules, in order to improve the safety and efficiency of the permanent way.

In this context, the idea of developing a prototype arose, which would be capable of providing data from the permanent way in real time, enabling predictive and corrective maintenance actions to be better planned. In this way, non-conformities would be prevented from developing into a possible unsafe situation. Furthermore, it would be excellent to create a database to monitor defects on the permanent way, enabling the general context of nonconformities to be assessed and more globally effective decisions to be made.

Using the Arduino in conjunction with the accelerometer and GPS, it would be possible to obtain graphical variations in real time through vibrations perceived in the device on board the train. It is assumed that such variations would have certain signatures, assigned to each specific permanent way problem. This way, it would be graphically possible to observe where there would be unconformities on the road.

Thus, such a vibration monitoring device can be used to identify abnormal variations and potential problems before they become more serious or cause a decrease in system availability. By analyzing these variations, irregularities in the tracks can be detected, such as misalignments, deformations, cracks and fissures. Broken, cracked or damaged sleepers may be observed, which affect the stability of the permanent track. Inadequate ballast compaction, presence of foreign objects or ballast erosion, defective or poorly fixed rail joints and other geometric problems, such as excessive curvature, inadequate elevation in curves, among others.

As a practical example, in this analysis, we can mention aluminothermic welding, which deals with a specific method of welding rails, carried out “in situ”, aiming to fuse the ends of the rails in a continuous and resistant way. With this method, the aim is to create a smoother and more uniform permanent route, providing a comfortable and safe journey. However, over time, small canoes shaped defects may appear, causing premature wear in the nearby rail region, in addition to discomfort for users of the system. Using the device, it would be possible to observe the evolution of the welds and the subsequent need to replace them, depending on the degree of degradation.

3. HYPOTHESES

The use of an accelerometer to compose the proposed prototype takes into account that it is a sensory device capable of measuring the acceleration in a given axis. In the expected context, which would be the perception of vibrations in the permanent way, the accelerometer can capture important information, such as the amplitude of vibrations, frequency and direction, shocks or impacts and abnormal vibration patterns.

Regarding the amplitude of vibrations, the accelerometer can measure the magnitude or intensity of the vibratory movement along a specific axis, quantifying how strong the vibration is. With the frequency of vibrations, specific patterns or types of vibrations can be obtained. Depending on the configuration of the accelerometer, it can detect vibrations in the horizontal, vertical or multiple axes. If there are sudden variations in acceleration, shocks or sudden impacts may be detected, indicating abnormal situations or structural or functional problems.

As the aim of the prototype is to detect vibrations in the train along the track during trips carried out during daily operation, possible locations for installing the device were analyzed, so that it could detect the signals more clearly and effectively. Thus, in the research carried out, it was observed that they could be installed in different locations on the train depending on the data that was desired to be obtained, which include: bogie, wheels and axles, couplings, suspension equipment, wagons, braking.

However, due to the difficulties in installing the prototype depending on the chosen location - which include excessive heating, bad weather, such as rain -, the safest location was chosen, from the point of view of fixing and protection against the weather, in order make it possible to obtain initial data to validate the potential for capturing vibrations corresponding to track defects.

From these hypotheses, it was decided, in the first analysis, to install the device in the front cabin of the train, in order to collect initial data, thus evaluating the perception of the system’s users. It is not yet known which will be the best location for data collection, including the limitations of each option. However, for initial analysis, the perception of data directly from the train cabin is suitable for this research.

The assumption is that the device records the vibrations experienced by the occupants of the train cabin during operation. However, this initial choice implies advantages and disadvantages. Advantages include evaluating comfort from the user's point of view and obtaining information to assist predictive and preventive maintenance, by contributing to the early identification of problems on the permanent way. As limitations, it is observed that the interpretation of vibration data can be complex and may require differentiated analyzes to identify significant patterns, in order to distinguish normal and abnormal vibrations. Regarding environmental variations, operational conditions are highlighted as a relevant factor in the analysis, considering the speed of the train, the number of passengers and characteristics of the permanent track can cause vibrations to vary.

The 2000 series trains were chosen for this analysis, considering that additional data can be collected in order to implement the analysis of the results obtained with the prototype.

As for the cost-benefit, for the prototype set up arduíno X, with external batteries was used, totaling around R$250,00 ($50,00). At this initial moment of the model validation, a negligible production cost is observed in relation to the expected potential reduction, being able to reduce future corrective maintenance costs.

After several inspections in train cabins, according to vibration noticed by the inspection team, many problems and non-conformities on the permanent way can now be readily identified during the analysis by the team's inspectors. Therefore, it was realized that with the use of the prototype, for each signature perceived in the data analysis would correspond to a specific defect. In this way, it is expected to be able to verify several signatures depending on the situation found on the spot.

4. GENERATE IDEAS

Brasília's subway system is currently operated using ATO (automatic train operation) technology, which means that human interference in operational processes is greatly reduced. In other words, the operation is automated, including with regard to the commands imposed on the trains, so that the train acceleration and braking processes are automatically controlled by the system, guaranteeing regularity of the process, with the aim of ensuring that the headway previously established is achieved. With this, we verified an interesting functional regularity of the system, which means that parameters, such as speed, acceleration, displacements, etc., can present a certain standardization in similar conditions, especially during the lower demand periods, when the distance between trains is longer and interference between the trains is minimal.

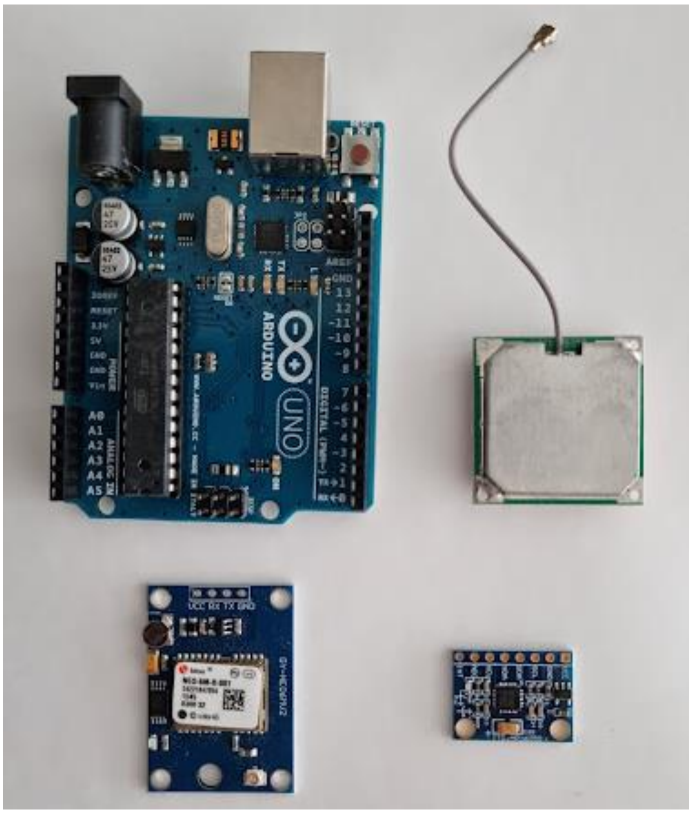
This is particularly useful when seeking an analysis where data repeatability is important to observe. In the case of the project in question, what is sought is an analysis, through the use of artificial intelligence, of data provided by vibration and noise sensors installed on the trains. Thus, the greater the repeatability of the analysis conditions, the greater the accuracy of the results sought.

The idea for the project arose from previous studies carried out at the Company where it was possible to verify that the use of low-cost sensors (Arduino technology) allowed excellent results in control applications. Based on the basic premise that the company is managed by public resources and that there are often financial constraints, using low-cost tools would be imperative for the success of the project.

Thus, the idea of a study that could combine automation tools, artificial intelligence and reduction of labor employment with the aim of anticipating permanent problems arises. With premature identification, more targeted interventions would be possible, with better results and less use of resources, in addition to ensuring greater operational availability and provision of trains to citizens.

A vibration analysis model is developed, using Arduino programming. The project, as shown in the Image 2, consists of a control board, plus an accelerometer sensor, which measures accelerations, in m/s^2 in three dimensions, and a GPS sensor, which records the positioning of the assembly at a given instant of time.

Image 2 - Materials used to assemble the prototype, including control board, accelerometer and GPS



Source: Track Viewer team.

a. The prototype is then programmed to record data every 0.02 seconds. Therefore, five different pieces of data are recorded in a table every 0.02 seconds, namely:
    - Acceleration of the equipment on the x axis;
    - Acceleration of the equipment on the y axis;
    - Acceleration of the equipment in the z axis;
    - Longitudinal position of the equipment;
    - Latitudinal position of the equipment.

b. Therefore, at a given moment, we will have the following information recorded (example):

Table 1 - Example of the recorded data

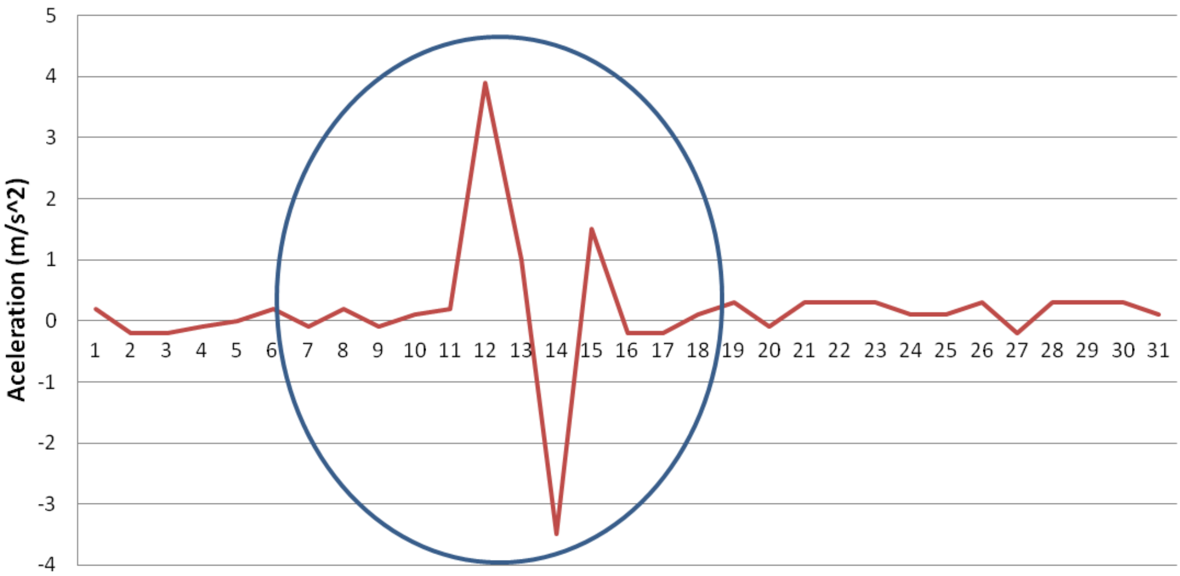
Time (s)	**Acceleration x (m/s^2)**	**Acceleration y (m/s^2)**	**Acceleration z (m/s^2)**	**Position latitude**	**Position longitude**

0	0	0	0	- 15.856.650. 005.080.800	- 48.069.906. 950.605
0.02	0,7	0,3	0,2	- 15.859.127. 208.552.700	- 48.068.963. 142.045.700
0.04	1	-0,5	1	- 15.860.861. 308.596.500	- 4.806.784.7 51.315.630
0.06	-0,3	-0,2	-0,5	- 15.863.833. 991.397.400	- 4.806.630.2 87.523.320
…	…	…	…	…	…

At the end of the measurements, there will be a mass of data that will indicate, for each geographical position taken, acceleration vectors of the composition (train). With this, it is possible to identify abrupt accelerations in each of the axles, which could, at first, indicate a problem with the track geometry or an evident failure.

For example, as shown in the Graphic 1 below, an abnormal phenomenon can be seen in the position, as there is an unexpected acceleration on the y axis.

Graphic 1 - Abnormal phenomenon observed in the selected position.



Once the situation has been identified, initially, a technical team travels to the location, with the aim of identifying the type of problem that caused such an anomaly in the data.

