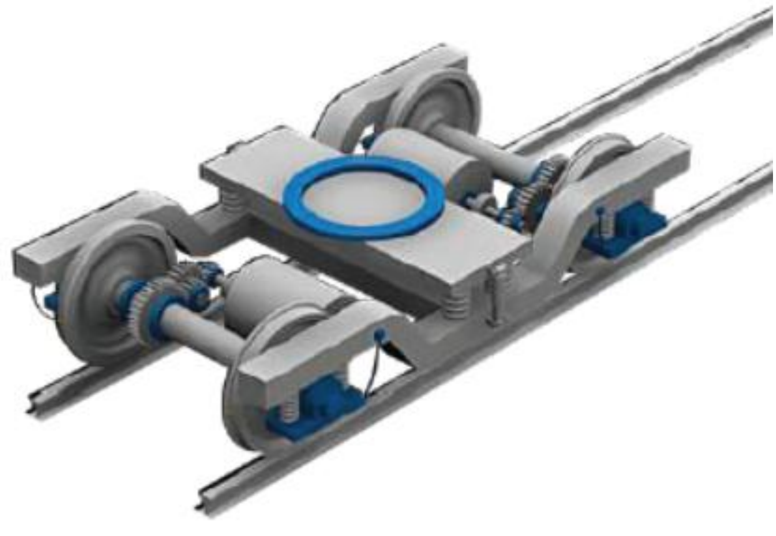
Internship

Mechanical Engineering

Description of 3 RET Metro Wheel Set Components. Multicriteria Analysis of the failures of these components

REPORT



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Preface

From 18th September to 22nd December 2017 I have performed an internship at RET consisting in the description of 3 metro wheels set components and a multicriteria analysis of the failures of these. The 3 month internship has been performed with a 36 hour per week policy, which includes working from Monday to Thursday from 8:30am until 5pm, and Friday from 8:30am until 1pm. The starting and ending hours have been flexible all along the period.

The internship has been performed at the central office of RET, situated in Laan op Zuid 2, in Rotterdam. This means that during this period I have lived in this great cosmopolitan city of South Holland and the experience has not only been professional but also fulfilling as a lifestyle. As well as this, RET is the main public transport company of Rotterdam, what means that it is has a lot of workplaces and employees. This has enabled me to visit many workshops, for tram and metro mainly and to investigate properly my research goals. Moreover, during the internship I have had the possibility to visit other related companies such as Stork or HTM and also keep contact with NS maintenance employers, between others.

My main tutor at RET, with whom I have had periodical meetings is Leo Koot, the main mechanical engineer of the fleet management department. As well as this, Karwan Hamamurad, also technical specialist at this department, has been keeping track and giving advice during the whole internship. Both of them have helped all along the three months and making my work easier. As well as these, the rest of colleagues from the department have been willing to help me all the time and also considered me as a part of their team, fact which I thank a lot.

Summary

This internship has three main parts. The description of the three studied elements of the bogie, a multicriteria analysis of the failures regarding these components and an advice on possible solutions or improvements to reduce the impact of these failures.

In the description a general overview of bogies at RET is given and the three components and its failures are described. The primary suspensions, the oil dampers and the flexible coupling are the three described components. The primary suspension has 2 main failures which are the rubber shrinking and the rubber getting loose, the oil damper has a main failure which consists of the oil leakage and the failure studied for the flexible coupling is the cracking of the elastic rubber element.

The second part consists of a multicriteria analysis which compares the 4 mentioned failures according to 9 main criteria which are: the costs associated to failure, the downtime due to failure, the safety , the lead time for receiving new parts, the maintenance of each component, the predictability of failure, the frequency, the damage caused and the monitoring possibilities. To do this analysis a strict process is followed and the results are analysed accordingly. Defining criteria, performing a qualitative analysis, scaling criteria and giving relative importance to them and making a quantitative analysis are the 4 main steps in the process of arriving to a numerical result for the multicriteria analysis.

The last part consists on giving advice and solution to the main problems that each component faces due to according to the analysis and advice on a possible solution or further research option. In the case of the primary suspension, a condition monitoring system can be considered, for the oil dampers a change in replacement conditions can be applied and for the cracking rubber elements of the coupling modifying the maintenance actions is an option.

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Introduction

Company description: RET

RET is the public transport company of the Rotterdam city region. The company is based in Rotterdam and it provides public transport, which includes bus, tram, metro and a boat. RET has 59 bus routes, 5 metro lines, 10 tram lines and a ferry service. The perfect condition of the infrastructure and vehicles is ensured by several departments which are: the Engineering offices; Fleet Services; Fleet management; Infrastructure management; Infrastructure services. Employees of these departments are in charge of performing all repair and maintenance works, including preventive maintenance. They also play a key role in new constructions and replacements.

Introduction to the subject

The maintenance policy for metros currently applied at RET is of preventive maintenance. One of the most critical assemblies are the bogies (wheel sets). Currently, these sets are revised 2 times during their 30 years' service life. However, when performing this intervention it is not clear if some of the components must be replaced or they can last more years. The objective of RET is to investigate the possibility and feasibility of applying a predictive maintenance concept that enables a just in time maintenance of these bogies. To do so, a previous study regarding failures of most critical parts must be done and conclusions concerning the possibility of applying predictive maintenance can be extracted.

Objectives

There are 4 main objectives to be achieved in the present document.

First of all, an insight of RET and a general overview of the metro bogies is intended. Before starting to analyse deeply the bogie components, it is necessary to have an overview of all the fleet a RET and to have knowledge of all the components of the metro bogie itself. All general information will help to make a better analysis of specific components.

Secondly, an analysis of 3 specific components of the metro bogie is performed. This 3 components are chosen due to the fact that currently these are the parts that fail before expected and are causing more problems to RET. The **primary suspension**, the horizontal and vertical **shock absorber dampers** and the **flexible coupling** are the 3 conflictive components. This analysis includes: a technical description; an analysis and description of the current component failures; maintenance tasks currently performed and time slots for them.

Moreover, having all the information mentioned, a **multicriteria analysis** of the failures is performed. The goal of this analysis is to decide which of the current failures of the three components is more relevant and critical to prevent or mitigate according to RET interests and to relevant criteria. All the criteria are defined and a comparison of all components failures according to these is made. All the parameters will be quantified so that the comparison is more reliable and clear. This enables to arrive to the conclusion of which of the components and which failure is the most critical and thus the one that should be solved preferably.

Finally, the last intention of this research is to **give advice on possible solutions** to the failures, based on the multicriteria analysis it is possible to give suggestions of further investigation possibilities and also of solutions to some of the failure problems of the three components.

Bogie general information

General overview

The bogie is one of the subassemblies which form the metro. It is the wheel set and thus it is the connection between the metro body and the railway. In annex 1, pictures of the bogies are provided..

In figure 1 it is observed the main systems and assemblies that form the metro, and also the main components that are part of the bogie. As well as this the diagram points out the three bogie components in which this report focuses.

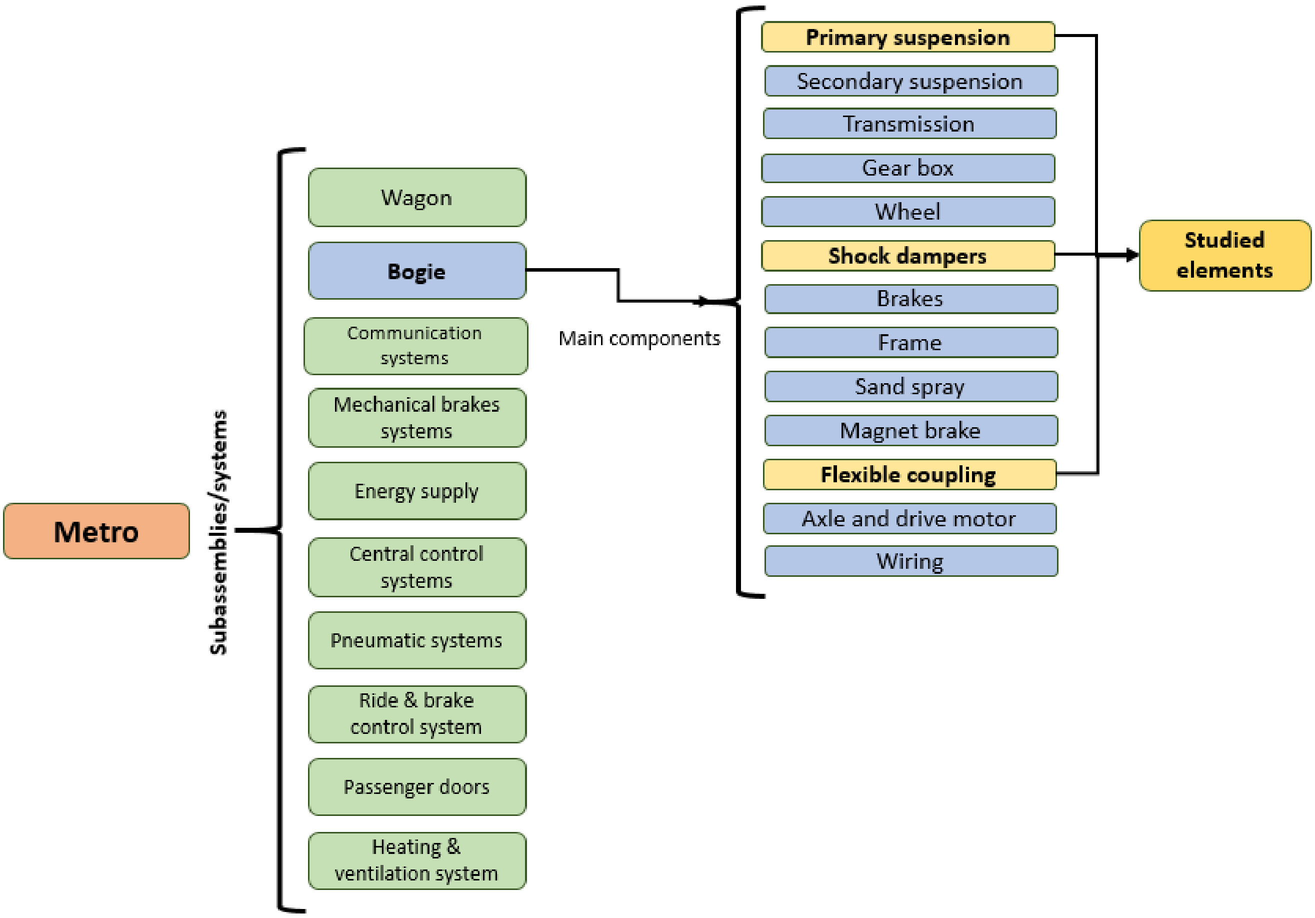


Figure 1: Main systems and assemblies of metro

At RET, there are 167 metro vehicles currently operative and there are 5 types of metro types. From these, there are two types which have identical properties and three other types which have also identical technical conditions, as shown in figure 2.

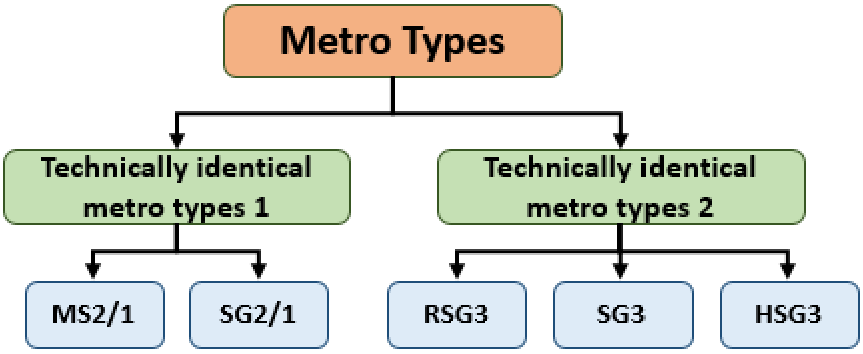


Figure 2: Metro types at RET

The metro types MS2/1 and SG2/1 are the old ones and they were issued from year 1999 until 2002, while the metro types RSG3, SG3 and HSG3 are newer. RSG3 metros were issued from 2007 to 2009, the SG3 from 2009 to 2012 and the HSG3 from 2015 until 2017.
Thus, there are a lot of bogies to be maintained and kept in good working conditions as it is crucial part of the vehicle. In the table 1, the types of vehicle at RET and the number of bogies are shown.

	n° of vehicles	Bogies per vehicle	Bogies per vehicle type
Identical **Type 1**: MG2/1 & SG2/1	81	3	243
Spare Bogies Type 1	-	-	7
Identical **Type 2**: RSG3, SG3, HSG3	86	4	344
Spare bogies Type 2	-	-	22
Total	**196**		**616**

Table 1: Bogies at RET

As seen, there are 616 bogies at RET, only including in this case the Metro wheel sets, without considering also the tram facilities.

3 main components to be analysed

As said in the objectives of the document, 3 of the components are the main focus of this assignment and these are the ones to be analysed and compared before determining the most critical one. These components are the following ones.

- Primary suspension
- Flexible Coupling
- Dampers (both horizontal and vertical)

The failure analysis of these 3 components will be performed in order to decide which one of these is the most critical one.

These three components are currently causing a lot of problems to RET and consequently are the most important ones to study due to several reasons.

The primary suspensions are failing before the expected dates. In 2014, nearly 70% of all primary suspensions were working out of specification limits [2] and thus an intervention was made to solve this problem. The height had to be adjusted to go back to the service the accepted level. Of course, driving all the fleet with failed suspensions is too risky, dangerous and also really expensive to solve. As well as this, this problem is currently happening in a lot of railway companies and the willingness of extending the lifetime of these suspensions is really high, helping to reduce maintenance costs considerably and making easier the maintenance.

The shock absorber dampers, both horizontal and vertical are also causing a lot of trouble regarding the oil leakage failure. This current problem is difficult to detect and thus the maintenance actions are not clear. It is necessary to study if it is cost effective to look into the detection of this problem or keeping the current maintenance policy.

