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Handling increased need of maintenance to meet future freight demands

Deterioration and effective maintenance strategies for track system and rail vehicles

Project report 2022:04 in MMS200 - Project in railway technology

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Cover: Shunting of freight wagons at a railway station in Sweden. Figure by the authors.

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Summary

This report addresses future increased demands of freight on the Swedish railways. To achieve an increase in total freight, different forms of operations can be utilized like increasing the axle load, speed, or frequency which are all scenarios that will be evaluated in the report. The impact caused by those measures will affect both deterioration and the need for efficient maintenance regarding rail vehicles and track systems. Different methods of maintenance, both currently used and newly developed methods are discussed in this report to be able to evaluate how it is possible to become more efficient. The deterioration that occurs during the operation of freight trains is described in the report since an understanding is needed to address the problems and possible solutions. What also plays a vital role in the maintenance plan is to detect faults efficiently. To get an idea about how all of these issues are handled in the industry, interviews have been held with professional staff at four large companies in Sweden. Together with literature studies, this forms the foundation of this report.

Keywords: railway, deterioration, maintenance, track, vehicles, freight

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We would like to extend our appreciation to the railway industry personnel, who took their time for interviews. Their experiences and insights have contributed to our report significantly. Based on their answers, the authors could understand current practices in the railway industry and how to better support and improve railway maintenance engineering. In this regard, we are deeply thankful to Björn Nordh, Håkan Larsson and Anders Dahlqvist at Green Cargo, Ivan Nalovski at Atkins, Robert Pallari at LKAB and Per-Olof Larsson Kråik at Trafikverket, Sweden.

The authors in Göteborg, May 2022

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1
Introduction

1.1 Background

The global energy system is in a transforming phase of becoming more sustainable and Sweden has the goal of zero net emissions of greenhouse gases by 2045 [1]. One important technique which will help to achieve this is using bio-energy with carbon capture and storage. This technique captures the carbon dioxide from renewable sources and stores it permanently.

Transportation of CO_2 will be necessary to achieve this and rail freight transport will play a vital role. This means an increase in the amount of total cargo on the Swedish railway, which besides many opportunities also comes with complications. This report will focus on how this increase in traffic on the railway can affect the deterioration, both when it comes to the rail system and the vehicles. It will also focus on the maintenance actions required to handle the increase.

Rail transportation in Sweden is already used to a large extent today, the amount of freight transported by rail was 22 222 million tonne-kilometer in 2019 [2]. In the same year the percentage of the total inland freight transport in Sweden measured in tonne-kilometers, was 30.6% by rail [3]. A company which was interviewed during this project is Green Cargo, they estimate that transport of CO_2 can increase their transported volume by 50%.

1.2 Problem definition and research questions

With an increase in freight train demands the loading weight on train and track will increase. As a consequence, this will accelerate deterioration rates of track systems and rail vehicles. Thus, malfunctioning tracks and vehicles on operations may increase. Such problems will disrupt efficient transport of goods and hence add more logistics costs. However, to meet the increasing freight demands, there could be shortage of time and personnel for maintenance and reparation. It is therefore important for freight train transport to handle the increased deterioration and set operational strategies in an efficient and successful way [4].

1.2.1 Problem definition

This study defines the problem as two following questions:

- How increasing freight volumes affect required maintenance actions?
- What maintenance strategies that are recommended?

1.2.2 Research questions

To fulfil the objectives of the research, the following questions can be answered:

- What deterioration mechanisms and maintenance actions for infrastructure and vehicles will be affected?
  This is mainly presented in Chapter 2 and Chapter 3.
- Is the increase in maintenance demands expected to be linear or exponential in transport volumes?
  This is mainly presented in Chapter 2.
- How can adverse effects be minimized by decreasing maintenance needs and/or introducing more efficient maintenance?
  This is mainly presented in Chapter 4 and Chapter 5.
- How would this roughly affect the availability of track and vehicles?
  This is presented in various sections.
- What is the main challenges and most promising approaches?
  This is mainly presented in Chapter 6.
- Is the increase in capacity feasible from a maintenance perspective?
  This is mainly presented in Chapter 6.

1.3 Interviews

To get input from professional staff in the railway sector, four interviews were held. The industrial companies that were interviewed are active in slightly different areas.