Then, the construction of a database begins, which combines a vibration signature with a characteristic problem, whatever it may be (welding problems, misalignments, cracks, undermining, etc.), informed by the technical teams.

Next, a computational code is trained, through machine learning and artificial intelligence processes, to read and analyze the raw data obtained, specifically indicating existing problems or problems at an initial stage, which may worsen over time. time.

Furthermore, a study is important to determine the best position for installing the sensors inside the trains. It is important that previous parameters are defined in order to guarantee the greatest possible repeatability of parameters. It is known that, for example, the closer to the upper part of the train, the greater the longitudinal vibration amplitudes. And the closer they are to the bogie, the smaller these amplitudes will be. Determining the best positioning of the sensors and repeating it indefinitely ensures that data capture always occurs equally.

As initial parameters, it was defined that the equipment would be positioned in the train cabin, on the left side of the pilot.

The study, which is still ongoing, will evaluate the best positioning of sensors on the train. This is a long period of evaluation, where, in addition to hypotheses to be assumed, the results of the data obtained must be evaluated, identifying their feasibility. For example, it may be that, for technical reasons, positioning the sensors too close to the wheels or too far from the rail (top of the cabin) does not bring effective results, exactly due to the expected vibration amplitudes. Furthermore, the best car to position the equipment must be determined. It is possible that, dynamically, vibration levels are perceived differently between cars.

All of these hypotheses must be tested in order to determine the best location and situations in which the prototype should be used.

A powerful ally for data analysis is the software embedded in the trains that record some operational data, such as speed, train acceleration, loaded and total weight, as well as other parameters that are used by maintenance teams to provide data that may indicate failures. in the train systems. The software works as a “black box” for trains, recording important systemic records that can later be used to investigate errors or human actions.

This system is particularly useful in the application of this research as it allows the crossing referencing of information from the data obtained by the prototype's sensors with information coming from the train itself.

For example, if the train brakes suddenly (regardless of the reason), the onboard system will identify this situation. When making these data compatible with those acquired by the prototype's sensors, it will become clear that, at that moment, the data obtained is, in a certain way, “contaminated” with an external situation unrelated to the normal operation of the train. Therefore, the analysis of that data must be “ignored”, including with the aim of avoiding false positives.

5. PRELIMINARY REMARKS

a) Theoretical Foundation

As mentioned, Metrô-DF uses ATO technology that increases the regularity and reliability of the system. In particular for Series 2000 trains, this technology, used in conjunction with various sensors in the cars, provides the collection and control of several types of information such as: instantaneous speed of the train, point-to-point acceleration, weight of the trains (car weight + passengers) etc.

By combining this data collected through the ATO system with the data obtained by the Arduino prototype, it is also possible to determine the position of the train (GPS information) and any significant vibrations or displacements (information from the accelerometers) in the X, Y and Z axes measured at every 0.02 second. With all this, it becomes possible to record, among others, the following situations:

- For a given section, with a registered and constant speed, take positional readings of vibration or significant displacements that can be compared and confirmed (ruling out any measurement errors);
- For the same section, with known speed, compare positional readings of vibration or significant displacements in peak situations (train with high occupancy) and lower demand (train with low occupancy) to confirm the readings and check any changes in recording intensity;
- For sections where the durability of the rails is lower (curves with a smaller radius with higher elevation and higher speed, for example), take positional readings of vibration or significant displacements at different speeds

registered with the ATO to evaluate possible changes in intensity in the records (and so seek an optimal operating point);

- For the same section, with known speed and specific time (peak hour, for example), compare positional readings of vibration or significant displacements in different climatic situations such as days of intense heat versus days of rain or lower temperatures and evaluate changes in increase or reduction in intensity in records depending on thermal variation (and thus identify potential critical situations);
- This level of information is only possible thanks to the collection and storage of data using Arduino technology. For the data to be collected, it was necessary to code functions in C/C++ language to collect the accelerometer and GPS readings along the route, as shown in the example below. The tests indicated that the accelerometer readings present good accuracy and that the GPS readings sometimes present errors, a topic that deserves attention from the team to improve the prototype.

Image 3 - Track Viewer coding sample

```
void loop() {
  // Leitura dos dados do acelerômetro
  sensors_event_t event;
  accel.getEvent(&event);

  float xAccel = event.acceleration.x;
  float yAccel = event.acceleration.y;
  float zAccel = event.acceleration.z;

  // Leitura dos dados do GPS
  while(Serial.available() > 0)
    gps.encode(Serial.read());

  if(gps.location.isValid()) {
    // Dados do GPS
    float latitude = gps.location.lat();
    float longitude = gps.location.lng();

    // Exibir os dados
    Serial.print("X: "); Serial.print(xAccel);
    Serial.print("\tY: "); Serial.print(yAccel);
    Serial.print("\tZ: "); Serial.print(zAccel);
    Serial.print("\tLatitude: "); Serial.print(latitude, 6);
    Serial.print("\tLongitude: "); Serial.println(longitude, 6);
  }
  delay(100);  // Atraso de 0,1 segundos (100 milissegundos)
```

The idea of identifying significant vibrations or displacements arose from the content presented in Module 2 (Infrastructure), in particular the items that dealt with inspection and track pathology. The question was whether there was a more effective, automated and cheaper way to replace or assist the current visual process (at night) of permanent road inspection.

In Module 2, automatic track geometry inspection methodologies were also presented, the types of tests available on the market, the maximum tolerated limits for the types of defects per speed range in operation, the causes and treatments for the main pathologies of existing rails. Methods for inspecting welds and the rail profile were also presented and some suppliers present in Brazil were discussed.

In Module 5 (Rolling Stock), the dynamics of the train body, the wheel-rail interaction, topics on wheel maintenance, the composition of the bogie and the types of suspension and their main characteristics were discussed. After having contact with the subjects presented in this Module, a visit was made to the Metrô-DF yard to study these components in more depth and understand how a homemade track monitoring system could work.

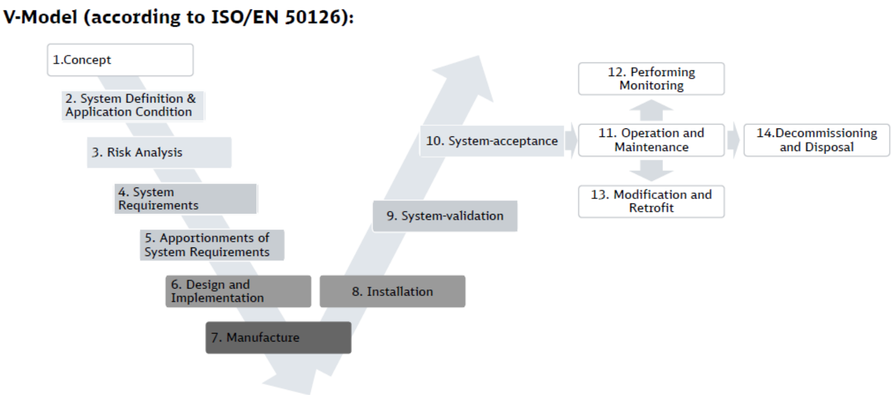
In the Brasília Metro, the most common types of track defects found on the track are: profile variations in the welding regions, damage to the mobile areas of the track changing devices, “canoes” in some specific regions, in addition to flaking and cracks in some sections of the road. Most of these defects are found in the crushed stone ballast region, precisely the area where it will be possible to use the Track Viewer at the moment (because in the tunnel region, with no technical solution for GPS yet, the track was built on a rigid slab).

Based on this information and the aforementioned conceptual framework, it was possible to design a possible solution to address the problem using the V-Model technique (Image 4), worked on in Module 3 (Rail Systems): first, the solution concept was designed based on the necessary requirements for a better reading and monitoring of problems on the permanent route. Next, the Risk Analysis was carried out (see chapter 9), some definitions were specified and what equipment was needed that could offer the best solution. The next step was to detail the solution and build the prototype and then test its use in some parts of the train seeking the best track reading condition. With the first data collected, it was possible to verify some necessary adjustments and improve the prototype (improving the details of the solution) to the current situation.

In this sense, after some tests, it was realized that, at the moment, the most suitable place to install the Track Viewer would be in the conductor’s cabin.

Additionally, after presenting the solution developed in Module 7 (Management & Leadership), a consultation was carried out with 5 colleagues from different companies that work with track maintenance about the regular use of an automated or electronic track monitoring system. In only two companies (one for freight transport and the other for passenger transport) was the systematic use of some market solution mentioned - albeit high-cost and low-frequency - in the other companies, only visual inspection was applied. These facts reinforce the scenario that a low-cost, on-board solution may have good potential to provide reliable information about the status of the tracks.

Image 4 - V-Model technique model according to ISO/EN 50216



b) Theoretical Background

The planning process is made up of a set of steps and techniques to overcome in order to design, develop and implement a new product. It starts with the conception of the idea, the business plan and the subsequent identification of the objectives to be achieved. Next comes the market analysis (with possible research into possible users of the product) and the first draft of pricing, marketing, sales strategies, etc. With these inputs, it is possible to design a schedule for the project as well as the allocation of resources necessary for each stage and carry out a risk analysis and preparation of contingency plans to deal with them. It can be said that without adequate planning, the product may not meet customer needs and have little chance of prospering among companies in the industry.

According to the American Planning Association, planning should emphasize learning and knowledge exchange around project priorities in order to build the cultural competence of those involved. In this specific case, the V-Model methodology was adopted for the development, detailing and evolution of the prototype - its details can be found in CENELEC Standard EN50126/2017. This methodology provides dialogue and innovation around the essential topics of a project in addition to organizing the construction and review of a solution surrounded by complexities such as the one proposed to be developed with the Track Viewer project.

Other planning tools were adopted throughout the development of this project, such as Brainstorming (which helped to build a step-by-step process for evolving the prototype and covering different situations in Metrô-DF), the Polarity Map (which led the team to think about contingencies for different scenarios and situations throughout the development of the product), the SWOT Matrix (which brought into account the market scenario where the project is being developed) and the Physical Financial Schedule (which detailed the development of the project over time, allowing to evaluate the evolution and completion of stages). All of these topics are detailed in Chapters 10 and 11.

The monitoring procedure is important in the metro-rail segment as it is an essential process to guarantee the safety and efficiency of transport. At Metrô-DF, the vast majority of monitoring services are carried out visually, through rounds, and focus on external defects. Occasionally, readings are taken by a specific contracted vehicle to identify longitudinal, lateral and vertical variations in the tracks, in addition to pointing out certain types of vibrations or specific defects in welds or in the region of track switches, for example.

In the case of visual monitoring at Metrô-DF, registers are made manually in reports and markings are made in the field to record the location where maintenance services need to take place. All history of this material is stored in a physical file (service orders - OSs) and, therefore, there is no statistical or positional control of maintenance events by type and frequency. In the case of automatic monitoring, the result is provided in physical and digital media, which allows the comparison of the progress of the road between inspections - it happens that, due to the period of time that the services have elapsed (and any repairs carried out in this interval), information and precision on the evolution of trail pathologies are lost.

The Track Viewer solution will enable, in a version where continuous monitoring of the Metrô-DF tracks can be carried out, a leap forward in reading and recording permanent way information, as it will provide an electronic record of defects located on the track and the evolution of same over time (possibly even with more than one reading of the same passage per day). This data will be stored on the Metrô-DF file server, which has a daily data backup, allowing future analysis and statistics with geolocation of the problems found, which will allow for much more effective preventive and predictive maintenance.

c) Performance evaluation

It is expected that the data Track Viewer will provide to Metrô-DF will be stored and organized in a database file where it can be researched and analyzed by the maintenance team in order to generate key performance indicators (KPIs) for the track. Some examples of KPIs might be: number of relevant defects per kilometer, quantity of relevant defects identified per month, quantity of relevant defects corrected per month, trip user satisfaction among others. Another possibility of evaluation can be done with financial indicators like: monthly cost with rail maintenance and annual expenses for the acquisition of new rails.