For the flexible coupling, the main problem is also the high amount of failures before expected. This is consequently also a part which must be studied, to investigate how critical the failure of the flexible coupling can be for RET and if it is worthy to solve this problem.

It is evident that the three components have two main common problems. Firstly, all fail often and earlier than the expected lifetime. Secondly, the impact and criticality of these failures is not clearly known and thus, it is necessary to make a deeper analysis to determine how critical each of these are for RET and to know which failures are worth to solve, by applying other maintenance policies, predictive maintenance or other solutions.

Primary suspension

Description

There are 8 primary suspensions per bogie (figure 5). The primary suspension is a rubber and steal type. It is formed by rubber positioned in a conical way and thin steal cones introduced in between this rubber. The conical form allows to absorb both horizontal and vertical vibrations. In figure 3 we can observe a photograph of the primary suspension.

Figure 3: Primary suspension

The primary suspension connects the axle box to the bogie frame. Its function is to mitigate the vibrations and forces. It reacts to the vertical jounce and loads that arise longitudinally and laterally from the influence of the rail track (and wheel) on the vehicle body.

In figure 4, the parts of the primary suspension are shown. In figure 5, the location of all 8 primary suspensions in the bogie is showed.

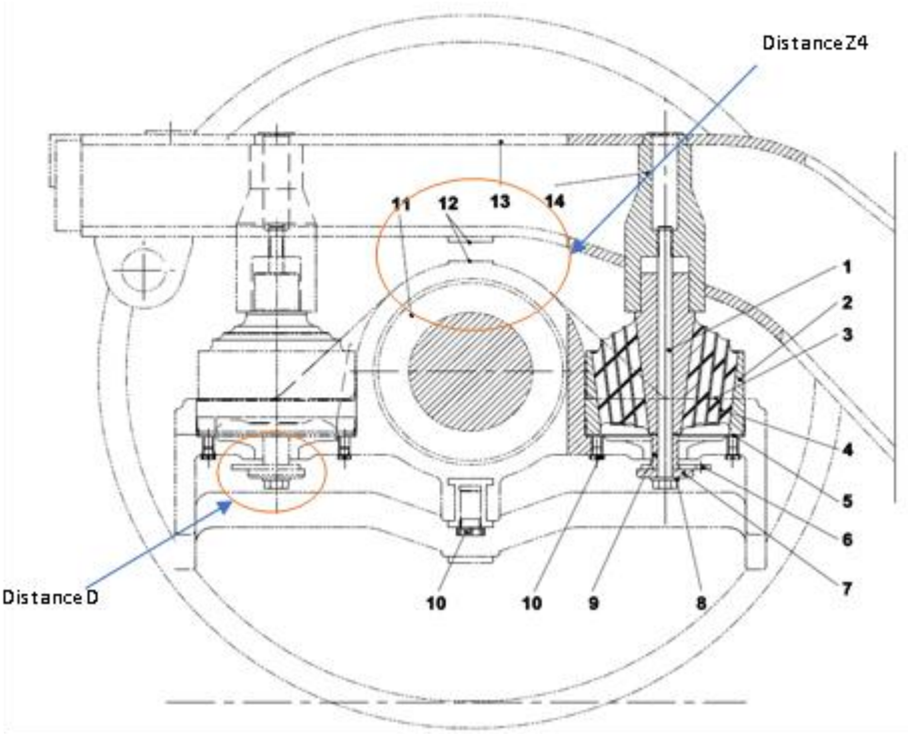


Figure 4: Distances D and Z4

1	Central hexagonal bolt	8	Washer
2	spring element	9	Element
3	Rubber	10	Plastic closure cap
4	Metal cone	11	Axle box (shaft)
5	Height setting ring	12	Stop Surface
6	Ring for protection in case of unloaded bogie	13	Frame
7	Stop for height limit	14	Spring retainer

Table 2: primary suspension parts

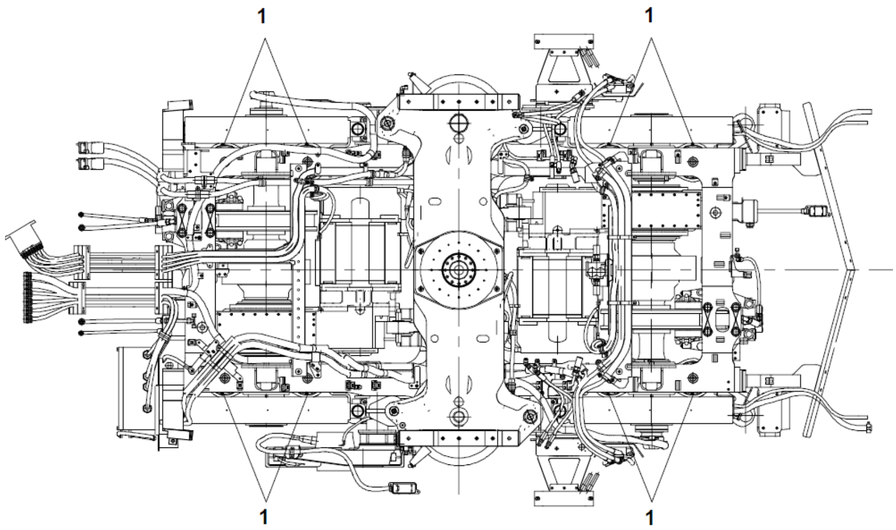


Figure 5: Location of primary suspension in Bogie

Failures

There are two main failures which have currently been observed in the primary suspensions. These are the non-expected early shrinking of the rubber and the rubber getting loose due to unknown reasons.

Rubber shrinking

The rubber positioned conically in between is shrinking quicker than expected. The actual expectation is to last 10 years but it is actually lasting only 6 or 7 years actually, for unknown reason. The shrinking pattern of the rubber is measured with distance D_1 and D_2 showed in figure 6. **When the rubber shrinks, this distance is enlarged**. The average distance **D is** calculated as the average of D_1 and D_2 as:

$$D = \frac{D_1 + D_2}{2}$$

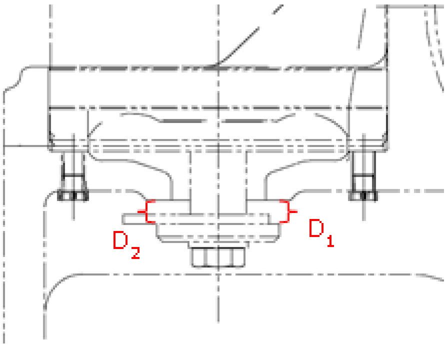


Figure 6: distance D

In **table 3 and** figure **7 it is observed the expected distances D,** thus, the expected shrinking pattern of the rubber.

	Distance D (mm)
New suspension	$6^{\pm 1,5}$
After 1 day	$9^{\pm 1,5}$
After 10 days	$10^{\pm 1,5}$
After 10 years	$12^{\pm 1,5}$

Table 3: expected distances D

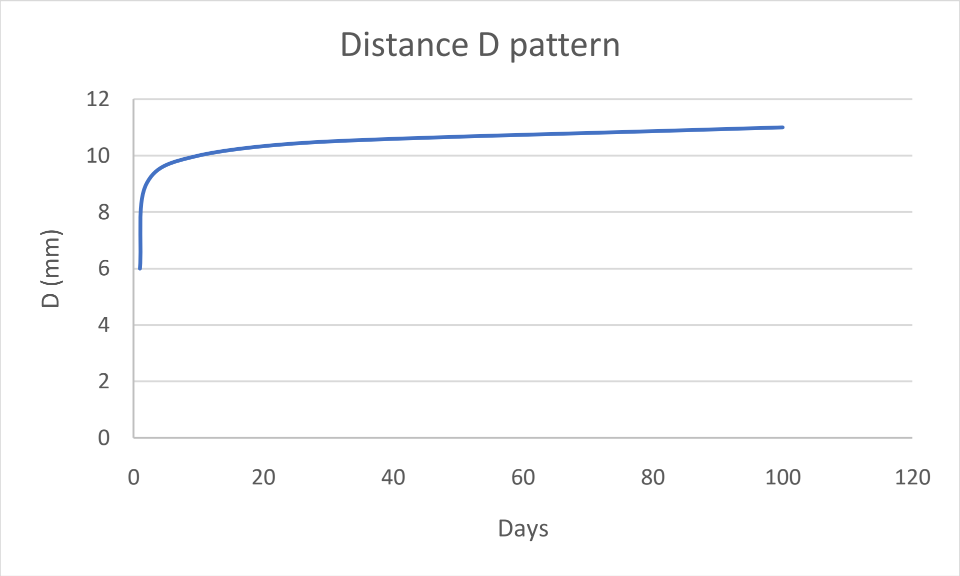


Figure 7: Distance D pattern

As seen, when the rubber is new, the distance D is enlarged really quickly, while after the first 10 days it is stabilized and shrinks really slowly. The idea is to last 10 years before we have to change the suspension, however, it is seen in the actual bogies that this pattern is not followed and the limits are surpassed in only 5 or 6 years, which is earlier than expected.

To control the rubber shrinking problem measure, it is possible to measure another distance which is associated to the primary suspensions condition. This is distance Z4, shown in figure 8 . This distance is the distance between the frame and the stop surface. Obviously these cannot touch each other as that means that the primary suspensions are in really bad condition.

Figure 8: distance Z4

Of course, as the rubber shrinks more during its lifetime, the distance Z4 **decreases,** contrary to the distance D explained previously. If this distance, Z4, is lower than 18mm, then the primary suspensions must be replaced as the working condition is harmful and unsafe.

Finally, there is another way of measuring the condition of the primary suspension. This measurement is done with a special tool depending on the type of bogie measured. The distance (H1) indicates the relative position of the massive shaft to the top surface. Thus, if the distance H1 is too low or too high it means that the top limiting surface and the massive shaft are too close and there is risk of contact. In the figure 9 we can observe the mentioned distance H1. As said, the obtained value depends on the tool used for the bogie type. For bogies in vehicles MG2-1 and SG2-1 the accepted distance is of 165,5 to 167,5mm, and for SG3 and RSG3 bogies the accepted distance goes from 211 until 219mm.

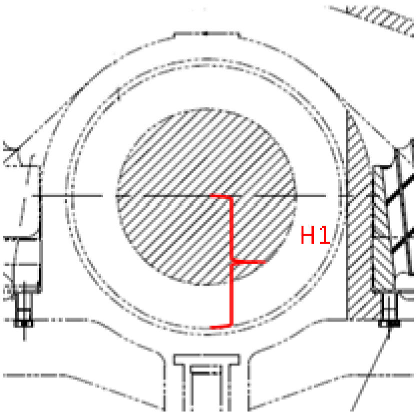


Figure 9: Distance H1

Thus, to be inside the acceptable conditions the requirements to be fulfilled are the following[2]:

1. if Z4 is smaller than 18 mm all springs of the bogie have to be replaced.
2. If Z4 left and Z4 right differ more than 2 mm, all springs of the bogie have to be replaced.
3. If the deviation of one of the distances D explained is significant, all the springs of the bogie must be replaced. A difference of 2 mm belonging together is the limit.
4. The distance H1 must be inside the limits: 166,5±1mm for old bogies; 217+2/-7 for new bogies.

All these conditions must be fulfilled to consider that the primary suspension are working properly and no risks are derived from it. Obviously there is relation between the distances so if one is wrong, probably the others are also not fulfilled.

Actual solutions

When the rubber shrinks, the distance between the top limiting surface and the shaft changes. In figure 6 we can observe the relative positions of the shaft with the top surface attached to the primary suspension. It is considered that no extra load apart from the wagon weight is applied to the bogie. Thus, it the goal is to avoid the left case of the three images in figure *10*, that is why the distance is readjusted in order to keep the standard distance as the right image in figure 10. In this case, when there is extra load and a lot of people enter the wagon, there is no chance that the shaft touches the bottom part of the surface.

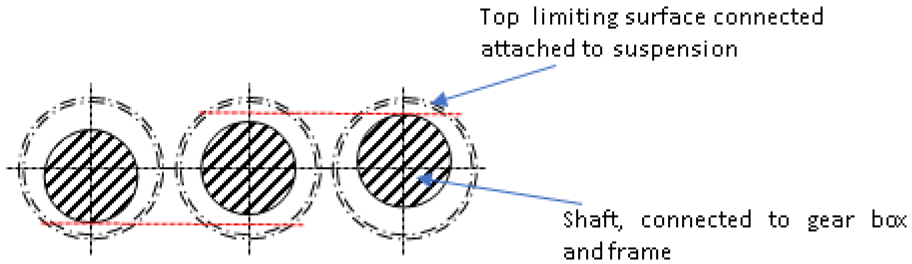


Figure 10: On the left, non-desirable position, the middle image shows the ideal situation, the right picture shows the position of the shaft without extra load other than wagon weight

In order to compensate and readjust this change there are currently 3 solutions.

1. Steel ring piece block at the bottom of the suspension

One of ways of adjusting the distance D so that it is within limits is to introduce a steel ring block at the bottom of the suspension. This action reduces the distance D (figure 6), meaning that if this steel ring is thicker, then the distance between the shaft and the top limiting surface connected to the suspensions is decreased on the top. In this case what is modified is the height of the suspension and the surface limit attached to it. In figure 11 the position of this piece is showed.