- Atkins
  Is among other things a rail consultancy. The focus during this interview was mainly planning and problems with maintenance and deterioration of wagons.
- Green Cargo
  Is a rail freight operator. The focus during this interview was mainly the need of increased freight capacity, and planning and problems with maintenance

and deterioration of locomotives and wagons.

- LKAB
  Is a mining company. The focus during this interview was mainly planning and problems with maintenance and deterioration of wagons.

- Trafikverket
  Is an infrastructure manager. The focus during this interview was mainly planning and problems with maintenance and deterioration of track.

1.4 Alternative ways to increase freight traffic

It is desired to achieve the most of every train operation, but there are constraints in the power of the locomotive, the axle load, the loading gauge and the length of the train. The number of train operations is constrained to the available time slots of the track.

1.4.1 Significantly higher capacity

When it comes to increasing the capacity, some things should first be mentioned.

- Multiple track lines
  The capacity of multiple track lines is significantly higher than for single track because trains can travel more undisturbed in each direction at the same time.

  In Sweden there are 10 909 km of trafficked track whereof 2 056 km are double or multiple track [5]. Trains on single track that travel in the opposite direction have to meet at meeting points to be able to pass each other, while they on double track can travel undisturbed from each other in both direction. One step to increase the freight can therefore be to build double track where single track is present today.

  Another advantage with double track, compared to single track, is that the maintenance work can be done at one of the tracks at a time, meaning that the traffic can be redirected and continued on the other track.

- Uniform traffic
  The capacity of uniform traffic is significantly higher than for non-uniform traffic because passenger and freight trains can travel more frequently and undisturbed from each other.

  In Sweden there is a mixed traffic situation with faster passenger trains and slower freight trains sharing the same track [6]. Passenger trains can have speeds up to 200 km/h [7] while freight trains can have speeds up to 120 km/h if they are unloaded [8]. Freight trains in un-uniform traffic may need to be put on side tracks for passenger trains to be able to pass them, while they in uniform traffic can travel undisturbed from each other in their own pace. The frequency of train operations can also be increased with uniform traffic since the speeds of the trains then are more equal. One step to increase the freight can therefore be to keep the passenger and freight traffic apart. This can for example be done by having dedicated lines for one type of traffic or by building quadruple track.

Another advantage with separate traffic is that the freight trains do not have to be put on side tracks for passenger trains to pass, meaning that the energy usage and wear on wheels and brakes from starts and stops of heavy freight trains can be reduced [8].

However, such upgrades are very costly and also space and time consuming.

1.4.2 Upgrading of existing lines

Most of the new railway lines that are built today around the globe are constructed for high speed or regional passenger traffic. Upgrading of existing lines is a more common way to increase the freight capacity. It is therefore important with efficient methods and means to be able to meet the higher demands [4].

There are various other ways to increase the total accumulated tonnes at the Swedish railway. Some of them will be presented here together with some of their practical needs in order to be feasible.

- Increased axle load of wagons
  The increase in freight is obtained by loading more weight on the wagons of the train, leading to an increased axle load while the length of the train, the loading gauge of the wagons and the frequency of train operations are kept unchanged.

  To be able to increase the axle load, the track needs to be upgraded with sufficient components. Also, for example bridges and culverts may need to be redesigned. The standard axle load in Sweden is today 22.5 tonnes, and often 25 tonnes [6]. Some lines in the north of Sweden have an axle load of 30 tonnes and aims to increase it to 32.5 tonnes. The wagons then need to be upgraded with running gear suitable for the higher axle loads [9].

- Increased length of trains
  The increase in freight is obtained by connecting more, or longer, wagons to the train.

  To be able to increase the length of the trains on single track, the meeting points need to be lengthened for the trains to be able to pass each other. The meeting points are today set from 450 metres up to 750 metres in Sweden. On multiple tracks, such as double track, it is not the same problem with longer trains out on the line as it is on single tracks [6].

- Increased loading gauge of wagons
  The increase in freight is obtained by loading more volume on the bulkier wagons of the train.

  To be able to increase the loading gauge, the surrounding infrastructure have to be redesigned. The Swedish gauging principles were defined 1893, but have been updated more recently. It would be very costly and create difficulties to change load profiles since it will affect the existing infrastructure and vehicles [10]. For example, the distance between the tracks on double track may need to be increased and tunnels may need to be redesigned.