To analyze these data and generate the KPIs, some variables will need to be considered as:

- Type of train Track Viewer is installed - in Metrô-DF, the mentioned Series 1000 trains and Series 2000 trains have differences in suspension systems which need to be considered depending on where the equipment is installed;
- Passenger load - Metrô-DF occupation has significant differences between peak and valley time, so these variations need to be considered in measurements (a fully loaded train may detect a certain defect that an out of service train may not);
- Train maintenance history - for a same train, depending on the kind of maintenance done, it is possible that measurement differences for the same rail defect may be registered. So, it is important to cross Track Viewer database with train maintenance records;
- Permanent way maintenance history - tamping services are frequently carried out along Metrô-DF line, these services may change ballast configuration and interfere on Track Viewer measurements, for this reason, it is important to consider these services on rail defects analysis;
- Train speed - Metrô-DF instant speed is controlled by the ATO system and can be considered constant for each section of the railway track. On the other hand, if ATO is reprogramed and change the speed in a specific

sector, Track Viewer readings may change and is important to cross the defects database with ATO speed changes;

- Climate and temperature - thermal expansion is another variable that needs to be considered on Track Viewer measurements. Very hot days versus rainy days or night and day collected data may vary significantly for the same rail defect.

d) Continuous Improvement

Incremental improvements are an essential aspect of the Track Viewer project once it can increase railway safety, optimize efficiency (expected cost savings and better availability) and improve customer satisfaction. In this sense, it is possible to say that the PDCA Cycle will be a very useful tool to foster continuous improvement: planning, implementing, monitoring and performing will help quality increase and better control of track characteristics.

e) Standards

Brazilian Association of Technical Standards (ABNT, in portuguese) has several documents that need to be observed, the main ones are:

a) ABNT NBR 7640 - Rail Defects: this Standard establishes the types and tolerances for rail defects and possible treatments
b) ABNT-NBR 7590 – Rail Requirements: this Standard specifies the dimensions and characteristics of rails
c) ABNT-NBR 16387 - Permanent Way: this Standard determines the quality parameters and maintenance criteria for permanent way

Metrô-DF also has documents and registered procedures that must be followed when doing rail inspection:

a) 2.VAC.RM.MP.SN.003.02 - Preventive Maintenance Guide - Inspection of the main track
b) 2.VAC.RM.MP.SN.007.03 - Preventive Maintenance Guide - Visual aspect of rails and weldings
c) 2.VSE.RM.MC.CD.009.01 - Preventive Maintenance Guide - Rails testing on the main track

5.1. Critical Review

Even though the vibration analysis and diagnosis are a well-established technique, using our own rolling stock to run a diagnosis of the conditions of our tracks is an untested idea, as such it faces the usual challenges any new technology or concept: There will be an implementation cost both in capital and man hours, to train the staff, upgrade our system, and disruptions of the normal workflow. The product may face resistance to be adopted, due to lack of understanding and attachment to older more established processes. There could be issues when integration to existing systems. We could face technical issues, bugs or system failures that could compromise the trust in the new concept.

What is most expected is to be able to develop a reliable concept where the vibration signature can be associated to each type of defect or abnormality on the track, at various stages, to accompany the progression of the severity of the defects. Thus, this concept would not only provide a solid historic profile of the quality of the permanent way, but how it deteriorates, where the most critical points are and what effect it has on the rolling stock, ballast, passenger comfort and satisfaction.

The strength of this concept it is simplicity, the equipment requirement is limited and the mechanics of vibrations as a diagnosis method is well known, however If we cannot develop a model where each type of failure or abnormality can be assigned to a particular vibration signature, then we will not have a viable concept and won’t be able to offer it as solution.

Given the different characteristics of each section of the track, the development stage of our concept will be done on the horizontal ground level section of the system, once we have a reliable concept, we will expand it across the system.

The Track view model implies a constant monitoring of the track, so a significant amount of data will be generated. Data treatment is a crucial aspect of the broader data management lifecycle, ensuring that data is reliable, accurate, and ready for analysis and decision-making. Many issues concerning this data will have to be considered.

Data Collection: data will be obtained from various sources, such as databases, and sensors, the data collected must be relevant to the problem or analysis at hand. Data Cleaning: missing or incomplete data must be identified and handled properly, and duplicate records removed. There must be a standardized format and units to ensure consistency. Data Transformation: This concerns the conversion of data into a suitable format for analysis, normalization or scaling of numerical values, encoding of categorical variables. new features or variables. Data Integration: Combining data from different sources to create a unified dataset, resolving inconsistencies in naming conventions or data formats. Data Exploration: Distribution analysis of data to gain insights. Identification of outliers and anomalies. Visualizing data through charts, graphs, or other visualization techniques. Data Analysis: Application of statistical or machine learning techniques to extract patterns or trends. Exploratory data analysis (EDA) to understand the characteristics of the data. Data Validation: Concerning the accuracy and reliability of the data. Cross-checking results with external sources or known benchmarks. Data Documentation: Documenting the entire data treatment process, including steps taken and decisions made. Recording any assumptions or transformations made to the data. Data Security: measures to protect sensitive or personal information. Compliance with data privacy regulations. Data Storage and Retrieval: Appropriate storage methods (databases, data warehouses) based on the volume and nature of the data. efficient methods for retrieving and updating data. Data Visualization and Communication: Results of the analysis are clear and understandable. visualizations, reports, or dashboards to communicate findings to stakeholders.

Continuous Monitoring and Maintenance: Regular monitoring of data quality and update of the treatment process. Adjustment of the treatment process based on feedback and changing requirements.

Given the volume of data generated, we may have to deal with data superposition. Some of the challenges arising from this issue are clutter, making it difficult to discern patterns or trends, interference, obscuring important information and difficult interpretation. To offset these problems, we will use different colors or shades to distinguish between different datasets, adjust the transparency of data elements to reduce visual clutter and reveal underlying patterns, provide interactive tools that allow users to selectively display or hide specific datasets for a clearer view, and consider aggregating data points if the level of detail is not essential for the analysis, reducing the complexity of the visualization.

Since the speed of the train influences dynamic loading, frequency and amplitude of vibrations, we will have to determine a optimal speed for data acquisitions, lower speeds may excessive vibration if it approaches the resonance frequency, and higher speeds may hide the acoustic signature of some defects, the speed should also not cause interference with de planned headway between the trains operating at the time.

Track viewer would rely on GPS, which has some vulnerabilities, for our project the most pressing issues would be, obstructions from buildings and other obstacles that can block or reflect GPS signals, leading to inaccuracies in positioning. Urban environments with tall buildings can be particularly challenging for GPS signals. Multipath interference could occur when GPS signals reflect off surfaces such as buildings, water, or the ground before reaching the receiver, causing the receiver to calculate an incorrect position. Weather conditions, such as heavy rain, or dense clouds, can attenuate GPS signals, reducing the accuracy of positioning. Ionospheric and tropospheric conditions can also introduce delays in signal transmission. Urban Canyons: In densely populated urban areas with tall buildings, the signals from GPS satellites may be blocked or reflected, causing signal distortion and reducing accuracy. Electronic devices, power lines, and other sources of electromagnetic interference can disrupt GPS signals, leading to inaccuracies. This interference can be intentional (jamming) or unintentional. Satellite Geometry: The geometric arrangement of satellites visible to the receiver can compromise GPS accuracy, if satellites are clustered in one area of the sky for example. The quality of the signal can be affected If a satellite is experiencing issues or is out of service, compromising the overall accuracy of the GPS system. Intentional interference through signal jamming or spoofing can disrupt GPS signals. Jamming involves transmitting signals on the same frequencies as GPS satellites, while spoofing involves broadcasting false GPS signals to deceive receivers. Changes in the GPS satellite constellation, such as the addition of new satellites or the decommissioning of old ones, can affect the overall performance of the system.

To mitigate the aforementioned issues, we will use a combination of technological advancements, signal processing techniques, and alternative technologies: Multi-Constellation Receivers to utilize signals from multiple satellite constellations. Augmentation systems, to provide additional corrections to GPS signals, improving accuracy. Real-Time Kinematic technique that uses a correction signal from a base station to improve the accuracy of GPS positioning in real time.

Differential GPS, which uses a fixed ground-based station to calculate and broadcast corrections to GPS signals. Receivers within the broadcast range of the station can apply these corrections to improve positioning accuracy. Anti-Jamming and Anti-Spoofing Technologies. Inertial Navigation Systems (INS), combining GPS with inertial sensors (accelerometers and gyroscopes) can provide continuous navigation information even when GPS signals are temporarily unavailable. Signal Quality Monitoring, GPS receivers can monitor the quality of received signals and assess the reliability of position estimates. If the quality falls below a certain threshold, the receiver can take corrective actions or switch to alternative positioning sources. Advanced antenna designs to mitigate multipath interference and improve signal reception in challenging environments. Adaptive antennas can dynamically adjust their reception patterns to optimize signal quality. Use of Signal processing algorithms, such as those for signal filtering and error correction, can enhance the accuracy of GPS positioning. Alternative Positioning Technologies, such Wi-Fi positioning, cellular-based positioning, and sensor fusion with accelerometers and gyroscopes can be used to supplement or replace GPS in certain situations. Improving and expanding Satellite Constellations, such as the addition of new satellites and advancements in satellite technology,

The system is being tested on the ground level section of the track system, as we upgrade track view to the whole network and therefore the underground sections, the data transmission while need to be taken into consideration as the systems uses ATO to control our trains and they do not transmit data, CBTC is a viable option, as is the WI-FI positioning and bluetooth connection.

6. SCOPE AND LIMITATIONS

The prototype must, in the future, be applicable to the entire permanent way, so that the entire system can be mapped. However, it should be noted that, considering the initial stage of the research, it is not possible to carry it out across the company's entire railway extension. As it is still in the adjustment phase, some parameters require further study, in order to evaluate the effect of some train dynamics on the computed data. As discussed previously, the location of the device installation; the cargo transported; and other parameters such as curve radio, can interfere with the data obtained and its interpretations. Additionally, there is an initial limitation of the GPS location system. The company operates in places where there are tunnels and at these points location information is not captured, so that the complete analysis of the system cannot be immediately provided.

Therefore, the section between Stations 114 Sul and Shopping was defined, within the Brasília metro system. This stretch is approximately 2.0 kilometers long. The choice was fundamental because, in this region, a series of problems related to welding were identified, as seen in the images below. It was expected that the train, when moving along the tracks and passing over welds with some type of failure, would present some type of “abnormal” vibration, which could be perceived by the prototype's sensors. Therefore, when evaluating the vibrational behavior of the site, one would expect to identify a problem. And so, over time, through a failure signature, it was determined that such behavior would be inherent to a welding failure. But this will only be achieved over time, after determining all the parameters involving data capture, and after analyzing a large mass of data, which could predict/determine situations and its occurrences.

The results obtained in two different sections of the permanent way are presented below. It is evident from the characteristics of the vibrations that an abnormal behavior occurs in the operation of the train at that specific point, highlighted in the Graphic 2.

Graphic 2 - Acceleration measured on a section of the permanent way. Starting position: -15.832855135055894, -47.947129444860806 ; ending position: -15.832833846262513, -47.947298423969954; liquid cargo transported: 9,5 tons; velocity: 76 km/h.

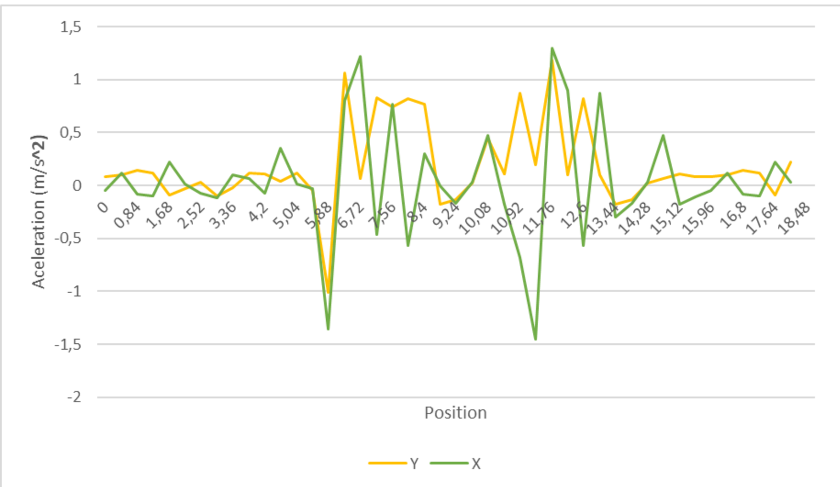
In the situation shown on Graphic 2, it was verified, in loco, that there was a welding problem in the region where there was abnormal vibration behavior, as can be seen in Image 5 below.