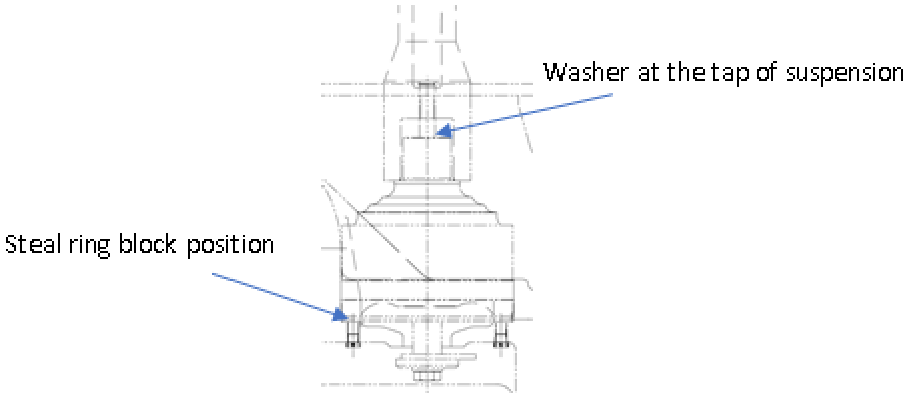


Figure 11: Position of pieces

This solution is easy to implement as the amount of work to do regarding dismounting is really low. However, in the last years, due to the fact that this piece has not been lubricated with anticorrosive material, it has been corroded causing problems. Thus, it is necessary to use lubricant next time new steel pieces are used.

2. Washer on the tap of the suspension

The alternative of putting a washer at the tap of the suspension has exactly the same effect that the one of introducing a steel ring block at the bottom. It decreases distance D (figure 4) and decreases the distance between the shaft and the top limiting surface connected to the suspension. In figure 11 shown previously the position of this washer is also indicated.

However, although it is a good solution because it is implemented currently using anticorrosive lubricants, it is tougher to perform due to the amount of work related to the change of washer. Dismounting the bogie and introducing a new ring to adjust the weight involves more work than putting the steel piece at the bottom.

3. <u>Washer in the mounting points of gearbox with the bogie</u>

This is the different method, which instead of modifying the height of the limiting surface it modifies the height of the gearbox, which is obviously linked to the shaft and the flexible coupling. There are 3 points where the gearbox is mounted to the bogie, showed in figure 12.

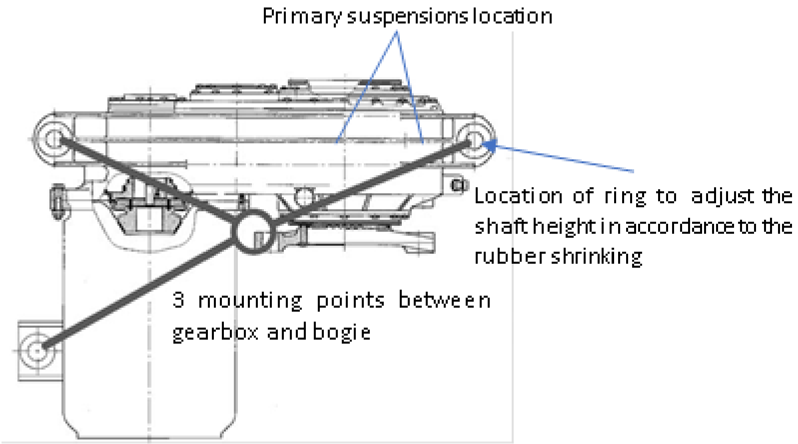
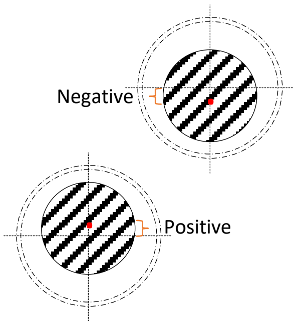


Figure 12 the 3 mounting points for gearbox and bogie, location of height ring, 2 primary suspensions location

The adjustment of the shaft height is performed in one of the mounting positions, also indicated in figure 12. According to the thickness of the ring introduced, there is a different compensation of height of the shaft with respect to the centre. In table 4 we can observe the equivalent relation of thickness of rings with the height of the shaft. As observed, as thicker the ring, the distance from the shaft to the bottom limit surface decreases. Beside the table 4, figure shows the position of the shaft depending if the compensation is negative or positive.

Ring thickness (mm)	**Equivalent height compensation of shaft (mm)**
19.5	-2,6
18	-1,5
16	0
15	0,7
14	1,6
13	2,1
12	2,8

Table 4: Relation of ring thickness to height compensation



Shaft position depending on compensation height

This alternative to changing the height of suspensions is also easily implemented but has a limit, as the procedure is to make the ring smaller each time, and at one point the ring cannot be less thick anymore, so it is limited to a compensation of 2,8mm maximum and a minimum thickness of the ring of 12mm.

The three methods to solve the rubber shrinking failure are have been used but are not sufficient to avoid the fact that after the 6/7 years of the 10 expected years of life the suspensions must be changed anyway. The adjustment of heights, with any of the three methods has its limits and if the rubber shrinks more than this limit, there is no way to solve it, so it is important to investigate this failure, why it happens, and if it is possible to prevent or monitor.

Rubber loose and cracked

Another problem observed in the primary suspension is the unknown reason of why the rubber gets loose. This means that its effect is partially or completely lost as it tends to go out of place and is not properly fixed. In figure 13 we observe an example of a loose rubber in an the inner ring of the suspension.

Figure 13: Rubber loose in Primary suspension

Actual solutions

For the actual problem of the rubber getting loose and cracked there are no current solutions. This problem which has appeared currently has no actual solution, thus it is important to research on the reasons why the rubber gets loose and to see if it is possible to prevent from occurring.

Differing from the rubber shrinking, which is a more visible and detectable failure, this failure is also not visible until the rubber is completely loose. From the outside no apparent fail is observed and therefore it is difficult to prevent. Now that it is known, it is possible to look for solutions.

Dampers (vertical and horizontal)

Description

The main goal of oil dampers is absorb quick movement vibrations or shocks. There are 2 vertical dampers and on horizontal damper in the bogie. In figure 14 both dampers are observed.

Figure 14: horizontal damper & Vertical damper

In figure 15 the position of all dampers is observed.

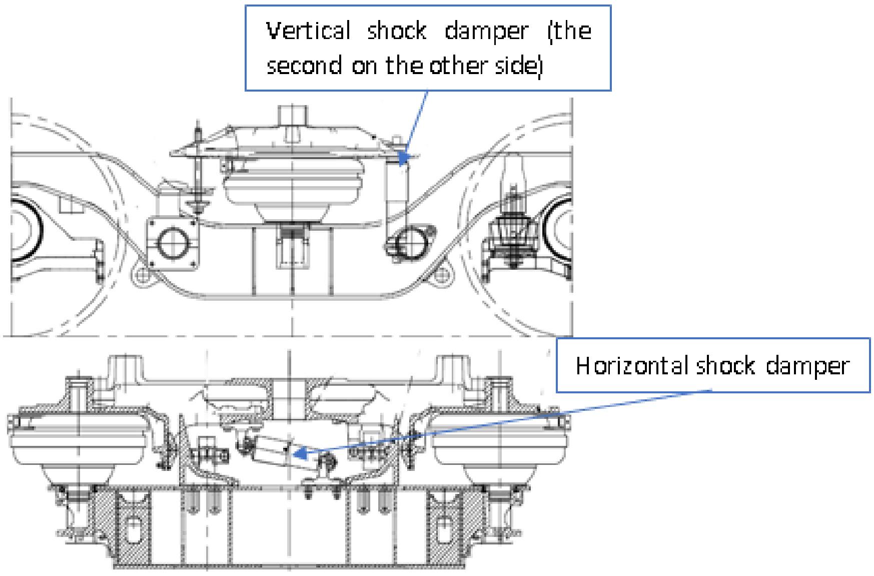


Figure 15: Damper positions

The 2 vertical shock dampers are intended for mitigating vertical sudden vibration, from up to down or vice versa. This includes, for example absorbing vibration if there is some obstacle in the track, such as a stone, or a piece of wood. In figure 16 and table 5 it is shown a drawing of the damper and its parts, respectively.

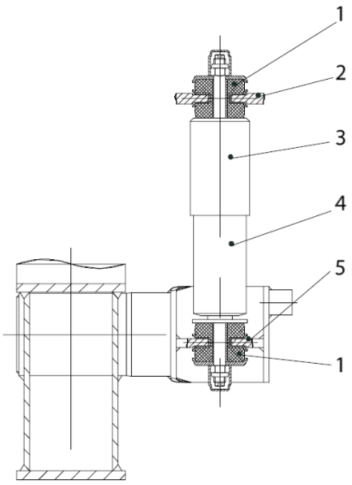


Figure 16: Vertical damper components

Number	Component
1	Rubber buffer
2	Attachment to cradle
3	Dust cover
4	Shock damper element
5	Attachment to frame

Table 5: Vertical Damper Components

The horizontal damper situated in the middle of the bogie, between the two secondary suspensions, has the same principles as the vertical damper but in this case it mitigates horizontal sudden movements, such as heavy shaking in a curve or railway shaking due to non-homogenous track points. In figure 17 and table 6 the drawing and parts are shown, respectively.

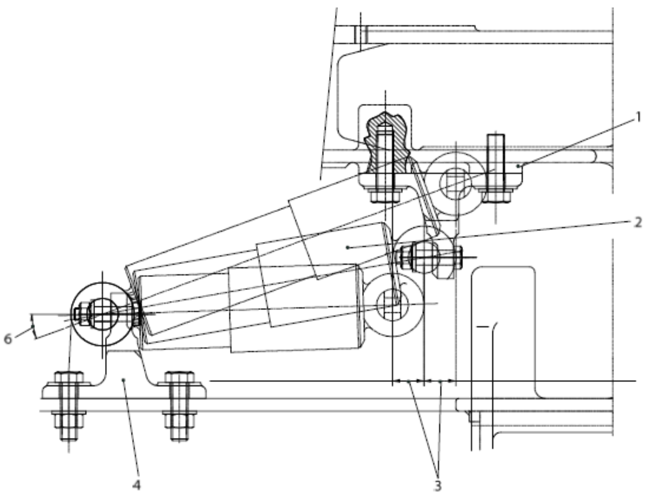


Figure 17: Horizontal damper components

number	Component
1	Mounting point with cradle
2	Horizontal damper
3	boundary
4	Mounting point with frame
6	Link damper-frame

Table 6 :Horizontal damper components

Failures

The main failure which occurs often on dampers is the oil leakage.

Oil leakage

This failure is really problematic due to the fact that it is not controllable currently. When the oil starts leaking out of the damper, independently if its vertical or horizontal, there is no way to determine the amount of liquid remaining inside the damper. In figure 18 we can observe 2 examples of dampers which a leaking oil.

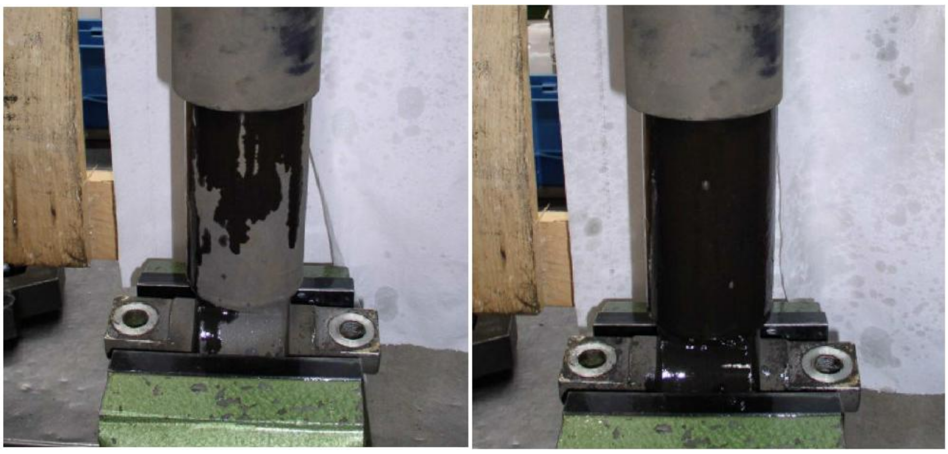


Figure 18: Damper leakage failure

As observed, we can see 2 images were the lower part of the damper is wetted with oil. This does not mean necessarily that the damper is leaking oil as there are also other reasons which can be the cause for it, which makes it even more difficult to detect the leakage.

a. <u>Oil from external elements</u>

One of the possibilities is that the oil does not leak directly from the damper but it arrives from other parts. If there is oil on the damper tap, this means on the top part, the oil cannot be from the damper. Thus, it comes from another part.

b. <u>Small amount leaked</u>

Sometimes, new dampers can leak some residual oil. A small amount of oil can cover a wide area of the damper.

c. <u>The damper has a severe oil leakage</u>

In this case, the damper is actually loosing oil from the inside and thus the damper force is slowly reduced. As mentioned before, there is no way to measure how much oil is gone so it is impossible to control the amount of leakage.
Of course, the worrying case, is c) as the shock absorber actually loses its function and thus the comfort inside the train is worse.

Actual solutions/maintenance

Currently, there are no real solutions to the leakage problem. Actually, it is not even possible to know if the damper is leaking oil permanently as a failure or not. However, there are maintenance procedures which help to control the situation.

In order to do so, the following steps are followed:

1. Check if the oil can come from another part

It is necessary to exclude the fact that the oil present on the damper is from another component. As mentioned before, if the upper part of the damper is wetted in oil, it is clear that it is not from the interior of the damper.

2. Clean the damper

It is necessary to clean the damper which we think that is leaking oil. The best way to do so is by dismounting it from the bogie, pull it to its maximum length and clean thoroughly.

3. Operate with the clean damper for a period

4. Check the damper again

After certain time has passed and the damper is checked again, it is possible to know more precisely if the damper is leaking oil. Of course, if the damper is again wetted with oil in its lower part, it may indicate that it is highly probable that the leakage failure is occurring.

In [6] the procedure is clearly shown and an example images of dampers are shown.

Flexible coupling

Description

The flexible coupling has the main goal of connecting the hollow transmission shaft that is connected to the gearbox and power drive (traction motor) to the massive shaft which is directly connected to the wheels. In other words, the coupling system is the linking point from the power drive arriving from gearbox and through the hollow shaft to the massive shaft connected to the wheels. In figure 19 the flexible coupling of the RSG3 bogie is shown and its parts are indicated in table 7.

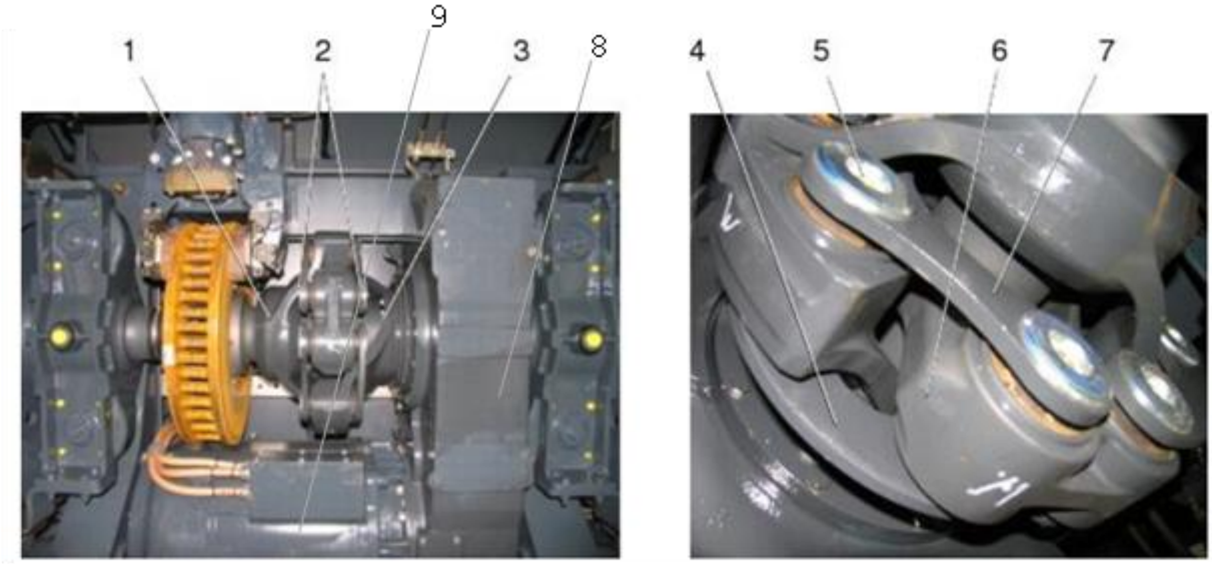


Figure 19: Flexible coupling parts

number	Component	number	Component
1	Coupling component 2	6	Spacer
2	Pair of connecting plates	7	Connection plate 2
3	Coupling component 2	8	Transmission
4	Connection plate 1	9	Traction motor
5	Set of elastic rubber		

Table 7: Flexible coupling parts

Failures

The major failure of the coupling system is the elastic rubber cracking.

Rubber cracking

The rubber cracking of the coupling elements is also a currently problematic failure. It is occurring before the expected time. These rubber elements situated between the coupling plates and the coupling element have the function of absorbing and mitigating all vibrations and movements of the flexible coupling, just as a silent block would do. In figure X the actual

The elastic rubber element has 4 levels of cracking process. In figure 20 the 4 levels are shown and the explanation is given.

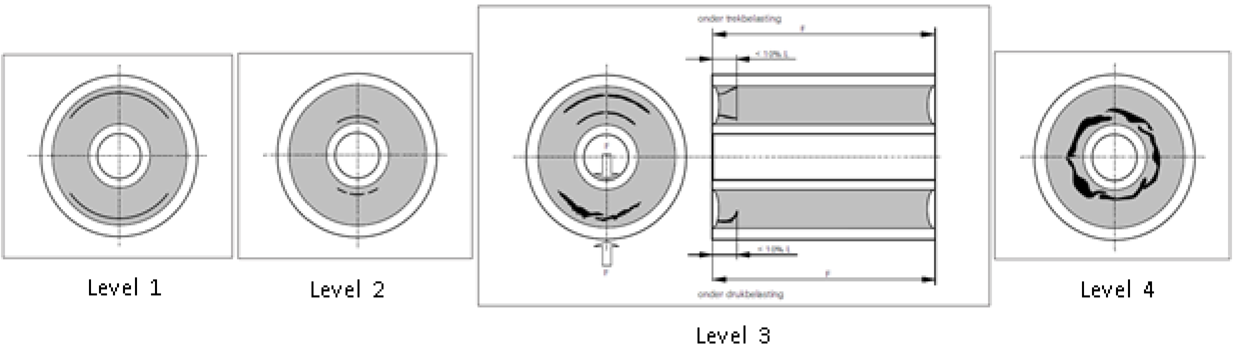


Figure 20: Elastic rubber element cracking levels

<u>Level 1</u>
No cracks are seen. The rubber element is in good condition.

<u>Level 2</u>
In one or more places of the rubber surface some narrow crack can be observed. These are small and do not grow so quickly. No replacement is necessary and the rubber keeps performing correctly even with small cracks.

<u>Level 3</u>
The rubber surface shows larger cracks but these do not complete the whole circumference of the piece. The depth of the cracks is lower than 10% than the depth of the rubber itself (it is possible to measure it, with a small screwdriver for example). The life of the rubber element is highly reduced and its performance is not optimal. It is possible to keep using the rubber but the inspection period must be shortened.

<u>Level 4</u>
The rubber shows crack that go all over the circumference. The rubber is completely cracked and the depth of these cracks is clearly more than 10% of the depth. The replacement of the elastic rubber element must be immediately replaced as the function is not accomplished anymore.

Actual solutions/maintenance

Currently, this failure is not predicted so it is impossible to know when is it going to fail. However, preventive maintenance is applied and visual inspections are performed periodically.

The rubber must be checked periodically to keep track of the condition of it. If the rubber is inspected and the level of deterioration observed is up to level 3, then the period of inspection must be shortened. Like this, although the prediction of the failure is not yet possible, keeping track is possible by dismounting the elastic rubber pieces to perform visual inspections periodically.

Multicriteria Analysis

A multicriteria analysis is performed in order to make a decision regarding which of the 4 failures explained previously is more critical and necessary to solve, according to several criteria. The 4 failures explained are shown in the table below.

Procedure of multicriteria analysis

To perform a reliable and precise multicriteria analysis the following procedure (figure 21) is

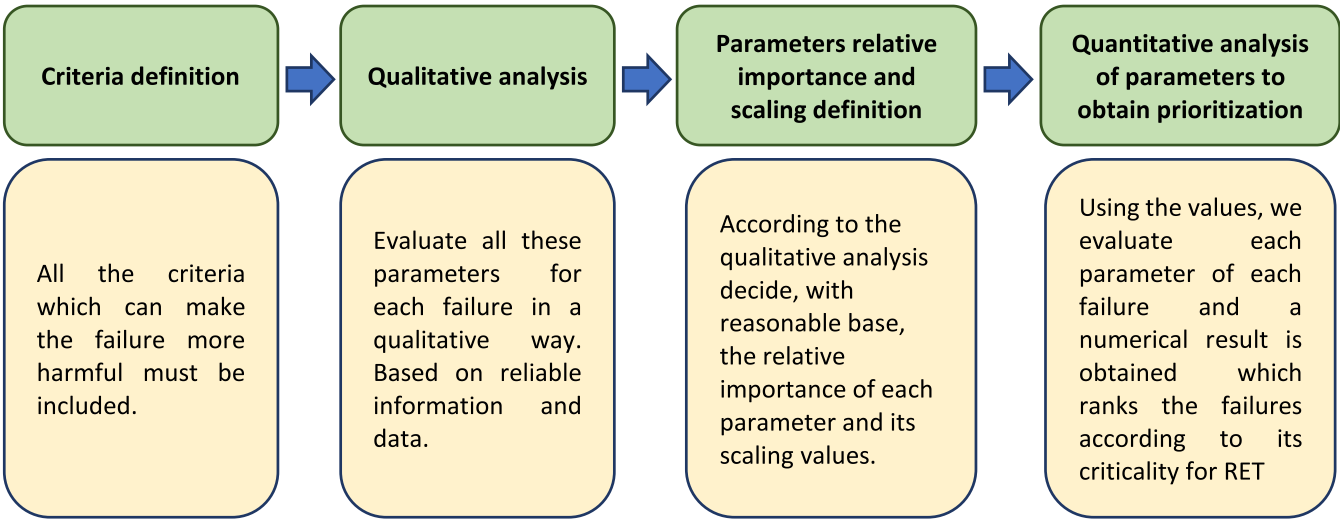


Figure 21: Multicriteria process followed

followed [1].

Criteria considered

As shown in the procedure followed to perform this criticality analysis, the first step is to define and quantify all the criticality parameters which will enable to prioritize and rank the failures of the 3 elements. It is basic to include all the parameters which might have an influence in the final prioritization of failures.

There are 9 criticality parameters which will be taken into consideration when choosing the most critical component of the bogie. In figure 22 these are shown.

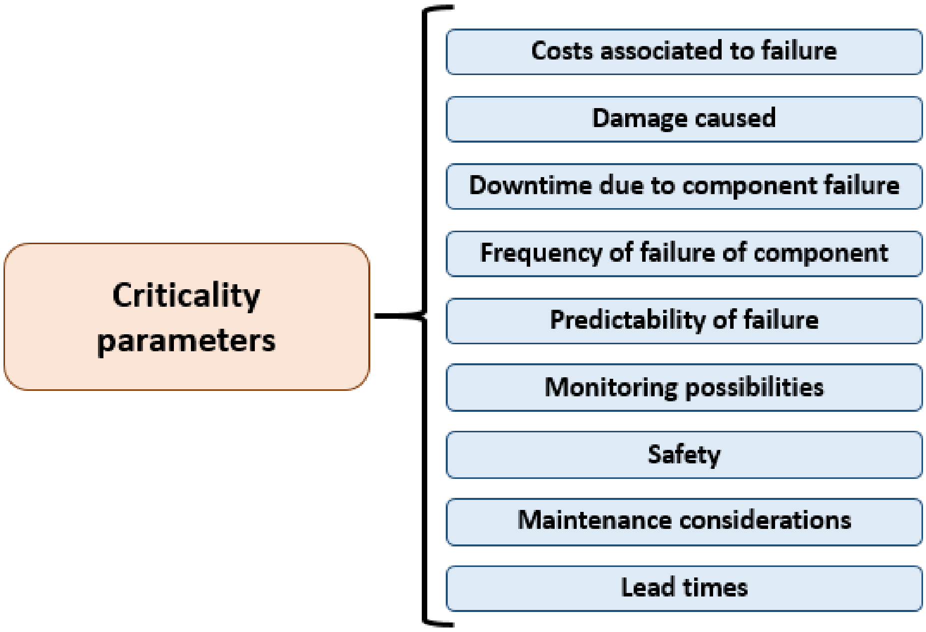


Figure 22: Criteria considered

The costs associated to failure

This is important to consider due to the fact that in the end one of the main goals of this research project is to reduce the costs of the overall bogie maintenance. Thus, one important factor is the amount of money it costs to repair the component and the bogie each time it fail

Damage caused

When the component fails, it always has damage to other things. This damage must be quantified and considered. This damage includes the possible failure of other related components and the safety issues regarding the failure of this component. For example, the failure of a primary suspension can cause damage also on the wheels due to the fact that vibration is not properly absorbed and also cause a possible train stop.

Downtime due to the component failure

The amount of time required to substitute this component in the bogie must be considered. It is true that there are many spare bogies available but still, the downtime caused due to the failure of a component is a problem to quantify.

Frequency of failure

Regarding the probability of failure it is important to know the frequency of the component failure. With proper failure data and experience at RET it is possible to know how often each component fails.

Predictability of component failure

It is obvious that it is necessary that component failure is predictable to a certain extent. If the failure is predictable, then it is a problem which can be solved.

Monitoring possibilities

Sometimes, the failure of a component might be predictable but either there are not many ways to do so or it is really expensive. This criteria is also a factor to be considered but it also difficult to quantify. For example, the vibration of the primary spring can be monitored and controlled. Thus it is only possible to make a qualitative approximation of the monitoring possibilities regarding the component.

Safety

The safety associated to the failure is a basic issue to be considered. Directly related to the damage caused parameter, the safety is more focused on the safety of passengers or employees. For example, if the damper has failed worse than expected, this can cause collateral damage, but the 'real' safety of passengers is not modified, it only makes an effect on the comfort.

Maintenance

This is also a consideration to be made due to the fact that the components studied need maintenance tasks periodically. The time to check a possible failure of an element, the periodicity of inspections or the duration of other maintenance tasks are factors that influence the criticality of the failure.

Lead time

It is necessary to know how much time it takes to reorder and receive the failed component if this one is required.

Qualitative analysis

Relevant information for each criteria associated to the component failures is given as a basis to perform a reliable quantitative analysis.

Costs

It is important to compare all the costs for the three components studied. First of all, we can see in table 8 below the costs [9] of each of the three components and the amount of each in the metro fleet.

	Price*	Element per bogie	Total number of components
Primary suspension	**473 €**	8	4928
Coupling elastic rubber element	**105 €**	16	9856
Vertical damper	**176 €**	2	1232
Horizontal damper	**192 €**	1	616

**price for RSG3 type, assumed for all*

Table 8: Components prices

Taking into account this prices and this amounts, it is possible to estimate how much would it cost to perform an overhaul of all the existing components in the metro fleet.
In tables 9, 10 and 11 we can observe the summary of the results of performing the overhaul of all the elements.