Image 5 - Welding problem in a section of the permanent way

Source: Track Viewer team.

On another section of the road, in similar conditions, the following data were observed, as shown in Graphic *3* below:

Graphic 3 - Acceleration measured on a section of the permanent way. Starting position: -15.83361301048701, -47.9430791097709; end position: -15.833539362484801, -47.94326411213974; liquid cargo transported: 10 tons; velocity: 76 km/h.



In the situation shown in Graphic *3*, it was verified, in loco, that there was a welding problem in the region where there was abnormal vibration behavior, as identified in Image 6. It is similar to that seen in the previous section, as shown in the image below:

Image 6 - Welding problem in the region where there was abnormal vibration behavior

Source: Track Viewer team.

It was also verified that there is no parallelism in the data obtained that could indicate that it was the same failure, even though the train, when passing through the locations, was in strictly similar operational conditions. This happens due to the fact that there is not yet enough data to allow a deep analysis, in order to determine, precisely, what the measured accelerations represent. Furthermore, it should be noted that there has not yet been enough time to assess the evolution of defects on the tracks and check when, and if, they reappear.

However, it is interesting to note that the data is promising. There is also a limitation in the scope of the project as it is a prototype under development, however, within time, more improved and more reliable information will be sought. The issue of data and information reliability is essential for the success of the project. It must be ensured that the information is made available and as accurately as possible. This issue is still a limitation of the project in question. It is not yet possible to guarantee that the data is correctly acquired, and that the information is fully verified, as these are low-cost sensors, whose accuracy is still questionable. And when it comes to subway operations, safety is fundamental. It is not possible to adopt good operation and maintenance practices with incomplete or unreliable information. Therefore, there is an effort to improve aspects involving the prototype, in order to guarantee its reliability.

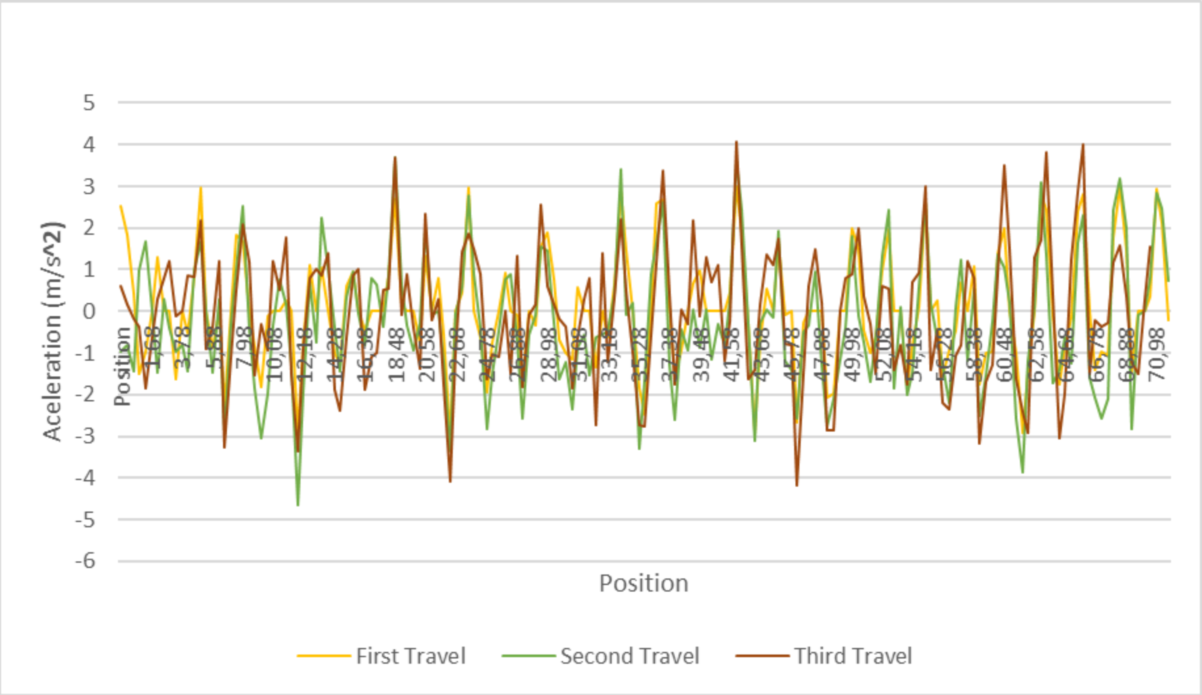
There are no similar solutions on the national market like the one being proposed. Therefore, it is not practical to evaluate possible results and try to compare them immediately, with the aim of making the development of this project simpler and more practical. Therefore, it is not yet possible to accurately measure the resource savings that may arise from the implementation of this project, if it actually occurs.

Some interesting situations could be observed. During the initial calibrations of the prototype, in a region other than that included in the scope of this work, abnormal behavior of the train was observed in a section of approximately 200 meters, presenting noticeable vibrations inside the train. Thus, three measurements of the local area were taken. In the graphics shown in Graphic *4* are presented the comparison between these measurements. Only the variations on the Y axis (transversal displacement) were presented, since those measured on the X axis (vertical displacement) are small and quite similar, not impacting the proposed data analysis.

There is an interesting similar behavior of vibrations in the three measurements carried out (overlapping), which is an excellent sign for the results expected when the prototype is fully operational. An important observation to be made is that the data were taken under the same operating conditions, that is, with the same positioning of the sensors on the train, the same speed characteristics and similar load transported.

This situation was later reported to the maintenance teams, who found that a mechanized tamping process had recently been carried out at that place, but without replacing ballast. This could initially indicate that the track was not adequately supported on the ballast, thus leading to behavior that could be noticeable by the sensors. From the prototype's point of view, the results were excellent, as they proved that there is an expectation that it will work properly and indicate that it will be extremely useful for the company's maintenance sector.

Graphic 4 - Acceleration measured on a section of the road. Starting position; end position; liquid cargo transported; speed.



However, during these tests, there was a situation in which data from the same location were obtained under different conditions. In the first graph presented, in Graphic 5 below, the train was traveling at 20 km/h, that is, about one quarter of the nominal speed expected for the section, 80 km/h. The behavior of the data turned out to be completely different from those initially obtained under normal operating conditions.

The presented information demonstrates the importance of analysis using artificial intelligence in relation to the data obtained. There is a need to exclude contaminated data that would only contribute to complicating the interpretation of the situations that occur. It is in this aspect that information from the train information recording system becomes particularly useful (example in

Image 7

Image 7). Through the data provided by it and an assessment carried out by an intelligent system, it is possible to determine situations that do not fit the expected standard, so that such data can be excluded. To do this, a large amount of data is required, so that the information is as accurate as possible.

Graphic 5 - Acceleration measured on a section of the road. Starting position: ; end position; liquid cargo transported; speed.

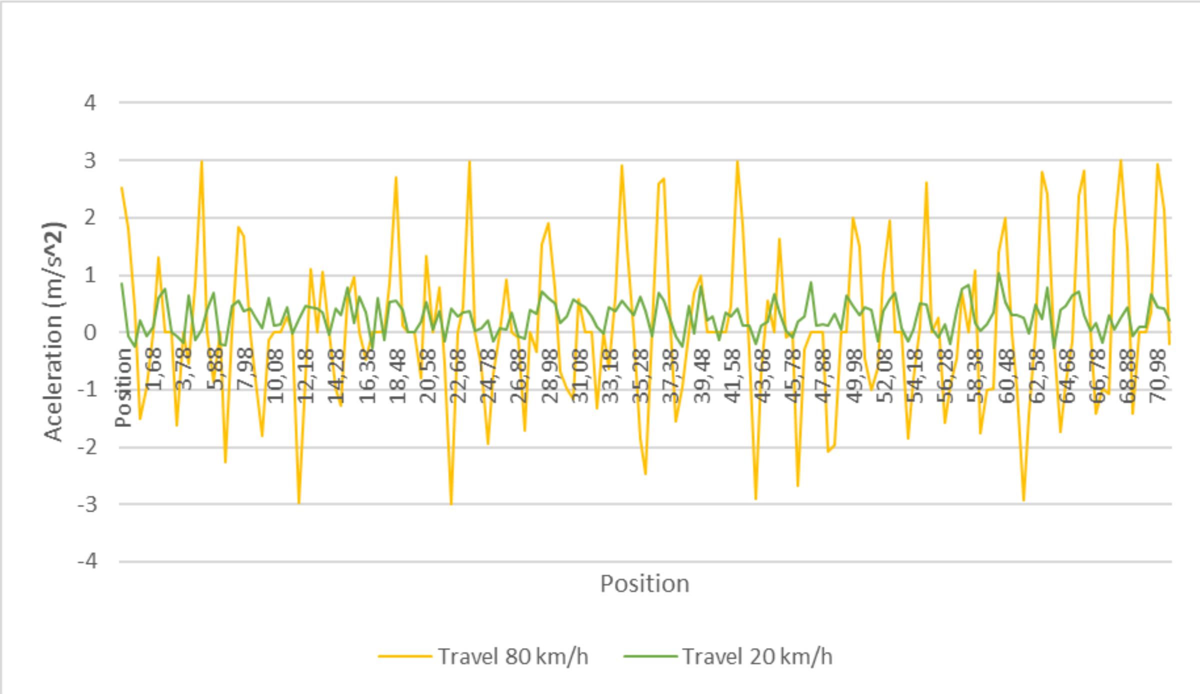
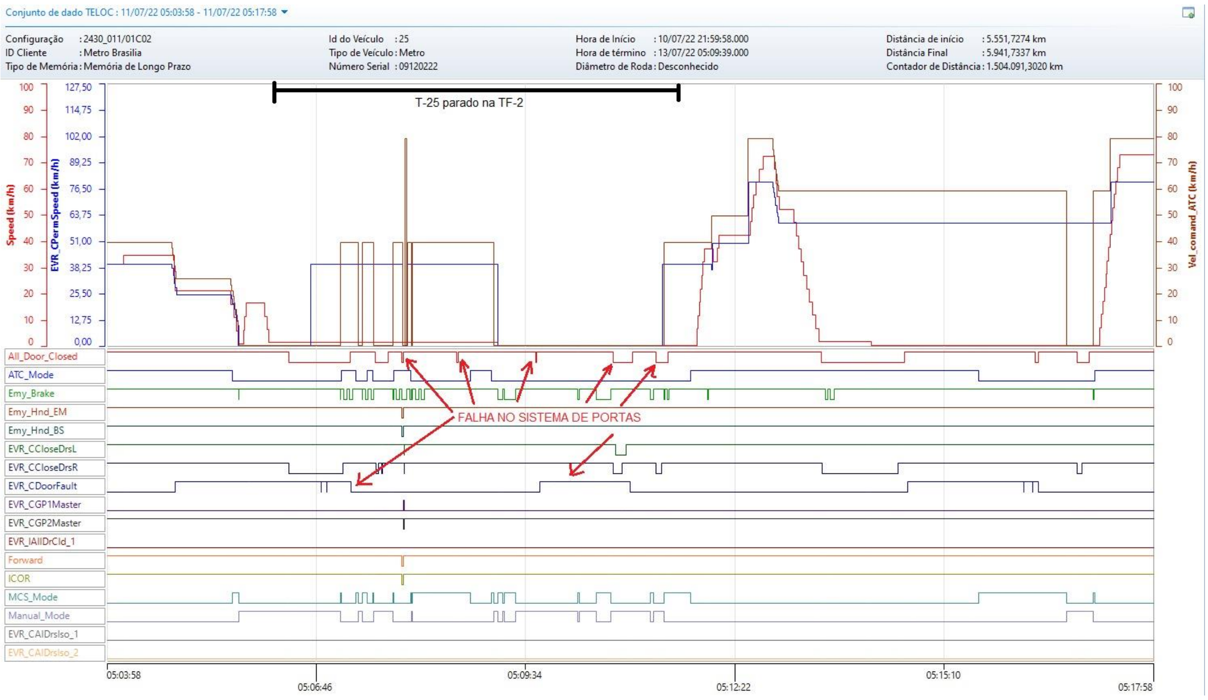


Image 7 - Example of information registered by the train data recorder.