	Primary supensions per fleet	**Total primary suspensions cost (€)**
Technical type 1	2000	946.000 €
Technical type 2	2928	1.384.944 €
Total	**4928**	**2.330.944 €**

Table 9: Primary suspension overhaul costs

	Elastic rubber elements per fleet	**Total Elastic elements cost (€)**
Technical type 1	4000	420.000 €
Technical type 2	5856	614.880 €
Total	**9856**	**1.034.880 €**

Table 10: elastic rubber element overhaul costs

	Vertical dampers per fleet	horizontal dampers per fleet	**Total vertical dampers cost (€)**	**Total horizontal dampers cost (€)**	**Total dampers cost**
Technical type 1	500	250	88.000 €	48.000 €	136.000 €
Technical type 2	732	366	128.832 €	70.272 €	199.104 €
Total	**1232**	**616**	**216.832 €**	**118.272 €**	**335.104 €**

Table 11: Dampers overhaul costs

As observed, the most expensive overhaul would be the replacement of all the primary suspension, which is clearly the most expensive part to replace. On the other hand, the dampers overall overhaul cost is relatively low, less than 400 thousand Euros for both horizontal and vertical dampers.

We also have to take into account that in this calculations do not include the actual replacing hours cost or the cost of the service to replace a part. As well as this, as shown in table 8. the prices used are the ones of the RSG3 metro, and these are assumed the same for the elements of other metros too.

To make a more precise study, it is useful to calculate the amount of money that would be saved if the replacement periods were longer for each of the components. In table 12 the costs of all the overhauls over a period of 20 years is calculated, considering that the parts are replaced every 6 years, every 10 years and every 12 years.

It is clearly seen, in table 12, that regarding cost, the best option to study is the primary suspension. If it is possible to extend its lifetime just a few years, the amount of money saved is high. Regarding the elastic rubber elements the price is also considerably high as the cost of changing the rubber itself is not included and it is performed by an external company (Stork). The case of the dampers, both horizontal and vertical is much cheaper than the other two components, so studying the possibility of optimizing the maintenance and extending the lifetime is not so clear, from a cost point of view.

	Overhaul cost
Primary suspensions	2.330.944 €
Vertical dampers	216.832 €
Horizontal dampers	118.272 €
Elastic rubber elements of coupling	1.034.880 €

		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total cost
Primary suspensions	6 year overhaul	1						1						1						1			9.323.776 €
	10 year overhaul	1										1										1	6.992.832 €
	12 year overhaul	1												1									4.661.888 €

		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total cost
Vertical dampers	6 year overhaul	1						1						1						1			867.328 €
	10 year overhaul	1										1										1	650.496 €
	12 year overhaul	1												1									433.664 €

		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total cost
Horizontal dampers	6 year overhaul	1						1						1						1			473.088 €
	10 year overhaul	1										1										1	354.816 €
	12 year overhaul	1												1									236.544 €

		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total cost
Elastic rubber elements of coupling	6 year overhaul	1						1						1						1			4.139.520 €
	10 year overhaul	1										1										1	3.104.640 €
	12 year overhaul	1												1									2.069.760 €

Table 12: Different overhaul periods costs in 20 years time

Maintenance

In order to compare the maintenance considerations, it is necessary to see what maintenance is performed in the three components and how long does it take to perform it.

At RET, the inspections and maintenance checks are distance based[8]. Every 12500 km, a maintenance check is performed for each metro vehicle, both the old ones (SG2-1 and MG2-1) and the newer ones (SG3 and RSG3). However, every 20000 km not only a small check is performed, some of the components are not checked every small inspection period.

In the case of primary suspensions, the overall inspection and measurement of distances like D, Z4 or the deviation of the shaft from the centre is performed every 200kkm. This inspection is performed approximately 1 time a year and it is a larger overhaul which includes many maintenance actions [10][11].

For the oil leakage dampers, the maintenance actions are performed more often, specifically every 50kkm, which is approximately every 3 months. The action is a visual inspection which determines if, according to the operator, the damper, vertical or horizontal, is in good condition or not. This means that if the operator believes that the damper is not in good condition this must be replaced.

Finally, for the rubber couplings there are 2 kind of actions performed. The visual inspection, performed every 50kkm, basically consists in checking if there is corrosion beginning or any incipient cracks seen. If there is a visual crack seen or the piece is highly corroded then replacement is considered. The second action is performed only every 200kkm, which means once a year approximately. This task implies a detailed check of each elastic rubber element, one by one, removing the connecting plates if necessary.

In table 13, the summary of the maintenance actions taken is shown.

Component	Distance based inspection (kkm)	Action
Primary suspensions	200	Checking & Measuring distances
Elastic rubber elements of coupling	50	Visual condition check
	200	More detailed check
Vertical Dampers	50	Visual Leakage check
Horizontal Dampers	50	Visual Leakage check

Table 13: maintenance distance based inspections

It is also important to know how long does it take to perform each. The tasks do not take very long, being the primary suspensions the longest task with the measurement of distances, and only lasting 2 hours. In the table below the inspection times for the three components is observed.

Component	Inspection time (hours)	Workers needed to inspect
Primary suspensions	2	1
Elastic rubber elements of coupling	0,5	1
Vertical Dampers	0,5	1
Horizontal Dampers	0,5	1

Table 14: maintenance inspection duration

Lead times

Knowing the lead times to order new components parts is essential to perform a maintenance plan of the components according to the failures. In table 15 we can observe the time it takes to receive a new order of each of the components.

Component	**lead times (months)**
Primary suspensions	7
Elastic rubber elements of coupling	6 + 2 weeks
Vertical Dampers	4
Horizontal Dampers	4

Table 15: Lead times

As seen, it takes a lot of time to receive new components. The primary suspensions and the Elastic rubber elements of the coupling assembly take approximately the same time to arrive, just around 7 months, while the dampers are ready in 4 months approximately.

Therefore, it is necessary to take into account the possibility of failures of the three components. For example, it would be useful to know exactly when will the primary suspensions fail, so that it is possible to plan ahead and order the new ones 7 months before the failure happens. If several components fail at the same time and no spare parts are available, then the lead time is really high and either the bogie cannot be operative or it has to operate with a failed components. None of these two options is suitable.

Thus, applying a correct maintenance, preventing failures, predicting and monitoring becomes even more critical to avoid these mentioned circumstances.

Damage caused

To evaluate the damage caused it is necessary to know the technical consequences of each component failure. Together with the technical consequences, the collateral effects of this damage must be considered, such as safety of the users, impact on RET image and the comfortability of passengers and workers.

- Technical consequences of failure
- Collateral effects considered:
    - Safety consequences
    - Impact on RET image
    - Passengers and operators comfortability

Regarding the primary suspensions, there are several technical consequences due to the rubber failure. First, one of the main problems of having a failed suspension, is that the possibility of failure of other components increases. When the distances D, Z4 and the shaft to top surface are not fulfilled, there is risk that parts of the bogie touch each other and also that the vibrations caused due to the non-functionality of the suspensions makes other relevant bogie components fail earlier. For example, there is a high chance that the massive shaft and the top limiting surface collide, causing a highly dangerous situation. As well as this, if the condition is really bad, there is a clear safety risk for passengers due to possible derailment of the vehicle. The fact of having a derailment, which is improbable, would also damage heavily the image of RET among the users and also among other stakeholders. Last but not least, a failed suspension causes that the vehicle vibrates and shakes more abruptly. This fact can also cause earlier failure of other components and has a direct effect on frequent users comfortability, both passengers and employees.

In the case of the dampers, both vertical and horizontal, the damage caused is low in most of the aspects. The reaction of the vehicle to the unexpected movements is more abrupt and the noise of the dampers that have leaked is also louder. The oil leakage of the damper does not cause any other risk of failure of other components, except form the possible fact that the oil itself can wet other parts and this can be a reason of deterioration. Moreover, the safety consequences are not severe in the case of the damper leakage, as an RET metro can function with a failed shock absorber without any safety threats for the users. Lastly, as said, the failed dampers can cause sometimes uncomfortable and quick movements and noise which is not pleasant and in a long term can damage the image of RET too. Evidently, the only difference between the vertical and horizontal dampers is the direction in which they absorb the shock, so the technical consequences and the collateral effects are the same.

Concerning the flexible coupling elastic rubber elements cracking, the consequences are slightly more severe. The flexible coupling is a critical component of the bogie, so the fact that the elastic rubber elements fail puts in risk the whole component and that can cause severe damage, starting from a stoppage of the vehicle to the safety of the passengers if the break down is complete. Previously in RET, due to an excess of torque in the flexible coupling assembly[15], a few of these components broke down causing a highly dangerous situation as pieces of the component flew out of the bogie and were even found in the metro rail. Although the reason was other than the elastic rubber element failure, the mere fact that the cracking of this component causes higher vibrations and les flexibility of the coupling assembly can also cause a complete breakdown. As well as this, the high vibration of the flexible coupling can have a direct effect on other components, including the primary suspensions, which will be more loaded with forces and also other components, as the gearbox, or the shafts. Finally, the failure of the rubber element itself does not have any critical consequences over the image of RET but the fact that the assembly vibrates too much, making noise also, or breaks down, would also have a negative effect on the image of the company.

In the table below a brief summary of the information explained is given.

<table>
<tr><th>Component</th><th>Failure</th><th>Technical consequences</th><th>Collateral effects</th></tr>
<tr><td rowspan="2">Primary suspension</td><td>Rubber shrinking</td><td rowspan="2">Risk of derailment, components colliding, high vibrations, other components failure</td><td rowspan="2">Safety of passengers in danger, uncomfortableness, if derailment occurs image of RET highly affected</td></tr>
<tr><td>Rubber loose</td></tr>
<tr><td>Vertical Damper</td><td>Oil leakage</td><td>Abrupt shocks horizontally, oil wets other components affecting their condition</td><td rowspan="2">uncomfortableness and noise, image of RET partially affected</td></tr>
<tr><td>Horizontal Damper</td><td>Oil leakage</td><td>Abrupt shocks vertically, oil wets other components affecting their condition</td></tr>
<tr><td>Flexible coupling</td><td>Rubber element cracking</td><td>flexible coupling failure risk, high vibrations, other components might also fail</td><td>Risk of stoppage, safety of passengers, uncomfortableness and RET image affected</td></tr>
</table>

Table 16: Technical consequences and collateral effects

Downtime due to the component failure

If the component has failed and a replacement is necessary to compare how much does it take to change each of the components. In table 17 the replacement times are shown. The times only consider the explicit time of replacement, and do not include the time to take the metro to the overhaul place or any other preparation tasks, as it is not necessary to compare the total time.

Component	Replacement times	Workers needed to replace
Primary suspensions	12 hours	2
Elastic rubber elements of coupling	2 weeks	Stork, external
Vertical Dampers	1 hour	1
Horizontal Dampers	2 hours	1

Table 17: Replacement times

As seen, the highest downtime due to failure is the one related to the flexible coupling. This would take 2 weeks as it is performed by an external company, in this case Stork. It is followed by the primary suspensions, which takes more than a working day with 2 employees working on it. To change the suspensions the bogie must be lifted and placed on a work stand, thus it is a time an energy taking action. Finally, the dampers are the easiest component to replace, it only requires 1 employee and it takes no more than a few hours, in the case of the horizontal damper, and approximately an hour for the vertical dampers. This is due to the central position of the horizontal damper which requires lifting of the bogie.

It must be considered the fact that all the downtimes of failure concern explicitly the process of changing the component, it does consider the time to bring in the bogie or the time of taking the bogie from the metro, among others. All these additional times are the same, independently from the component changed, thus they are not necessary to make the comparison.

Frequency of failure

The frequency of failure of each component is assumed using the little failure data available.

In the case of primary suspensions the frequency of the rubber shrinking and the rubber getting loose failures appears after 5 years of service []. The new RSG3 metros were officially accepted from October 2008 and August 2009 [] and the failures regarding the distance limitations (distance D and Z4), were not fulfilled in the test check of 2014. Actually, the distances were checked in April 2014 and October 2014, and it is clear that the primary suspensions were deteriorating quickly and earlier than expected. Nearly 70% of the suspensions were out of limitations at this time, meaning that 5 years is the approximate failure time of the current suspensions used.

Regarding the horizontal and vertical shock dampers, there is some information regarding leakage failures. From August 2017 until November 2017, which includes a period of 4 months, 12 dampers have showed a leakage failure, specifically 10 horizontal dampers and 2 vertical dampers. This means that on average around 3 shock absorbing dampers fail per month due to oil leakage, according to the data of the last months.

In the case of the rubber elements of the flexible coupling, according the failures observed from August to November 2017, there is only one rubber element failing in this period. This means that it is difficult to estimate an average failure rate, but it is clear that it occurs at least once in 4 months, as from RET experience, this is a current and often problem. Thus, it is assumed that each year at least 3 rubber elements have a bad condition and show cracks.

In table 18 we can observe the approximate failure frequencies deduced from the failure information explained.

Component	Failure	Failure frequency	Failure frequency (failures/year)
Primary suspension	Rubber shrinking	5 years	0,2
	Rubber loose	5 years	0,2
Vertical Damper	Oil leakage	0,5 per month	6
Horizontal Damper	Oil leakage	2,5 per month	30
Flexible coupling	Rubber element cracking	0,25 per month	3

Table 18:Failure frequency

It is seen that the dampers ate the components that fail more often, with a rate of 18 failed dampers per year, considering an average of horizontal and vertical dampers. The next most frequent failure is the rubber cracking of the flexible coupling element, with an approximate failure of 3 times per year. The least frequent failures are the ones concerning the primary suspension. Until now, the only reliable info obtained indicates that they start failing and working out of limitations after 5 years.

Predictability of component failure

The predictability of a component failure can be approached in two different ways. The first way to determine if a failure is predictable or not is by using reliable failure data. So, if there is exiting failure data, it is necessary to determine if this data is sufficient to perform a predictive model. The second way is to apply a theoretical model approach by using similar existing models for other failures or based on reliable literature regarding predictive models for specific failures.

Therefore, regarding the failures studied 4 main facts are considered: if there is existing reliable failure data for the component; if the data is useful to design a predictive model; if gathering new specific data would allow to make this model; if there is any currently existing theoretical model which enables a reliable prediction model of the failure without the use of failure data.

In the case of primary suspensions, there is very little data regarding the failures. There is a report from 2014 [2] , which includes a test measurement study of most of the RSG3 bogies and includes the measurements of distances D and Z4 explained. This proves that after a 5 year usage most of the primary suspensions were working in non-acceptable conditions, meaning that the rubber had shrank before expected. As well as this, there is a maintenance inspection distance based, as explained previously, which includes measurements of distances

However, this type of data is not useful to design a predictive model for the future, as this is a onetime measurement during the lifetime. In order to make possible a failure data based predictive model which predicts the shrinking and the rubber getting loose, it is necessary to have a continuous data set. This can be achieved by monitoring the distance D and/or distance Z4 in order to gather enough data in a period of time. With this information, the failures of the primary suspensions are predictable. Finally, there is no current available theoretical model, based on literature or similar cases, which adjusts to any of the 2 failures of the primary suspension. Thus, it is highly difficult to develop and more even to validate a predictive model based on a theoretical approach.

Regarding the shock absorber damper, there is failure data existing. Each time they inspect the damper a hand written check[10] is saved so it is known when the damper has been inspected and its result, meaning if it is in good condition or just it must be replaced. However, as this data is hand written it is complicated to recollect and properly analyse. As well as this, this data is not useful to create a precise predictive model for the oil leakage failure of the dampers due to the fact that the detection of leakage is complicated and often not certain. Moreover, it seems complicated to use a monitoring system or any maintenance plan to gather useful data which enables the design of a predictive model for both vertical and horizontal dampers. It is true that this option has not been deeply investigated but the current options for gathering oil leakage data are non-existent. Finally, there are theoretical models available concerning predictive models for oil leakage in oil pipelines [17], or studies regarding hydraulic dampers [16], but no explicit model adjusts directly to the damper oil leakage case and considering other criteria and comparing with other failures it is not the best investment to investigate in this area.

The rubber coupling elements have also very few data available regarding its condition. Similarly to the dampers, there is a hand written report [10] of every maintenance check which includes information of the rubber element condition. Again, the fact that this information is not strictly in a computer based system makes it difficult to analyse this data and as well as this the mere check is not precise enough to make a predictive model for the condition of the rubber. To make a useful data gathering, it is necessary first of all to monitor or check often the rubber and give precise information about the depth of the crack or the stiffness of the rubber, for example. With this kind of information, if monitorable, it is possible to design a predictive model which helps to know the future condition. Finally, with respect to the current theoretical models existing, no explicit or similar useful rubber element predictive model has been found and the creation and validation of a reliable new one requires a lot of time.

In the following table all the information explained about the predictability of the components failures is summarised.

Component	**Failure**	**Failure data existing**	**Failure data useful**	**Possibility to gather useful data**	**Theoretical model**
Primary suspension	Rubber shrinking	Very little	No	Yes	No
	Rubber loose	No	-	Yes	No
Vertical Damper	Oil leakage	Yes	No	Unknown	No
Horizontal Damper	Oil leakage	Yes	No	Unknown	No
Flexible coupling	Rubber element cracking	Yes	-	Yes	No

Table 19: Predictability of failure

Monitoring possibilities

To determine the monitoring possibilities of each of the 3 components studied, it is necessary to look into the easiness of detection of failures first, and then to determine if the failure can be permanently or partially controlled.

In the case of the primary suspensions, the monitoring possibilities are currently in development. To measure the state and condition of the primary suspension rubber is possible by measuring the distance D explained in this report. Thus, if instead of measuring this by hand we can do it with an implemented system, then the we would be able to know the condition of our primary suspensions on time. As said, this implementation method is being studied by other companies and it includes the use of a magnetic field proximity sensor which can measure this distance precisely allowing to perform a just on time maintenance and to save data to predict future failures. In the meeting with Stork (annex 2) this method was discussed as other companies are already making testing cases.

In the case of the dampers, the problem is bigger. In the description it has been explained that it is difficult to know if the damper is leaking or not for sure. This means, that it is difficulty detectable and consequently the monitoring possibilities are really few. The only possible option is the actual maintenance solutions applied which have been previously explained.

The rubber elements of the flexible coupling also have difficulty to be monitored and currently no solution is considered. The visual inspection enables to detect if the rubber element is in good condition or not, which makes the failure detectable. However, implementing a system able to measure the degradation of the rubber to know when is it necessary to change it or predict its behaviour is not feasible currently.

In the table below the information regarding the monitoring possibilities is briefly summarised, according to the detection and the actual current monitoring options.

Component	Failure	Detection	Monitoring possibilities
Primary suspension	Rubber shrinking	Measurable	Yes
	Rubber loose	Measurable	Yes
Vertical Damper	Oil leakage	Non detectable	No
Horizontal Damper	Oil leakage	Non detectable	No
Flexible coupling	Rubber element cracking	Visually possible	Not considered

Table 20: Monitoring possibilities

Safety

To evaluate and classify the safety of each of the component failures 2 conditions will be considered[7]: the severity or consequences of the failure, meaning that how harmful is for the people itself; the frequency of failure, discussed already previously. In figure 23 [7], we can observe the applied analysis done.

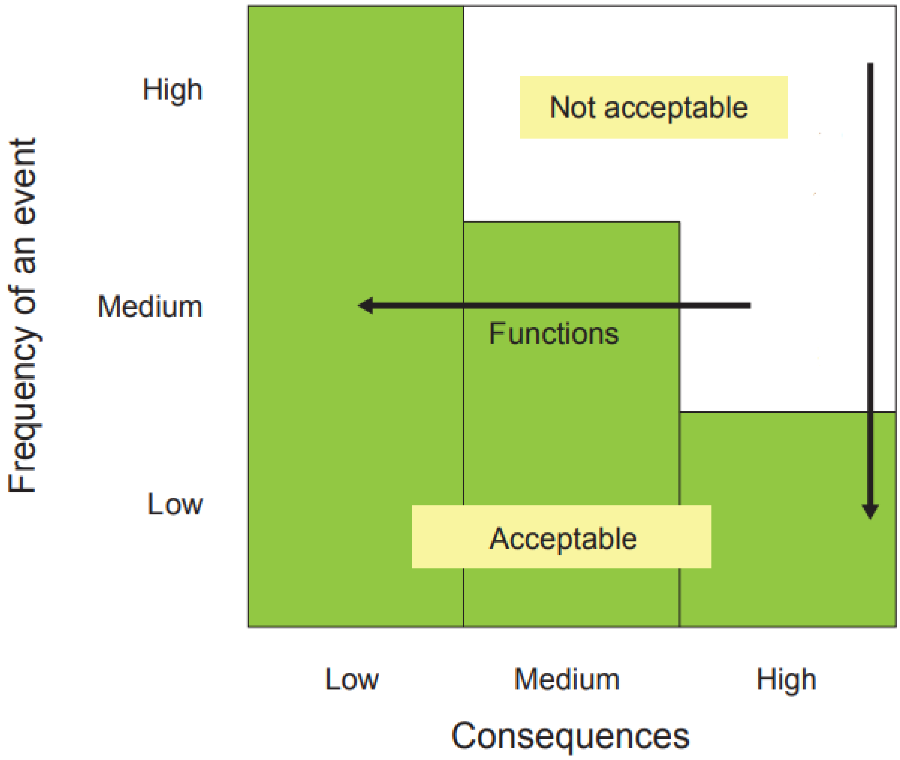


Figure 23: Safety levels [7]

Regarding the primary suspensions, there are several safety risks to be considered. First of all, if the suspensions fail, the safety consequences are potentially high. There is a risk of derailment, which endangers the safety of passengers and the fact that there are colliding components, like the shaft touching top surface, can cause other failures which are also dangerous for passengers. The frequency of failure is not so high, but it is clear that it occurs unexpectedly, every 5 years (on average), before expected lifetime, and the problem must be solved. Therefore, the safety consequences are high, and the frequency of failure, though not being high, must be considered, so the level of safety is not acceptable.

In the case of the vertical and horizontal dampers, the case is completely the opposite. The frequency of oil leakage is really high, but the safety consequences of having a failed damper are very few. The main inconvenient of having a failed damper is that the shocks of the metro are not absorbed and thus the movements are more abrupt, but this is not a threat for the passengers nor employees of the metro. As well as this, there is a small chance that the oil leaked wets other components, making them function non-optimally. Therefore, as the severity of a failed damper is really low, even though the frequency is high, the safety level is acceptable.

Finally, concerning the safety analysis elastic rubber element failure, the consequences are certainly more unclear. First of all, there is a risk of failure of the flexible coupling. This might cause an unsafe situation for passengers due to the fact that the coupling assembly break down can cause a stoppage of the train in a non-desirable condition. Secondly, the fact that the rubber is cracking will cause high vibrations which will certainly have an effect on other components failures, such as the shafts, the axle and obviously the primary suspensions itself. Thus, the failure of this elastic rubber element indirectly causes unsafe situations for all users. As well as this, the frequency of failure is considerable, as seen previously in this paper. Therefore it is concluded that the safety level of this failure is not acceptable, although it is not as clear as the effects of the failed primary suspension.

In table 21 below, a summary of all the safety information given is summarised and adapted to the information given in figure 23.

Component	**Failure**	**Severity factors (S)**	**F**	**S**	**Safety level**
Primary suspension	Rubber shrinking Rubber loose	Risk of derailment, components colliding, high vibrations, other components failure	Medium	High	Not acceptable
Vertical Damper	Oil leakage	Abrupt shocks horizontally, uncomfortable	High	Low	Acceptable
Horizontal Damper	Oil leakage	Abrupt shocks vertically, uncomfortable	High	Low	Acceptable
Flexible coupling	Rubber element cracking	flexible coupling failure risk, high vibrations, other components might also fail	Medium	Medium	Not acceptable

Table 21:Safety level of failures

In the table below the qualitative criticality analysis which summarizes all the relevant information explained for each failure and each parameter is given. The information shown is also furtherly explained and compared after the table.

Component	Failure modes	Costs	Damage caused	Predictability of failure	Possibilities to monitor	Frequency of failure	Downtime due to failure	Safety	Maintenance Considerations	Lead times
Primary suspension	**Rubber shrinking**	473 € per primary suspension	Massive shaft and suspensions limit frame can collide causing major bogie failures.	Possibility of controlling distance D and predicting future tendency	Magnetic field sensor to control distance D allows monitorization and quantification of rubber shrinking	Trains received between 2008 & 2009, with primary suspension completely failing at the beginning of 2014	12 hours for 2 man and 1 bogie to replace	The derailment of the train is a danger for safety. Failure of other major components can also cause unexpected train stops which are also unsafe. Level Not acceptable	Inspection takes 2 hours for 1 man.	7 months
		Overhaul cost of all suspension: 2.330.944€	Train vibrates and shakes more abruptly even with small bouncing, If vibrations are too much, derailment can be caused						Inspection every 200kkm, once a year	
	Rubber getting loose	473 € per primary suspension	Train vibrates and shakes more abruptly, less comfort in train						Inspection takes 2 hours for 1 man.	
		Overhaul cost of all suspension: 2.330.944€							Inspection every 200kkm, once a year	
Horizontal shock absorber/dampers	**Oil leakage**	192 € per horizontal damper	Comfort in train is highly reduced. The quick vibrations and shocks are not absorbed any more causing to both vertical and horizontal abrupt movements	Not possible, only checking maintenance tasks help to determine if leakage is occurring	Currently, as mentioned, only visual inspections, no electronic possibilities	In the last 4 months, 10 horizontal dampers and 2 vertical dampers	Horizontal dampers replacement takes long, not worth it. Vertical damper replacement in 1 hour 1 damper	No real safety threats, less comfort for passenger. Level acceptable	Inspection takes a few minutes	4 months
		Overhaul cost of horizontal dampers: 118.272€							Check every 50kkm, every 3 months	
Vertical shock absorber/dampers		176 € per vertical damper	Other parts can also be damaged due to this abrupt movements, wheel for example.						Inspection takes a few minutes	
		Overhaul cost of vertical dampers: 216.832 €							Check every 50kkm, every 3 months	
Flexible Coupling	**Elastic rubber element cracking**	105 € for elastic rubber element of coupling	High vibrations of flexible coupling system assembly.	By analysis of rubber possible to know when the cracks will increase quickly	Apart from current visual checks, no monitoring system is considered for it. Writing down crack depths is possible	In the last 4 months, 1 rubber element has failed	Replacement in 6 hours for 1 man to change all elements of coupling if done internally in the future, otherwise 2 weeks by stork	The breakdown of the coupling causes a direct non-functionality of the bogie, thus an unexpected stoppage and lack of passenger safety. Level not acceptable	Inspection takes half an hour	6 months and 2 weeks
			If the cracks are complete, a breakdown of coupling can occur							
		Overhaul cost for all rubber elements: 1.034.880 €	Poor coupling of hollow shaft with massive shaft						Visual check every 50kkm. More thorough check every 200kkm	
			Vibration can cause damage in suspensions too							

Table 22: Summary of qualitative analysis

Quantification and scaling of criterion

In order to make a precise analysis all the parameters previously explained must be clearly quantified and scaled. To do so, all the parameters will have a **relative importance** and a **scaling system**. The relative importance is the weight that each parameter has compared to the rest, and the scaling system is to quantify the effect of the parameter on the failure.

Scaling values

The scaling values are normalized for all parameters. The values given are from 1 to 10, meaning 1 that the effect of the parameter is not significant and 10 that the influence is high or the possibility of solving the failure is more feasible and profitable. To make reliable the difference, only 4 values will be applied, as shown in table 23

Scale value	Meaning
1	The parameter has very little effect/influence on the failure problem
3	The influence of the parameter is noticeable, but not very relevant
6	The parameter has a highly noticeable influence on the failure, clearly relevant
10	The parameter has a strong influence on the failure

Table 23: Values of scaling

All the values and its explanations are shown in the following tables for each parameter.