Source: Metrô-DF.

If, for example, in the case in question, there were only two data collections, as shown in the graphs presented in Graphic 3, the information presented would be inconclusive and the project would not be technically interesting. Therefore, it is necessary to acquire a large volume of data, in order to guarantee data repeatability and the possibility of reliable analysis.

As already discussed, the prototype is still in the initial implementation phase. There are still adjustments to be made in the programming codes and the use of artificial intelligence, however, preliminary results have already shown themselves to be promising. Subsequently, management with the company's stakeholders, especially senior management, is still necessary to finance the project and effectively implement it in the company.

Another important aspect to be observed refers to the accuracy of the GPS. During testing of the prototype, it was found that there are errors ranging from a few centimeters to several meters, reaching 32 meters. This is an important factor to note that must be considered when it comes to the reliability of the information to be analyzed. The system must be automated so as not to allow the analysis of data that is outside a stipulated margin of error.

As a possibility of adjusting to this problem, two ideas emerged, which may even be complementary. Firstly, two GPS modules can be used to improve the accuracy of positioning data. This way, it is possible to exclude from the analysis data that is outside a previously defined margin of error. Due to the time required to evolve the prototype model, it was not the scope of this work to carry out this analysis, so this situation will be developed over time.

The second idea relies on use of NFC modules installed along the permanent way, at predetermined points. Thus, every time the prototype comes into contact with the module, it will make a record indicating its current positioning. By installing several modules along the path, the error associated with positioning the train on the track can be reduced. However, the disadvantages of using such solution are the increased cost of the project (numerous NFC sensors installed) and the fact that the positioning of the prototype must allow the NFC sensors to be read. In other words, in general, the prototype must be installed below the train, close to the tracks, so that reading can occur effectively. Furthermore, as disadvantages, it is possible to verify the possibility of not reading a sensor, making it difficult to identify the position of the train on the permanent track.

The tool defined to carry out data analysis will be, initially, Julius (https://julius.ai/). The choice was made based on the practicality that the tool offers and the results that can be obtained. When the prototype is advanced, more robust tools, such as those programmed in Python, will be used. For now, at the current stage of prototype development, the methods for analyzing the data have not yet been defined, nor have their coding been defined.

7. LITERATURE REVIEW

The creation of a startup focused on developing a low-cost monitoring system for metro railways represents an innovative response to the challenges faced by urban passenger transport systems.

Currently, track condition analysis mainly relies on traditional methods such as visual inspection, which can be limited in terms of accuracy and cost, or railway sweeps carried out by control cars, which can be costly, such as:

a) Vibration Sensors;
b) Visual Monitoring Cameras;
c) Drone Inspection Systems;
d) Wear and Temperature Sensors;
e) Derailment Monitoring Systems;

f) Geometric Measurement Systems;
g) Object Detection Sensors on the Road;
h) Big Data Analysis Systems;
i) Material Fatigue Measurement Equipment;
j) Ultrasound and X-ray; etc.

This equipment is an integral part of a comprehensive monitoring system, often combined to provide a complete view of the status of the metro permanent way and ensure safety and operational efficiency, despite high costs that prevent greater testing and analysis with a better periodicity.

7.1. The current state of metro rail monitoring, its challenges, and gaps

The current state of metro rail monitoring highlights the pressing need for advances. Challenges include over-reliance on manual methods, creating gaps in problem detection and harming operational efficiency and safety. The lack of low-cost solutions contributes significantly to these gaps, compounding the challenges. The extension of subway networks, the short daily work time for maintenance and the complexity of urban infrastructures are additional challenges, demanding more accessible, fast, and comprehensive solutions.

There is a critical relevance of effective monitoring of the metro railway to ensure the operational safety, punctuality and sustainability of urban transport systems. Therefore, there is a dependence on a better, faster and more effective form of monitoring analysis.

Still, the current state of metro rail monitoring varies considerably between different metro systems around the world, including those in Brazil.

Many metro systems face the challenge of aging infrastructure, highlighting the critical need for investment in modernization. These investments are critical not only to maintain operational safety and reliability, but also to ensure operational efficiency and adaptation to the latest technological standards.

7.2. Integration of technologies for operational efficiency

There is a real need for an integrated approach, combining new technologies such as IoT (Internet of Things) sensors, big data analytics and machine learning. The joint implementation of these tools allows for continuous data collection in real time, enabling predictive analysis and preventive maintenance. It also allows for better operational efficiency, reducing downtime and enabling more proactive management of the metro rail infrastructure.

Another important aspect is system interoperability. There is a need for integrated platforms that can consolidate data from different sources into a single control panel. This simplifies operational management and also enables faster and more informed decision-making in critical situations.

Several innovations are being applied to traditional equipment, significantly increasing their capabilities, such as:

a) Artificial Intelligence (AI) and Machine Learning;
b) Smart Sensors and IoT;
c) Prototyping platforms;
d) Computer Vision and Image Recognition;
e) Intelligent Drones;
f) Big Data Analysis and Advanced Analytics;
g) Augmented Reality (AR) and Virtual Reality (VR);
h) Multispectral Sensors;
i) Blockchain for Data Traceability;
j) Autonomous Monitoring; etc.

7.2.1. A brief introduction to Artificial Intelligence

Artificial intelligence (AI) represents a dynamic and multidisciplinary field that seeks to replicate the human capacity for learning, reasoning and decision-making in computer systems.

The history of AI dates back to the 1950s, with pioneers such as Alan Turing and John McCarthy. Over the years, there has been an evolution from classic techniques, such as symbolic logic and neural networks, to the emergence of modern approaches, such as machine learning (ML) and deep learning (Deep Learning - DL). Machine learning stands out as a crucial subarea of AI, using algorithms to enable systems to learn patterns and perform tasks without being explicitly programmed.

AI has found application in several industries. In healthcare, AI systems assist in accurate medical diagnoses. In finance, AI algorithms optimize investments. In the automotive sector, autonomous vehicles use AI for safe navigation. These applications highlight the transformative impact of AI on our society. As can happen in the metro-rail industry.

The future of AI involves trends that point to the convergence of AI with other disruptive technologies, such as the Internet of Things (IoT) and quantum computing. This integration promises to drive innovations in several areas, from smart cities to personalized medicine. In terms of smart cities, modern and connected public transport is an extremely important factor.

When examining the history, evolution and practical applications of artificial intelligence, it is clear that not only are the advances notable, but also that the ethical and technical challenges demonstrate the difficulties and concerns for its implementation.

7.3. Low cost solution necessity

The integration of emerging technologies in the monitoring of metro systems, in line with the lack of resources and the need for low-cost solutions, is a field that promises a profound and sustainable transformation in the sector. This strategic convergence is crucial to face the growing challenges of metro rail infrastructure, offering not only immediate responses, but also promoting efficient, data-driven management over time.

The need to reduce costs with traditional track monitoring methods, which are expensive and limited, and the need for faster responses are part of a new market strategy to improve overall operational efficiency.

These solutions offer not only reduction in financial costs, but also a substantial improvement in operational safety and system availability. Plus, better predictive maintenance.

Furthermore, the need for low-cost solutions is directly linked to the expansion and modernization of metro rail networks. As new lines are added or existing infrastructure is renewed, the search for affordable technologies becomes even more pressing. The scalability and adaptability of these solutions are key to ensuring that implementation can be extended efficiently as the metro rail infrastructure grows.

The convergence of emerging technologies with the need for low-cost solutions represents a paradigm shift in the approach to metro monitoring. The search for operational efficiencies, reduction of maintenance costs and optimization of resources makes the adoption of these innovations not only a strategic choice, but often an imperative necessity for metro rail operators seeking to remain competitive and sustainable in the long term.

7.3.1. Arduino – a low-cost prototyping platform model

Arduino is an innovative open-source electronics prototyping platform that has become a phenomenon in the community of makers and electronics enthusiasts. The introduction to Arduino is an invitation to explore a universe of creativity and innovation in the field of DIY electronics. Since its conception in 2003 by a group of visionary engineers at the Interaction Design Institute Ivrea, Arduino has been a driving force in democratizing access to electronics and programming. This open source electronics prototyping platform offers an accessible approach, allowing makers, enthusiasts and students to enter the exciting world of electronics in a practical and intuitive way.

Arduino's simple architecture, consisting of a microcontroller and an easy-to-use programming interface, became the basis for a wide range of innovative projects. From robotics to home automation, interactive art and education, Arduino has become the preferred choice for those looking to turn ideas into reality. The diversity of types of boards and additional modules, known as shields, offers flexibility and expandability, allowing Arduino to be adapted to a variety of applications.

It is important to highlight Arduino's crucial role in promoting hands-on science, technology, engineering and mathematics (STEM) learning and its ability to inspire a global community of innovators. By diving into the world of Arduino, individuals discover not just a hardware platform, but a philosophy that values accessibility, collaboration and creativity.

In this way, Arduino transcends its role as an electronics prototyping platform. He became a catalyst for the democratization of electronics and programming.
In short, Arduino is not just a hardware platform. It is a philosophy that advocates accessibility, collaboration and practical learning. Their journey from classrooms to research labs, makers' garages, and global impact projects is a testament to how a

simple idea can become a driving force for innovation and creativity. And Arduino is the basis of this low-cost monitoring prototype proposal for metro railways.

7.3.2. Low cost project management

Low-cost project management in this case is a strategic foray into a fundamental approach to addressing the complex challenges and financial demands inherent in modernizing public transport infrastructure.

In a scenario where operational efficiency, security and financial accessibility are crucial imperatives, managing low-cost projects is not just a matter of limiting expenses. It is a strategic approach that prioritizes efficiency in resource allocation, the adoption of agile methodologies and the proactive identification of accessible solutions.

By understanding the interdisciplinary and multifaceted nature of subway monitoring systems, low-cost project management seeks to align efficient technologies, risk mitigation strategies, effective collaboration with stakeholders and the implementation of cost-effective maintenance practices. The following are essential actions for effective management:

a) Cost Minimization Strategies;
b) Agile and Flexible Methodologies;
c) Assessment of Risks and Contingencies;
d) Effective Collaboration with Stakeholders;
e) Low-Cost Technologies for Monitoring;
f) Training and Qualification;
g) Predictive and Preventive Maintenance; etc.

There is also a need for strong risk and contingency management, on a proactive basis, providing a safety net against unforeseen events that could impact the budget and schedule. By anticipating potential challenges, project teams can respond quickly, minimizing adverse impacts and ensuring efficient continuity of operations.

7.3.3. Technological innovations developed by companies

Technological innovation developed internally by companies, especially in public companies that have more restrictive budgetary resources, highlights the creative and adaptive capacity of employees themselves in finding efficient and economical solutions to the problems faced. Also noteworthy is the inherent engagement of employees themselves in the search for efficient and accessible solutions for their companies. This scenario challenges traditional financial barriers, highlighting the resilience and adaptability of teams when faced with complex challenges.

By adopting this approach, companies not only solve problems efficiently, but also build an organizational culture capable of adapting to future challenges. Internally developed innovation is not an isolated event, but rather an ongoing process that fosters an agile and collaborative mindset.

7.4. Metrorail Monitoring Regulations and Standards

Metro rail monitoring is subject to rigorous safety and performance standards. The implementation of low-cost solutions must be carefully designed to meet these requirements, ensuring approval by regulatory agencies. Compliance with regulations and standards is crucial to the safety and reliability of metro rail operations.

7.5. Similar experiences in other companies and countries:

There are several successful implementations in metro rail systems around the world. Experiences that highlight the effective use of low-cost sensors, real-time data analysis, and integrated solutions offer valuable insights. These studies demonstrate not only the technical feasibility, but also the tangible economic and operational benefits of affordable monitoring solutions.

Similar experiences in other companies and countries highlight the globalization of innovative practices in track monitoring in subway systems.

The incessant search for innovative solutions in monitoring tracks in metro systems transcends geographic borders, demonstrating a convergence of ideas and efforts in the creation and implementation of advanced strategies to ensure the safety, efficiency and sustainability of their metro systems.

The global dynamics in this field highlights not only the universality of the challenges faced, but also the adaptability and inventiveness of organizations when facing similar difficulties.

This great number of experiences, such as those exemplified by London Underground, New York City Subway, Seoul Metropolitan Subway, Shanghai Metro, Indian Railways and Deutsche Bahn, not only reveals the adaptability of organizations, but also drives a global mindset in the pursuit of innovation.

7.6. International experiences in rail monitoring:

a) London Underground (United Kingdom): London Underground has implemented a comprehensive approach using integrated vibration and temperature sensor systems, which are embedded into the tracks to continuously monitor operating conditions.
b) New York City Subway (USA): the New York subway system has incorporated drone-assisted visual inspections. Drones perform detailed inspections of tracks, providing a clear view of hard-to-reach areas.
c) Seoul Metropolitan Subway (South Korea): Seoul Metropolitan Subway has taken an advanced approach by implementing artificial intelligence-based systems. The A.I. uses machine learning algorithms to analyze historical data and identify patterns that precede rail failures, acting in a predictive manner.
d) Shanghai Metro (China): Shanghai Metro has invested in ultrasound and X-ray technologies for detailed inspection of the tracks. Specialized equipment performs regular scans to identify cracks and structural flaws invisible to conventional methods, contributing to more precise maintenance.
e) Indian Railways (India): In India, a country whose railway system is one of the most extensive in the world, Indian Railways introduced the "Smart Track Monitoring System", with advanced sensors and communication technologies to continuously monitor the condition of the track, detecting wear, cracks and other problems early.
f) Deutsche Bahn (Germany): Known for its excellence in railway technologies, and one of the giants in the sector, Deutsche Bahn has been leading the introduction of cutting-edge solutions related to permanent track. German researchers have explored advanced approaches, including the use of smart sensors and predictive analytics systems. Examples such as DB Netz AG's "Railway Inspection Wagon", which uses ultrasound for rail inspection, and Siemens Mobility's "SiTraffic Concert" system, which employs intelligent

sensors, illustrate the technological sophistication adopted to ensure track stability and safety permanent.

7.6.1. Brazilian experiences in rail monitoring:

a) São Paulo Metro: São Paulo Metro is the most extensive systems in Brazil. Although there is no better disclosure on the subject, the company has a history of investing in technologies to improve operational efficiency.
b) Rio de Janeiro Metro: the Rio de Janeiro Metro is also an important Brazilian public transport system. The Rio de Janeiro Metro has faced challenges and sought innovative solutions.
c) Other Initiatives: Brazil, in general, has seen an increase in interest in more efficient and safe public transport technologies. Innovations in track monitoring may be occurring at the local level or through partnerships with companies specializing in transportation solutions.

In addition to the subway systems in São Paulo and Rio de Janeiro, other Brazilian cities have sought innovative solutions to public transport challenges. Innovations may include the use of advanced technologies such as integrated sensors, real-time data analysis and drone-assisted visual inspection tools. While these initiatives may not have achieved widespread national visibility, they reflect the growing interest in modern trail monitoring practices.

Although specific practices may not be as widely publicized, it is important to recognize that public transport companies in Brazil have demonstrated an increasing commitment to adopting innovative technologies. Track monitoring, being a vital part of maintenance and safety, is likely to be among the areas of focus for continuous improvements in operational efficiency and service quality.

8. COST BENEFIT ANALYSIS

In the cost-benefit analysis regarding the effective implementation of the prototype for inspection of defects on the permanent way, it is initially worth highlighting the total costs that are spent annually on the current contract in force, for preventive, corrective and conditional maintenance of the Permanent way of Metrô-DF. The costs highlighted with preventive/conditional maintenance with services related to the scope of this analysis are real and could be reduced with more frequent use of the device under study. In addition to these costs, it is estimated that there will be a reduction in the amount spent when carrying out corrective maintenance, considering that defects in the permanent road would be detected in their initial stages, meaning that the non-conformity would be resolved as quickly as possible.

Therefore, according to surveys carried out in the current contract, quality control of the tracks and welding is currently carried out using ultrasound coupled to a railway vehicle at an annual value of R$ 459,846.00. In addition, inspection and survey of defects on the railway line are carried out, with a road-rail control car, totaling an annual expenditure of R$ 348,186.60. As preventive maintenance, weekly inspection of the main road with a subway car is mentioned, with a total value of R$ 7,017.40. There is also an inspection of the welds of the main and secondary road tracks, carried out quarterly, with an annual value of R$ 102,270.25. The conditional ultrasound maintenance to be carried out on the main track costs R$ 2,481.36, which is also carried out on the aluminothermic welds on the secondary track, R$ 15,383.20. This amounts to a total value of R$ 935,184.81.

It is worth highlighting the other corrective maintenance services, which in 2022 totaled R$ 14,250,000.00. In other words, the costs related to the inspection of defects obtained through the prototype under analysis correspond to 6.56% of the total cost of the contract in force in 2022.

In addition to this data, there is also the cost of Metrô-DF's own workforce, which routinely carries out patrol inspections on foot on the track, or even in the train cabin. By consulting the transparency portal, where it is possible to observe the remuneration of employees of the Federal District Government, the average monthly salary of the 8 employees working in these activities could be observed, which corresponds to R$ 13,106.30 and amounts to a total annual value of R$ 1,258,205.16. In other words, there is a significant cost of own labor that could be better used in monitoring other priority activities, as well as in analyzing the data from the prototype.

9. RISK ANALYSIS

Using the V-Model as a reference in the product development, a risk analysis was conducted to identify and mitigate potential challenges throughout the process. By applying the V-Model approach, possible failures were identified, and strategies were outlined to overcome them, aiming to meet the essential requirements for the prototype construction.

Risk analysis can be carried out using different tools depending on the context in which it is used. However, the concept of risk is basically the same, regardless of the area, undergoing adaptations for each reality.

In the definition presented in ISO 31000, which “[...] provides a common approach to managing any type of risk and is not industry or sector specific”, risk is basically the “effect of uncertainty on objectives”, which can be positive, negative or both, and can address, create or result in opportunities and threats.

According to APM (2004), in the context of projects, risk is "an event or set of uncertain circumstances that, if it occurs, will have an effect on the achievement of one or more of the project objectives", and this effect can be positive or negative and, therefore, with the potential to harm the project (in this case being called a threat) or benefit it (being called an opportunity).

Likewise, the PMBoK (Project Management Body of Knowledge), through the PMBOK Guide (2008), defines risk as an uncertain event or condition that, if it occurs, has a positive or negative effect on at least one objective of the project, such as schedule, cost, scope or quality.

When developed into a process to avoid and/or minimize threats, as well as explore and maximize opportunities, risk management is formed (APM, 2004) and identifying, analyzing and evaluating them are part of this management.

When implemented, risk management makes the project much less susceptible to unforeseen events, since threats have their impact reduced, or even eliminated, and opportunities are enhanced. Therefore, the project becomes less exposed to 'crisis' situations, with a greater probability of success in achieving its objectives within the planned time and cost, resulting in a more attractive project (APM, 2004).

In the context of a new business, where a product or service has not yet been validated by the market and where, normally, modifications are made throughout the validation process, risk management is fundamental to guarantee the safety of the product, increase its quality and efficiency and contribute to the long-term sustainability of the business, reducing the likelihood of failures, losses and market objections.

Thus, the objective of the risk analysis at this stage of product development was to list all risks that could contribute to or prevent the identification of faults on the rails through vibration promoted by wheel-rail contact, and/or the reading and recording made by the equipment. The objective is to find their causes, consequences, level of priority and then assess whether and how to treat them.

There are several tools for carrying out risk analysis. In this case, however, Failure Mode and Effect Analysis (FMEA) was chosen. The choice was made because FMEA "is one of the most widely used error analysis techniques in machining today" (ARSLAN KAZAN et al., 2023), and also for being successfully applied in several areas such as healthcare processes in hospitals, environmental risk assessment, wind turbine system, service system, quality process (LIU et. al., 2019; ZAMBRANO & MARTINS, 2007; ARABIAN-HOSEYNABADI et. al., 2010; CHUANG, 2007; SAXER, 2015).

9.1. FMEA

FMEA (Failure Mode and Effect Analysis) is a systematic method of identifying and preventing product and process problems before they occur and is focused on preventing defects, enhancing safety, and increasing customer satisfactions (MCDERMOTT et al., 2017).

The tool was created in 1949 by the US Army with the aim of identifying the effects of failures in systems and equipment and classifying them based on their impact on mission success. In 1963 it was formally used by the aerospace industry, through NASA, with a view to contributing to the safety of the APOLLO program. In the 1980s, automobile industries began to use it in the development of new products and processes, with the Ford Motor Company achieving significant advances in the areas of design and manufacturing, which led to the publication of manuals for applying the tool in automobile engineering: Potential Failure Mode and Effects Analysis in Design (Design FMECA) and for Manufacturing and Assembly Processes (Process FMECA) Instruction Manual (SOUZA, 2014).

According to Stamatis (2003), there are four types of FMEAs, based on different focuses and objectives: System FMEA, Design FMEA, Process FMEA and Service FMEA, where the first is focused on failure modes between functions of a system, caused by its deficiencies; Design FMEA is aimed at analyzing products before they are manufactured; Process FMEA focuses on failure modes caused by process or assembly deficiencies; and Service FMEA analysis services before they reach customers.

For Pedrosa (2014), however, there is no unanimity regarding the types of FMEA, since some authors classify the method into just three categories (System, Product/Project and Process), and others into just two types (Product/Project and Process)), this being the most common classification in the literature.

Due to the embryonic stage of the project, where the consolidation of the equipment is still in progress, it was admitted that the use of Design FMEA or Product/Project FMEA would bring more contributions to the development of the project, which is why we opted for its use.

According to Pedrosa's classification (2014), the Product/Project FMEA analyzes product designs (machines, tools, components) before production, covering their entire lifespan. In this sense, it identifies potential design flaws - such as inappropriate material choices and inadequate specifications - that can lead to poor performance or short service life, pointing out critical features, prioritizing necessary changes and improvements, and assisting in testing.

To do this, it uses an indicator called RPN (Risk Priority Degree), which points out the most critical failure modes, directing the management team's actions. The RPN is calculated by the product between the Detection level - probability of a failure being detected by the established control; the Occurrence level - the frequency with which a given cause of failure can occur - and the Severity level, which measures the effect of the failure mode on the customer (SCHIMITT & LIMA, 2016).

The application of FMEA in this work used as a basis the method planned by Stamatis (2003), according to which there is no standardized and universal classification form and guidelines for its application: “Each company has its own form that reflects the needs of the organization and the customer concerns.”

Therefore, the expected results for this stage were (STAMATIS, 2003):

- A potential list of failure modes ranked by the RPN.
- A potential list of critical and/or significant characteristics.
- A potential list of design actions to eliminate failure models, safety issues, and reduce the occurrence.

- A potential list of parameters for appropriate testing, inspection, and/or detection methods.
- A potential list of recommended actions for the critical and significant characteristics.

Table 2 - Criteria for defining severity effect ranking

Severity Effect	Rank	Criteria
None	1	No effect
Very slight	2	Customer not annoyed. Very slight effect on product performance. Nonvital fault noticed sometimes
Slight	3	Customer slightly annoyed. Slight effect on product performance. Nonvital fault noticed most of the time
Minor	4	Customer experiences minor nuisance. Minor effect on product performance. Fault does not require repair. Nonvital fault always noticed.
Moderate	5	Customer experiences some dissatisfaction. Moderate effect on product performance. Fault on nonvital part requires repair.
Significant	6	Customer experiences discomfort. Product performance degraded, but operable and safe. Nonvital part inoperable
Major	7	Customer dissatisfied. Product performance severely affected but functionable and safe. Subsystem inoperable
Extreme	8	Customer very dissatisfied. Product inoperable but safe. System inoperable
Serious	9	Potential hazardous effect. Able to stop product without mishap—time-dependent failure. Compliance with government regulation is in jeopardy
Hazardous	10	Hazardous effect. Safety related—sudden failure. Noncompliance with government regulation

The form used to apply the tool is generally divided into three parts. The first provides general information such as the names of the responsible team, the date of preparation, etc.