Costs associated to failure

Scale value	Meaning
1	The costs associated to the failure are low and/or it's not worth to consider preventing the failure
3	The costs must be considered but still compared to other failures is not such a high cost
6	The costs associated to the failure are high and the possibility of reducing this cost must be studied
10	The costs associated are higher than most of the rest of the failures

Damage caused due to failure

Scale value	Meaning
1	No relevant damage is caused due to the failure
3	Some damage regarding other components might be caused
6	The failure of the component can cause the failure of other components and can cause the train breakdown
10	The failure will cause the failure of other parts eventually and can provoke a train breakdown

Predictability of failure

Scale value	Meaning
1	The failure is currently NOT predictable and no perspective to make this possible in the future
3	The failure is not predictable currently
6	The failure can be partially predicted
10	The failure can be predicted

Monitoring possibilities

Scale value	Meaning
1	No possibilities to control, detect or monitor the failure
3	Actions which might give an indication of the failure situation, but still no current monitoring or detection options
6	There are possibilities to monitor the system, but not developed or not yet necessary
10	There are clear monitoring possibilities studied which enable to control the failure

Frequency of failure

Scale value	Meaning
1	The failure is not frequent or sporadic
3	The failure occurs periodically, but compared to other failures still not very frequent
6	The failure occurs periodically and often before expected
10	The failure is very frequent and mostly occurs even before the expected time

Safety

Scale value	Meaning
1	No safety threats due to failure
3	Minimal safety of passengers threatened
6	The failure can cause unsafe situations for passengers
10	The failure can cause major safety issues which are unsafe for passengers

Downtime due to failure

Scale value	Meaning
1	The failure does not cause downtime
3	The downtime due to failure is low, but still the problem is solved quickly
6	The downtime is high as it takes long to change the failed part
10	The downtime due to failure is very high

Maintenance considerations

Scale value	Meaning
1	The maintenance is easy, not frequent, and does not take long
3	Often maintenance tasks, but easy to perform and short times
6	Periodical maintenance tasks which take longer time and might need more people
10	Frequent maintenance tasks which take long time and need more people

Lead times

Scale value	Meaning
1	The lead time is lower than a month
3	The lead time is from 1 to 3 months
6	Lead time is from 3 to 6 months
10	Lead time over half a year

Relative importance

The relative importance of each parameter is decided by evaluating how important each one is for RET. Thus, the decision is made putting as a priority the safety, the costs and the image of RET. These 3 factors and using the qualitative analysis it is possible to make a reliable relative importance assignation. In figure 24 we can observe a pyramid that classifies all the parameters by importance.

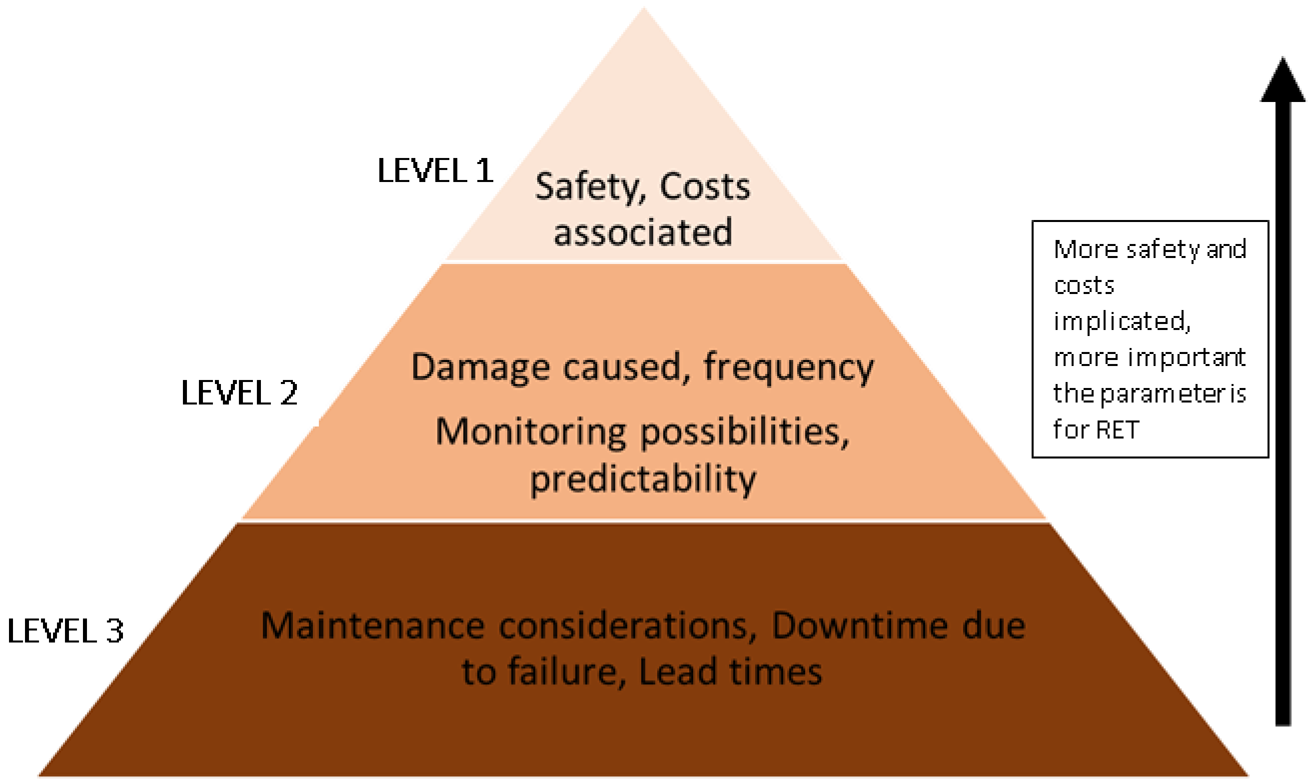


Figure 24: Relative importance of criteria

Level 1

As seen in the pyramid, it is observed that the most important parameters are the safety of the passengers and the costs associated to the. These are critical not only because of course it is basic to reduce the costs as much as possible and at the same time keeping the safety, but also the impact on RET image can be influenced by these factors. If a safety problem occurs in an RET metro or tram during service time, the consequences regarding social image are high.

Level 2

In level 2 we can observe that the relative importance of the damage caused, the frequency of failures, the monitoring possibilities and the predictability is considerably important. It is evident that the damage caused can affect the safety of passengers, and the three other parameters in this have a direct effect on the costs wasted to solve the failures.

As well as this, the monitoring possibilities and predictability are directly related to a predictive maintenance concept, which if applied is really cost beneficial in a midterm period.

Level 3

These criterion are considered to have the least influence in the three mentioned factors, the safety, the costs and RET image. However, they must be considered with a low relative importance. As well as this, both the maintenance and the downtime due to failure have a high impact in the overall costs, as seen in the overhaul costs comparison for the components. The most critical failure must be investigated so that also the effect of these parameters is improved, and thus the money wasted optimized.

According to the defined levels, it is possible to give values to the relative importance of each parameter. It is important to highlight the fact that the sum of all relative importance's is 10, so the relative importance value is out of 10. These values are observed in the following table 24.

Parameter	**Relative importance**
Safety	2
Costs	1,75
Frequency	1,5
Damage caused	1,25
Predictability	1
Monitoring possibilities	1
Maintenance considerations	0,5
Downtime due to failure	0,5
Lead times	0,5
Total	**10**

Table 24: Relative importance values

Quantitative criticality analysis

Having all the criterion scaled with numerical values, given the relative importance of each and having all the qualitative information previously explained, it is possible to evaluate numerically all the criteria for each failure.

To do so, table 25, which includes the 4 failures studied and all the criteria analysed, shows all the values given to each of these together with the relative importance of the criteria. With these values, it is possible to calculate a final criticality value by multiplying each criteria rated value times the relative importance of the respective criteria and successively summing up all the criterions result. The calculation is as follows, **for each failure.**

$Relative\ importance\ of\ criteria\ i = R_i$
$Scale\ value\ of\ criteria\ i = \ S_i$
$Criticality\ value\ for\ failure\ j = CV_j$

$$CV_j = \sum_{i=1}^{n} R_i \times S_i$$

Where: $i = 1 \ldots.n$ and $n = 9$, which means that there are 9 different criterions considered.

$j = 1 \ldots.m$ and $m = 4$, meaning that there are four different failures studied, and each one has its own criticality value.

To determine the value of each failure criteria, a direct rating method has been used. This means, that using all the qualitative information explained previously in this paper a logical value has been given. It must be reminded the fact that all the qualitative analysis is based on reliable RET & associated companies information/data and on experience of main RET employees regarding the matters studied.

In table 25, the results obtained are shown.

Parameters / Failure modes	Costs		Damage caused		Predictability		Possibilities to monitor		Downtime due to failure		Frequency		Safety		Maintenance		Lead times		Total criticality number
	Scale (S)	Relative importance (RI)	Scale	Relative importance	Scale	Relative importance	Scale	Relative importance	Scale	Relative importance	Scale	Relative importance	Scale	Relative importance	Scale	Relative importance	Scale	Relative importance	
Rubber shrinking of primary suspension	10	1,75	10	1,25	10	1	10	1	6	0,5	1	1,5	10	2	6	0,5	10	0,5	**82,5**
Rubber in primary suspension getting loose	10	1,75	10	1,25	6	1	6	1	6	0,5	1	1,5	10	2	6	0,5	10	0,5	**74,5**
Oil leakage in vertical and horizontal dampers	3	1,75	1	1,25	1	1	1	1	1	0,5	10	1,5	1	2	3	0,5	6	0,5	**30,5**
Elastic rubber element cracking of flexible coupling	6	1,75	6	1,25	3	1	3	1	10	0,5	6	1,5	6	2	3	0,5	10	0,5	**56,5**

Table 25: Criticality analysis results

Criticality results

Analysing the results, it is seen that the **most critical** component failures are the ones of the **primary suspensions**. According to the total value which includes all the criterions, the rubber shrinking of the primary suspensions with a value of 82,5 overall is the most critical failure, while the oil leakage of dampers has less impact in general, with a total CVj value of 30,5.

Rank	Component	Failure	CV_j
1	Primary suspension	Rubber shrinking	82,5
2		Rubber loose	74,5
3	Flexible coupling	Rubber element cracking	56,5
4	Vertical Damper	Oil leakage	30,5

Table 26: ranking of failures according to analysis

In order to make a correct advice of possible solutions or future research option, an analysis per component is performed.

Primary suspension results

It is seen that both the rubber shrinking and the rubber getting loose are the most critical failures. Actually, both of the failures are equally ranked in most of the criterions, except the monitoring possibilities and the predictability of failure. This is due to the fact that both failures are closely interrelated. The information gained regarding the distances D, Z4 or shaft distances in the last years is directly related to the shrinking of the rubber but it is also affected by the rubber getting loose.

Concerning the monitoring possibilities, having a permanent control of how much the rubber has shrank is more feasible than controlling the looseness of the rubber. For example, when controlling the distance D, the direct result is knowing the thickness situation of the rubber, but not so clearly the looseness. Regarding the predictability, the case is similar, as with reliable failure data the shrinking pattern is, a priori, more predictable than a looseness prediction.

With respect of the rest of the criteria, the results can be analysed together as the rated values for both failures are the same. The most remarkable fact is that the failure of primary suspensions is the less frequent among the three components, failures registered only once every five years. However, it is still the most critical component, and it is due to the fact that the most important factors, cost and safety are really affected by the failure of primary suspensions. It is clear that the replacement of the primary suspensions is the most expensive one and the risk of having a failed suspension in a metro implies high safety risk for all the users, which is unacceptable.

Vertical and Horizontal Shock Dampers

In the case of the dampers, the overview is very different. The most critical point of the damper failure, both vertical and horizontal, is the frequency of failure registered. Compared to the rest of the failure frequency it is really high, and it is even more impressive due to the fact that it is not sure if the damper has failed, sometimes there is a small leak and the damper is considered failed without certainty.

Regarding the rest of the criteria, the damper oil leakage failure is not worrying as it has no outstanding effect. The safety of passengers is not threatened, the costs associated are not high, the damage caused is also lower than other failures and there is no predictability or monitoring possibilities currently, and it is not worth to investigate either. The only considerable fact is that the lead time to receive new components is over 4 months, so the number of spare parts must be controlled properly.

Flexible coupling elastic rubber element

For the flexible coupling assembly, the numerical result of the CVj is of 56,5 which makes it a considerably high number even though it is far from the primary suspensions failures. The analysis of the failure of the elastic rubber element is more complicated as it is one part of the whole assembly. However, there is some information which is really clear. First, if the elastic rubber element is in really bad condition, there is the risk, due to vibrations and overload that the whole assembly fails, and that threatens the safety of all the users because a failure in the flexible coupling can cause, among other things, a metro stoppage. Secondly, the cost and time of changing the rubber elements is also considerable, as the downtime due to failure is high and the time to order new pieces is over half a year. Finally, it is also a frequent failure, not as the case of the dampers but still often enough to take into account the possible damage caused by the cracking of this element.

Concerning the rest of the criteria, the predictability and monitoring possibilities are unclear for this element and again, it is not a very convincing possibility to investigate on this path. What refers to maintenance, the visual inspection is performed every 3 months, and a more deep check is done once a year, but it would be a possibility to search other ways of checking the condition of the rubber.

Main points

All in all, there are main criteria which outstand for each component specifically.

For the primary suspensions, it has been seen that the main concern is the **costs** associated to the failure and the **safety**, as well as the high possibilities of **monitoring the condition** of the component.

Regarding the vertical and horizontal dampers the principal concern is the **frequency** of failure. It is the component with most registered leakage failures (not always certain) and as well as this the **lead time** to receive new parts is considerably high.