The second reflects the items for any Design FMEA and can be considered as the body of the FMEA, presenting information on product objective, potential failure mode, failure effects, critical characteristics, severity of effect, potential cause of failure, frequency of occurrence, detection method, detection rate, Risk Priority Number (RPN), recommended action, responsible area or person and Completion Date, action taken and Revised RPN.

Table 3 - Criteria for defining occurrence ranking

Occurrence	Rank	Criteria
Almost impossible	1	Failure unlikely. History shows no failures.
Remote	2	Rare number of failures likely.
Very Slight	3	Very few failures likely.
Slight	4	Few failures likely.
Low	5	Occasional number of failures likely.
Medium	6	Medium number of failures likely
Moderately high	7	Moderately high number of failures likely.
High	8	High number of failures likely.
Very high	9	Very high number of failures likely
Almost certain	10	Failure almost certain. History of failures exists from previous or similar designs

Table 4 - Criteria for defining detection ranking

Detection	Rank	Criteria
Almost certain	1	Has the highest effectiveness in each applicable category
Very high	2	Has very high effectiveness
High	3	Has high effectiveness
Moderately high	4	Has moderately high effectiveness
Medium	5	Has medium effectiveness
Low	6	Has low effectiveness
Slight	7	Has very low effectiveness
Very Slight	8	Has lowest effectiveness in each applicable category
Remote	9	Is unproven, or unreliable, or effectiveness is unknown
Almost impossible	10	No design technique available or known, and/or none is planned

The third part, although not mandatory, reflects the team's authority and responsibility to carry out the application of the FMEA and consists of the signatures of those responsible (STAMATIS, 2003).

For the case, the reference tables to indicate the severity of the effect (S), frequency of occurrence (O) and rate detection (D) followed the model indicated by Stamatis (2003).

9.2. Priority risks and mitigation strategies

The most critical failure modes, which therefore require priority corrective action, were: External HDD Storage; Extreme Weather Conditions; GPS Signal Issues; Power Supply Failure; Train Speed; Weight on the Train; Blind Spot on the Tracks; Train Heating.

Table 5 - Correlation between mode, effect and cause of failures (Full table in the attachment)

Potential Failure Mode	Potential Failure Effect	Potential Cause(s) of Failure	NPR
External HDD Storage	Data Loss	Equipment Damage	280
Extreme Weather Conditions	Damage to Internal Components	Inadequate Sealing	280
Extreme Weather Conditions	Reading Failure	Equipment Overheating	245
HDD Storage	No Recording of New Data	Full Storage	240
GPS Signal Issues	Total Loss or Inaccuracy in Location	Interferences (e.g., tunnel)	240
Power Supply Failure	Execution Failure of Reading	Discharged Battery	216
Train Speed	Inaccuracy in Failure Signature	Contact-wheel rail vibration may vary with speed	210
Weight on the Train	Inaccuracy in Failure Signature	Contact-wheel rail vibration may vary due to train weight	210
Blind Spot on the Tracks	Failure Not Detected	Specific points of the track	180
Train Heating	Equipment Damage	Train Heating	147
Extreme Weather Conditions	Reduced Lifespan	Humidity	140
Inadequate Fixation on the Train	Equipment Displacement or Detachment	Inadequate Fastening Design	126
HDD Storage	Loss of HDD	Human Error	84
Equipment Wear Due to Railway Conditions	Reading Failures	Low-Quality Components and Lack of Maintenance	80
Inadequate Performance of the Accelerometer	Inaccurate Readings	Manufacturing Defect	80
Electromagnetic Interference with Train Components	Reading Failures	Proximity to Other Electronic Devices	75
Defects in Adjacent Systems (Wheel, Ballast, Suspension)	Recording of Other Issues	Vibration may be caused by a defect in the train or ballast	70
Mismatch of Train Data with Equipment	Impairment to Data Analysis	Difficulty in the train-equipment interface	40
Power Supply	Restricted Time for Action	Battery Capacity	30
HDD Storage	Increase in Response Time	Data not sent remotely to a central system	20

The decision to use an external HD was motivated by the fact that the equipment is still in the development phase, leading to the adoption of the premise of employing simpler solutions to enable the use of the device and validate the solution. Four effects resulting from this limitation were identified: total loss of data, no new data being recorded, the possibility of losing the HD and an increase in response time. To correct such effects, it would be necessary to develop a remote data transmission system. However, since this system is not yet available, the option adopted was to carry out measurements directly from the train cabin under the supervision of a trained technician.

In relation to extreme weather conditions, potential effects have been identified that include damage to the equipment's internal components, data reading failures and possibly a reduction in the device's useful life. As an indicated measure, it was identified that it would be crucial to carry out an in-depth study of the materials currently available on the market, by conducting specific tests, in order to select appropriate materials that demonstrate adequate resistance and durability to face extreme climatic conditions. Due to the lack of resources to immediately carry out this study, as well as the priority given to validating the solution, an immediate corrective measure was chosen carrying out the measurements in a safe environment, specifically in the train cabin.

Another failure mode considered was the use of GPS to pinpoint the exact location of the fault, as its absence could compromise the monitoring of the problem. This vulnerability could lead to serious complications for the effectiveness of the solution. Therefore, the optimal approach involves calibrating the equipment and identifying possible interferences, followed by the development of solutions, such as support with Bluetooth-enabled devices, to minimize such impacts in specific locations, such as tunnels. As a temporary measure, it was decided to conduct controlled measurements outside of tunnels and in areas compatible with GPS signals, as a strategy to circumvent this momentary limitation.

Critical is also the power supply, as the device operates using a battery. This circumstance may result in the reading not being performed due to lack of charge in the battery and may also impose a restricted operating time for the equipment, limited by the energy capacity of the battery. The solution to correct this failure mode would be to connect the device directly to the train's electrical system, allowing a continuous supply of energy. However, this implementation is not yet viable at the current stage of development, as it would require additional advances in improving the equipment. Given this limitation, the measure was to carry out the measurements under the supervision of a trained technician, thus ensuring the feasibility of using the equipment in the current context.

Failure modes related to the weight and speed of the train were also assessed as critical, as they are components susceptible to variations that can impact the reading results. The solution found would be to conduct comprehensive measurements of track failures, taking into account different levels of degradation, as well as variations in train weights and speeds. These measurements provided substantial data to feed software capable of correlating failures in different operational situations. However, given the initial phase of the measurements, a controlled approach was adopted as a solution, carrying out the measurements at a specific speed and at specific time.

Inadequate detection of blind spots by the equipment, or even their identification, sometimes masking potential problems on the rails, constitutes a possible occurrence. This can occur, for example, when the train passes through a track switch. As a mitigating measure, it is urgent to find effective alternatives to monitor these locations. The identification of other blind spots may emerge throughout the solution development process, providing new opportunities to improve the equipment through in-depth analysis. In the current stage, focused exclusively on validating the use of the equipment, it was decided to exclude points known to be critical from the sample, such as track Switch, in order to ensure the integrity and reliability of the results obtained.

Another failure mode was the overheating of the train, susceptible to causing damage to the equipment, resulting in the loss of data and possible damage to its internal components. As a mitigation strategy, it would be necessary to carry out an individual study for each type of train, in order to identify the most appropriate and safe location for installing the equipment. Likewise, the analysis of the failure mode related to fixing on the train is crucial, since installation in certain locations can increase vulnerability to falls and detachments. In this context, in addition to site selection, it is necessary to develop a fixing system that minimizes this possibility. Simultaneously, when selecting a secure location for the installation of the equipment on the train, it is imperative to consider avoiding potential electromagnetic interferences. This aspect has been identified as another mode of failure that could compromise the proper functioning of the equipment and lead to reading failures. As an immediate measure, it was decided to carry out measurements directly from the cabin, under the supervision of a trained technician, while more lasting solutions are developed.

In relation to equipment wear resulting from railway conditions, the ideal approach is to carry out studies on materials that can minimize this effect, as well as establishing partnerships with high-quality suppliers and periodic maintenance. At the moment, the strategy adopted consists of taking measurements in a controlled environment, directly from the train cabin. Additionally, the quality of suppliers also plays a crucial role in preventing manufacturing defects in accelerometers, which can result in inaccuracies in readings, causing the "Inadequate Accelerometer Performance" failure mode. As a preventive measure, tests were carried out on the accelerometers before measurements began.

Lastly, it is important to consider the potential impact on the interface between the train and the equipment, due to compatibility issues between the train's operating system and the data interpretation software. This could lead to inconsistencies in the analyses. However, since this failure mode does not have the potential to cause errors in the equipment's readings, it has been classified as low-critical in this development phase, with the potential to become more significant in subsequent stages.

10. PROJECT PLAN/ IMPLEMENTATION PLAN

Modern management practices have demonstrated that each hour spent on planning is equivalent to around ten hours saved during execution. Therefore, the Track Viewer project team sought to look in detail at each planning topic, as will be seen below.

In terms of schedule, the following steps are being followed, inspired by the V-Model technique for developing solutions. Further details of the schedule will be seen in the following chapter (Financial Plan):

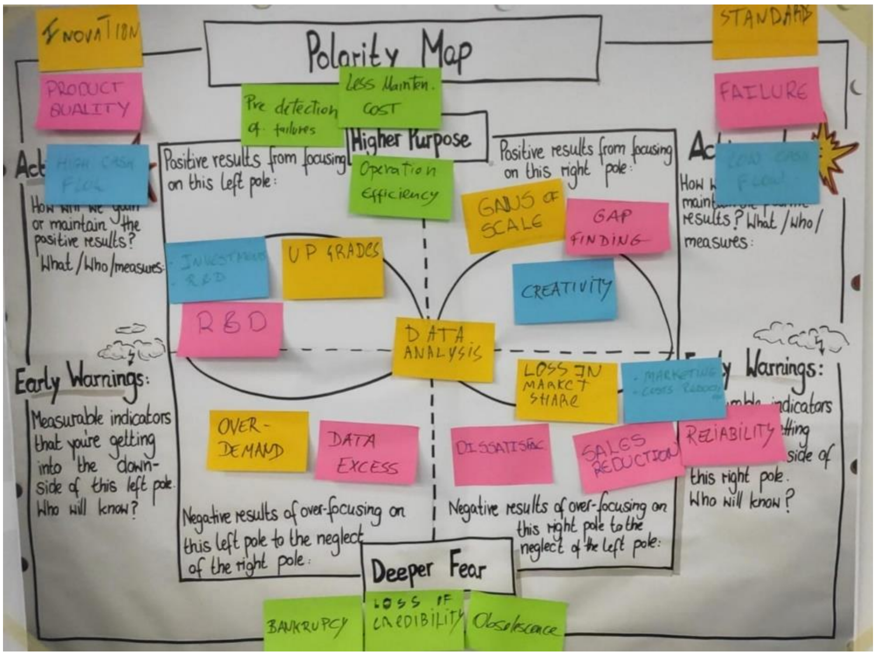
- Concept - Set/23
- Business Model - Out/23
- Risk and Requirements Analysis - Nov/23
- Modeling and Tests - Dez/23
- Settings and Acceptance - Jan/24
- Open Line Scanning - Mar/24
- Tunnel Line Scanning - Jun/24
- Transmission Data Improvement - Set/24
- Metro-DF Year Data Report - Dez/24
- Brazilian Market Expansion - Mar/25

A planning technique presented in Module 7 (Management & Leadership) and selected to refine the project design was the Polarity Map (see photo below). As is known, the polarity map planning technique is a visual tool for dealing with complex and costly problems, which involve opposing factors or poles that influence each other.

It is a technique especially applied to problems that do not have a single right answer, but rather polarities that need to be balanced. Trying to resolve these polarities as if they were problems can lead to unnecessary conflicts, but the benefits and disadvantages of each pole must be recognized, looking for a way to make the best of both, minimizing the risks.

A polarity map is a diagram that shows the two poles, the benefits of each, the problems of focusing on one pole and neglecting the other, and the actions that can be taken to maintain balance. The polarity map helps facilitate debates on complex topics and create a shared vision and strategy for dealing with them.

Image 8 - Polarity Map of Track Viewer Project



Source: Track Viewer team.