With respect to the flexible coupling the possible **safety risks associated**, the **downtime to failure** and the **lead times** to receive new parts are criteria which are a concern.

Solutions advice & Further research

Each of the components failures studied has some points which are more critical and have space for improvement. Therefore in this section possibilities to improve and to do further research are suggested. These will enable a future cost reduction policy and safety improvement.

Primary suspensions

As the primary suspensions are the most critical components of the metro bogie according to the study performed. The main goal is to reduce the costs wasted in replacing primary suspensions and to decrease the safety risks associated. In other words, make that the lifetime of the primary suspensions is longer and avoid working with failed suspensions for prolonged times.

To solve this, one of the directions the future research and improvements at RET should be the condition monitoring of the distances in the suspension

Regarding the object of my internship research, one of the parts that is going to be monitored is the *distance D* of the primary suspensions. By including a magnetic field sensor, a condition monitoring system can be created, allowing to receive information every day and thus allowing to perform a just on time maintenance. As well as this, monitoring this distance enables to predict how the suspension will behave as the amount of data gained is enough to design a predictive model. Like this, not only a just in time maintenance can be performed, optimizing the maintenance periods, but also the new parts can be ordered at the correct timing, considering lead times, knowing when the primary suspension will be failing.

It is known, that the lead time to receive new primary suspensions is of approximately 7 months, thus it is necessary to know "when" the distance will be out of range so that the new suspensions can be ordered on time.

<u>Magnetic field positioning and explanation</u>

In order to measure the distance, the apparently best option and the investigation that Stork is carrying out is the implementation of a Magnetic field proximity sensor.

Therefore, it is advisable for RET to look into this option and study the possibility of monitoring the distance. This sensor can be easily implemented as it only consists of a magnet and an electronic board with a hall element. In the picture [13] we can see both elements. The hall effect element [12] allows to measure a voltage variation which can be directly related to the distance from the magnet to the hall element. As the magnet gets closer to the hall sensor, the voltage measured is higher, thus it is possible to make a relation.

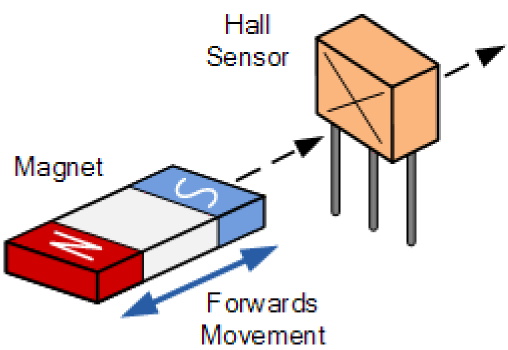


Figure 25: Magnetic field sensor

Vertical & horizontal dampers

Knowing that the possibilities of detection of sure oil leakage are not really feasible and the predictability and condition monitoring of dampers is difficult to achieve, it is not worth it to investigate in this way. As well as this the costs associated to the dampers are not so high so it is also not necessary to implement complex detection systems or condition monitoring investigation.

What it is clearly possible to achieve is reducing the frequency of damper replacement. As seen in the analysis, the dampers are sometimes changed and replaced without complete certainty of its leakage. The dampers are checked every three months and it is known that the safety risks of using a leaked damper are not so critical for users.

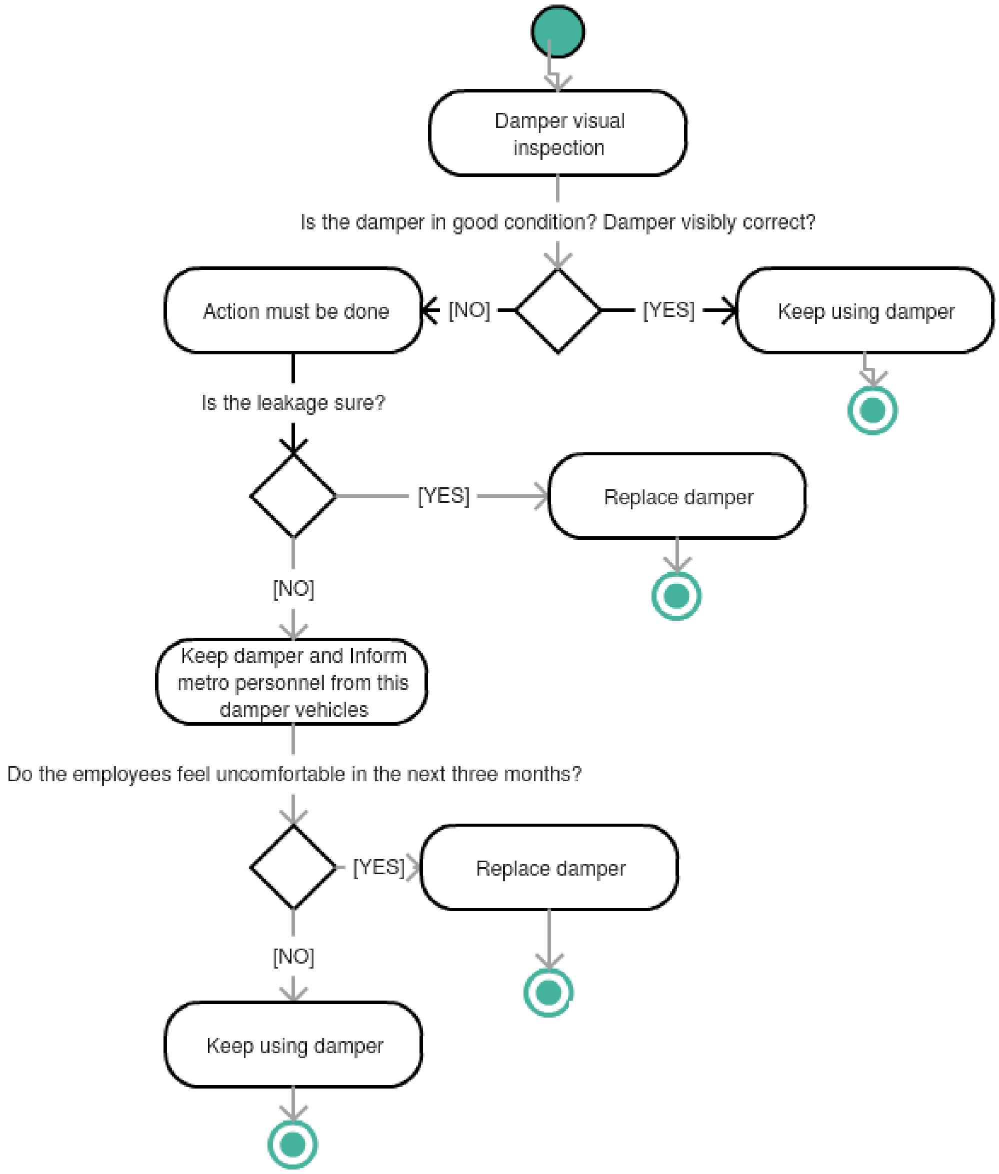


Figure 26: Damper replacement diagram

Therefore, it is a really good solution to keep the dampers if there is a reasonable uncertainty regarding its leakage. In figure 26 the process followed is observed briefly. For example, if the operator in charge of doing the maintenance observes a possible leakage but he is not sure, then the decision is to keep the damper in the bogie and inform the employees that work in the metro which has the bogie to take into account the fact of a failing damper. Then if the employee can feel any severe difference, regarding the comfortability of the metro in the following three months, then this damper must be replaced, otherwise it is not necessary.

This system has 2 main advantages. First of all, it is easy to implement, with a simple form (for example) that the employees of the respective vehicle must fill during the 3 month of checking period, easily and without losing time. Secondly, the amount of money wasted is also decreased due to the fact that less number of dampers are replaced.

Therefore, for RET it does not imply nor an economical nor a time effort, and thus it is clearly a procedure to be followed in the future.

Flexible coupling

The third studied component has a more unclear solution and research path for the future.

Again, compared to the primary suspensions, investigating a possible condition monitoring or developing a predictive model is not the most profitable option due to the fact that it would cost more to implement the system than the actual benefits of having it. As well as this, although the failure of the coupling assembly is more critical for the safety of users, it is not so clear that the elastic rubber element causes harmful situations in short periods of time.

Currently, as explained previously, the flexible coupling is checked every 50kkm visually, and more thoroughly every 200kkm [7]. Every 50kkm the checking is more general, including activities such as: checking if the elastic rubber elements have cracks; checking the screw connections… The main activity added for the annual maintenance task every 200kkm, is the deeper inspection of the coupling to look for cracks or deformation, including, obviously, the elastic rubber element. This extra task is showed in figure 27 [10].

1195	0	**Controle TBG-koppeling**	
1199	VI	TBG-koppeling grondig controleren op barsten	02 04 00 B 5

Figure 27: Intensive check of flexible coupling every 200kkm

The exact meaning of the written task is: ‘’ Thorough check of coupling for cracks’’

However, although all this tasks are performed every 50 and 200kkm respectively, it is not included yet a maintenance action which includes the depth of cracks or holes in the rubber. This action, using a special device can help to keep track of the development as the maximum wanted is of 10mm. As the case of the primary suspension distances measured every year, D, Z4 and H1 which help to know a clearer condition of the suspension. Equally, if cracks exist, knowing the length of them is an advantage to know if the element must be replaced or not and the effort to measure it is not so high.

Therefore, as an advice for future RET actions which will help to control better the elastic rubber element cracks, is to write down the crack depth and length in each maintenance inspection every 3 months or 50kkm, if this one exists. Of course, it is also necessary not only to write down on paper but introduce this information in a computer system. Like this it is possible to know if it is necessary to change or it can last more time, with a maximum crack depth limitation of 10mm. As well as this, a record of crack lengths growth can help in the future to make better crack growth predictions and prevent possible future elastic rubber element failures. Finally, the lead times can be prevented and avoided knowing this information, as it is easier to order new pieces in advance.

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Annexes

Annex 1: Bogie Photos

Bogie type MG21

Bogie type RSG3

Annex 2: Meeting stork

During the internship at RET, I had an important meeting for my research at Stork the 13th October 2017.

STORK is the company that takes care of the maintenance and pieces overhaul of the metro bogies pf RET. In this sense, they have the necessary machinery and equipment to perform some maintenance tasks that cannot be done at RET. These include, regarding the bogies[]:

- Changing primary suspensions or height correction

- Checking and testing the primary suspensions
- Replacement steel rubber elements of flexible coupling

From the meeting with Sir Loek Alta, one of the most relevant subjects discussed is the development of the Smart Bogie. This new bogie style is being developed by Stork together with Trelleborg/a private railway company and consists of the usage of sensors to control and monitor different parts and components of the metro wheel set.

Regarding the object of my internship research, one of the parts that is going to be monitored is the *distance D* of the primary suspensions. By including a magnetic field sensor, a condition monitoring system can be created, allowing to receive information every day and thus allowing to perform a just on time maintenance. As well as this, monitoring this distance enables to predict how the suspension will behave as the amount of data gained is enough to design a predictive model. Like this, not only a just in time maintenance can be performed, optimizing the maintenance periods, but also the new parts can be ordered at the correct timing, considering lead times, knowing when the primary suspension will be failing.

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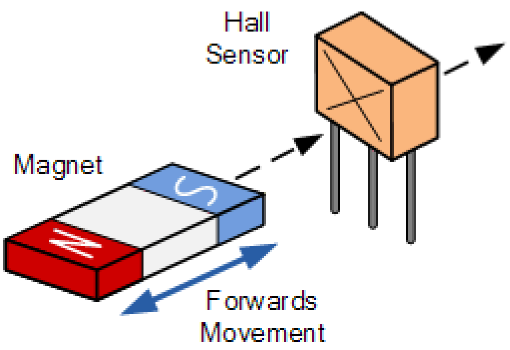

<u>Annex 3: Meeting HTM</u>

<u>Company overview</u>

HTM is the tram and bus company of Den Haag. They take care of all the public transport in the city of Den Haag and surroundings, being in charge of the maintenance and correct performance of or the vehicles. With 8 bus lines and 12 tram lines it covers around 37000km of route line in total.

Meeting purpose

The 23rd of November I had a meeting at HTM with Eric Van Zanten, maintenance engineer of the trams at Werf workshop of HTM. The objective of the meeting was to see if there where similarities between the problems and failures in HTM and RET regarding the three components studied in my research: the oil dampers, the primary suspensions and the flexible coupling. As well as this, possible failure data existent for each of these at HTM would also be useful for the research performed.

Outcome and conclusions

Unluckily, even though the current problems regarding the components are comparable, from a research point of view, the information and failure data of HTM is not useful.

With respect to the primary suspensions, the ones used at HTM are mostly conventional metal spring primary suspensions, as seen in picture 1. Therefore, the failures which occur to these kind of components is completely different to the ones used at the RET metros. Of course, the usual steel springs also fail, due to oxidation, rust and corrosion. As well as this, the functionality might decrease, but obviously these failures are not related to the rubber and steel suspensions used at RET metros. Moreover, due to the fact that the way of failing is different, the failure data of metal springs is not useful for the current research.

Figure 28

Related to the dampers, in HTM they are also obliged to change the oil dampers time to time due to oil leakage, which is the main failure of oil dampers in general. However, it is difficult to compare the performance of the dampers as the provider is different, so the comparison cannot be reliable as many conditions of the damper can be different. As well as this, the frequency of failure varies from the dampers used at RET.

Finally, regarding the flexible coupling, both the provider and the type used at HTM differ from the ones at RET metros. This means, again, that the comparison of failures is not possible and the failure data not useful.

Below a picture of the a bogie at HTM is observed. It is seen how different it is from the ones studied at RET.

Figure 29

The conclusion of the meeting was that even though some of the components failed similarly, the comparison with RET failures is complicated. Thus, the failure data from HTM, which is also very limited is not useful and the outcome of the research of this internship will also not be so helpful for Eric Van Zanten, as a real solution to his failure problems.