In the case of the Track Viewer project, the main purposes identified were: Operational Efficiency (greater availability and comfort for the user), Prior identification of defects on the tracks and consequent reduction in maintenance costs. On the other hand, the project's main fears are: Loss of credibility (due to data inaccuracy or diagnostic inefficiency), Obsolescence (with the advent of a cheaper and more accurate failure detection technique) and Bankruptcy of the startup (due to a problem in the financing of costs or non-adherence of customers).

Reflecting on the poles "High Cash Flow" versus "Low Cash Flow", it is clear that, on the one hand, relevant investments in research and development can be made when in the first scenario, creative and low-cost alternatives, in addition to expense reductions and marketing solutions need to be taken in a second scenario.

Here, it is understood that this is a plausible polarization, but not very likely, as the Track Viewer is a solution that requires low capital for implementation.

Moving on to the "Innovation" versus "Standardization" polarization, successive upgrades and diverse user demands may appear in the first scenario, while scale gains is the main characteristic of the second scenario (even with the risk of loss of market in case of a very rigid solution). The "data analysis" service appears in both scenarios, but in a creative form and with personalized reports in the case of the first and standardized and poorly formatted information in the case of the second.

The "high quality product" versus "dysfunctional product" polarization brings new research and developments in addition to a good amount of data (perhaps excessive) in the first scenario, while user dissatisfaction, loss of reliability and reduced sales may occur (with an immediate search for the causes of problems and their solutions) in a second scenario. At this point, the urgency for the data generated by the tool to be robust and highly reliable is inferred.

Based on the analyzes and plans described previously, it was possible to develop a SWOT matrix for the Track Viewer project - this technique was also presented in Module 7 (Management & Leadership). Among the benefits of using this technique are: a better understanding of the scenario in which the product is inserted, the identification of internal characteristics of the team to be improved or reinforced, the addressing of improvements based on comparison with other solutions and preparation of the product for any future adverse scenarios that may occur.

Among the STRENGTHS that the Track Viewer presents, we can list: the early automated identification of track defects, the low cost of the solution for the company (as it is embedded hardware and requires little investment for installation) and the reduction operational costs with maintenance and inspection teams in addition to increasing the useful life of track materials (with improved predictive maintenance).

On the WEAKNESSES side, one can identify: the potential difficulty for the equipment to reach the necessary precision to correctly identify the different types of failure, the possible loss of data if it is not possible to implement the online transmission of the collected information (which may make it infeasible the tool for longer readings) and the failure to position the equipment in a suitable location on the train to correctly identify track defects (for prototype purposes, the Track Viewer was positioned in the conductor's cabin; however, it is understood that a reading more refined can be achieved by positioning the tool on the car's truck, for example - regardless of possible displacements and vibrations in that location).

Moving on to the OPPORTUNITIES, we can list the scenario of expansion of the Brazilian railway network with private concessions and public investments planned for the coming years (an on-board and accessible solution could greatly contribute to the operation of these routes); according to the research mentioned in chapter 5.a, the Track Viewer would create an unexplored market niche for track monitoring technologies (this factor could be crucial for the dissemination of the system among companies operating in the country); Once the aforementioned data transmission issue was resolved, the system could be used both by companies that operate urban trains and by cargo companies that operate on continental networks.

Coming to THREATS, it should be mentioned the existence of market solutions that already monitor tracks (even if they are technologies that use large equipment and much more expensive processes), add the fact that the equipment can have its functionalities copied by a competing developer who wants to compete in the market with the proposed solution (which could be combated with the development of specific functionalities that differentiate the prototype), the regulatory risk (not present today) can also be brought to the fore, which can bring limits or specificities for this type of reading and which could, at the limit, harm or even make the product unviable.

With the planning analysis carried out and a consistent plan of steps to follow, an additional work technique can be adopted to seek continuous improvement of the product. After collecting and verifying the first data, the team will carry out a PDCA cycle (Plan, Do, Check, Act) in order to refine the results and work on improving the prototype. With the rollout of the improved version of the Track Viewer, a new PDCA cycle will be carried out and so on until the equipment matures with the production of consistent and satisfactory data.

The expectation is that the PDCA cycle can definitely contribute to increasing the project's added value by being based on data-based decision making, by providing the system's adaptability to the diversity of conditions on the Metro-DF track, by the incremental search for quality and productivity of the data produced, in addition to innovation based on the team's discussion around concrete problems in search of building a specific solution that is difficult to reproduce by potential competitors.

In this sense, feedback from the operational staff responsible for visual inspection of Metrô-DF track will be essential: the idea is to integrate practical knowledge into the automated solution in search of the precise identification of defects and problems on the track. By crossing referencing the information produced by the Track Viewer with the reports prepared by the visual inspection team, it will be possible to add even more improvements to the system up to the point of complete identification of points of interest for the product. Therefore, bimonthly meetings will be scheduled between the project team and the road maintenance team with the aim of seeking to align information and exchange experiences.

From this stage, it will be possible to draw an accurate map of track defect information, monitor the evolution of problems over time and eventually predict the emergence of new defects on tracks after solving problems already identified. With such data in hand, Metrô-DF will be able to understand recurring problems and design improvements in order to increase the useful life of materials (through adjustments in the route or adjustments in operating speed, for example), not to mention the potential reduction maintenance costs due to better predictability.

11. FINANCIAL PLAN

FINANCIAL PHYSICAL SCHEDULE (X 1.000,00 Reais)

EXECUTION PHASES		Sept/23	Oct/23	Nov/23	Dec/23	Jan/24	Feb/24	Mar/24	Apr/24	May/24	June/24	July/24	Aug/24	Sept/24	Oct/24	Nov/24	Dec/24	Jan/25	Feb/25	Mar/25
Concept	Execution																			
	Expenses for materials/equipments	5																		
	Labor expenses (6 analysts)	150																		
Business Model	Execution																			
	Expenses for materials/equipments		2																	
	Labor expenses (6 analysts)		150																	
Risk and Requirements Analysis	Execution																			
	Expenses for materials/equipments			2																
	Labor expenses (2 analysts)			50																
Modeling and Tests	Execution																			
	Expenses for materials/equipments				5															
	Labor expenses (2 analysts)				50															
Settings and Acceptance	Execution																			
	Expenses for materials/equipments					5	5													
	Labor expenses (2 analysts)					50	50													
Open Line Scanning	Execution																			
	Expenses for materials/equipments							2	2	2										
	Labor expenses (4 analysts)							100	100	100										
Tunnel Line Scanning	Execution																			
	Expenses for materials/equipments										2	2	2							
	Labor expenses (4 analysts)										100	100	100							
Transmission Data Improvement	Execution																			
	Expenses for materials/equipments													5	5	5				
	Labor expenses (3 analysts)													75	75	75				
Metro-DF Year Data Report	Execution																			
	Expenses for materials/equipments																2	2	2	
	Labor expenses (6 analysts)																150	150	150	
Brazilian Market Expansion	Execution																			
	Expenses for materials/equipments																			50
	Labor expenses (6 analysts)																			150
MONTHLY FINANCIAL DISBURSEMENT (X R$ 1.000,00)		155	152	52	55	55	55	102	102	102	102	102	102	80	80	80	152	152	152	200
ACCUMULATED FINANCIAL DISBURSEMENT (X R$ 1.000,00)		155	307	359	414	469	524	626	728	830	932	1.034	1.136	1.216	1.296	1.376	1.528	1.680	1.832	2.032

Obs.: R$ 25.000,00 - Average monthly salary per Analyst.

12. ATTACHMENT

Potential failure mode and effects analysis (design FMEA)															
Design function	Potential failure mode	Potential effect(s) of failure	S	Causes	O	Current process controls	D	NPR	Recommended action	Action taken	S	O	D	NPR
Identifying rail faults through the reading of vibrations generated by wheel-rail contact.	External HDD Storage	Data Loss	8	Equipment Damage	5	Watertight box	7	280	Remote Data Transmission System	Conducting measurements inside the train cabin with monitoring	1	1	1	1
	Extreme Weather Conditions	Damage to Internal Components	8	Inadequate Sealing	5	Watertight box	7	280	Acquisition of suitable materials	Conducting measurements inside the train cabin with monitoring	1	1	1	1
	Extreme Weather Conditions	Reading Failure	7	Equipment Overheating	5	Acquisition of suitable materials	7	245	Acquisition of suitable materials	Conducting measurements inside the train cabin with monitoring	1	1	1	1
	HDD Storage	No Recording of New Data	8	Full Storage	6	Reduced operation	5	240	Remote Data Transmission System	Conducting measurements inside the train cabin with monitoring	1	1	1	1
	GPS Signal Issues	Total Loss or Inaccuracy in Location	8	Interferences (e.g., tunnel)	6	Data Checking	5	240	Using complementary equipment	Measurements with monitoring	1	1	1	1
	Power Supply Failure	Execution Failure of Reading	8	Discharged Battery	9	Reduced operation	3	216	Using the train's electrical power	Measurements with monitoring	1	7	1	7
	Train Speed	Inaccuracy in Failure Signature	3	Contact-wheel rail vibration may vary with speed	10	Controlled operation	7	210	Include in the software the data at different speeds	Measurements with monitoring	1	7	1	7
	Weight on the Train	Inaccuracy in Failure Signature	3	Contact-wheel rail vibration may vary due to train weight	10	Controlled operation	7	210	Including in the software failure data with different weights	Measurements with monitoring	1	1	1	1
	Blind Spot on the Tracks	Failure Not Detected	2	Specific points of the track	9	Reduced operation	10	180	Manual and periodic inspection only at these locations	Limiting the analysis	1	1	1	1
	Equipment overheating	Equipment Damage	7	Train Heating	3	Secure Installation	7	147	Secure Installation	Conducting measurements inside the train cabin with monitoring	1	1	1	1
	Extreme Weather Conditions	Reduction in equipment life expectancy	4	Humidity	5	watertight box	7	140	Acquisition of suitable materials	Conducting measurements inside the train cabin with monitoring	1	2	1	2
	Inadequate Fixation on the Train	Equipment Displacement or Detachment	9	Inadequate Fastening Design	2	Controlled operation	7	126	Developing a fixation system for the equipmen	Conducting measurements inside the train cabin with monitoring	1	2	1	2
	HDD Storage	Loss of HDD	7	Human Error	4	Follow the procedure	3	84	Follow the procedure	Follow the procedure	1	1	1	1
	Equipment Wear Due to Railway Conditions	Reduction in equipment life expectancy	4	Low-Quality Components and Lack of Maintenance	4	Monitoring	5	80	Acquisition of suitable materials	Test components	1	1	1	1
	Inadequate Performance of the Accelerometer	Inaccurate Readings	8	Manufacturing Defect	2	Test	5	80	Good suppliers	Measurements with monitoring	1	1	1	1
	Electromagnetic Interference with Train Components	Inaccurate Readings	5	Proximity to other electronic devices	3	Installation in a secure location	5	75	Installation in a secure location	Conducting measurements inside the train cabin with monitoring	1	2	1	2
	Defects in Adjacent Systems (Wheel, Ballast, Suspension)	Detection of issues beyond the tracks	2	Vibration may be caused by a defect in the train or ballast	7	Controlled operation	5	70	Enhance the equipment	Measurements with monitoring	1	2	1	2
	Mismatch of Train Data with Equipment	Impairment to Data Analysis	2	Difficulty in the train-equipment interface	4	Limited analysis	5	40	Enhance the data interpretation software	Limiting the analysis	1	2	1	2
	Power Supply	Restricted Time for Action	3	Battery Capacity	10	Reduced operation	1	30	Using the train's electrical power	Measurements with monitoring	1	1	1	1
	HDD Storage	Increase in Response Time	2	Data not sent remotely to a central system	10	Limited analysis	1	20	Remote Data Transmission System	Limiting the analysis	1	1	1	1
Product: Track View Equipment						Design Responsability: Track View Team				FMEA date: 27 nov. 2023.				
Type of FMEA: Design FMEA						Involvement of others: METRÔ-DF Maintenance Team				FMEA revision date: 01 dez. 2023				
Prepared by: Dalmo; Luciano; Nathalia; Roberto; Slany; Tomás														

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