- Increased frequency of train operations
  The increase in freight is obtained by driving more separate trains.

  To be able to increase the frequency, there must be available time slots that work with the infrastructure. This is a consequence of the mixed traffic situation in Sweden. If more freight trains operations are to be done, the track will be more crowded and more time slots will be occupied leading to a harder interplay with the passenger trains. For example, the number of meeting points may need to be increased. There will also be less time slots for track maintenance.

An increase in freight can of course also be a combination of those alternatives. The alternatives can also be combined with an increased speed, and this can especially be desired with an increased frequency of train operations.

1.4.3 Some challenges beside deterioration and maintenance

The different alternatives in Chapter 1.4.2 have some important challenges beside deterioration and maintenance. Challenges regarding the deterioration and maintenance will be covered more later in the report.

1.4.3.1 Utilisation of the upgrade

It is important that it is possible to utilise the upgrade in a good way for it to increase the total accumulated tonnes. For example, for low density goods an increased axle load may not be sufficient since the goods already occupies a big part of the loading gauge. In that case an increased loading gauge or train length would probably be more efficient. On the other hand, an increased axle load can be sufficient for high density goods, while an increased loading gauge may not be.

1.4.3.2 Interplay with passenger traffic

The passenger traffic will be disrupted with more, long, heavy and slow freight trains. Combining the alternatives with higher speed will lower the time on track and make the interplay with passenger trains better, especially if the frequency of freight train operations is increased. It will also be more time available for track maintenance, although the increased time available for track maintenance may not be corresponding to the increased need of maintenance that comes with the higher speed.

1.4.3.3 Longitudinal forces in the train

With heavier trains, both higher axle load and longer train, the tonnage is increased. The couples further back of the train will get more load which can cause unwanted dynamic longitudinal forces in the train. The locomotive should also be driven in a different way to manage the increase in load, and length, making the skill of the driver more important [8].

The brake systems on freight trains are usually pneumatic and controlled by pressure variations through a main brake pipe. The pressure drop, that brakes the wagons, propagates from the front of the train to the back. If it is not correctly arranged in a smooth way it can lead to that unbraked wagons in the back of the train push on braked wagons in front. This can give longitudinal forces that can lead to lifting of wagons in long and heavy freight trains [11].

1.4.3.4 Parking spaces and handling of wagons

Higher axle loads limits the need for more parking space since the amount of wagons can remain the same. This also limits the number of wagons that have to be handled with loading, unloading, shunting and maintenance. However, an increase in the amount of wagons may be needed with an increase in the train length and the number of train operations. This will result in a need of more space at shunting yards and at parking tracks near workshops, as well as more wagons have to be handled.

1.5 Limitations in research

The limitations of the research are as follows:

- Only an increase of the rail freight in Sweden will be investigated.
- Life cycle cost assessment will not be considered or discussed at any large extent, although it is very vital and plays a major roll in decision making.
- An increase of freight will only be investigated for pure upgrade alternatives, see Chapter 1.4.2, meaning that combinations of those will be left aside.

- An increase in loading gauge, see Chapter 1.4.2, will not be investigated as it will not independently affect the deterioration of track and vehicle.
- The investigation will be quite broad and general, it will not be focusing on specific items such as bridges and tunnels.

2

Deterioration

2.1 Deterioration mechanisms

Plastic deformation

The meaning of plastic deformation is permanent deformations in a solid body. In the railway field, plastic deformation can mainly be caused by contact load between track surface and wheels. For instance, tracks on the iron ore transport line experience a load higher than 250 kN in a small contact area of 80-200 mm^2. The high stress loading generates plastic deformation on the railhead [11].

Wear

Wear constitutes gradual material removal due to contact and sliding motion. Rolling wheels on tracks generate slip with high contact loads. The slip between rolling wheel and track wear rail head as shown in Figure 2.1. Since wear changes wheel–rail contact geometry, it can lead to contact stress increases, resulting in faster track deterioration. Magnitude of contact load, slip, and rail hardness determine wear rates of track. Wear can also occur in the ballast, which can cause track geometry irregularities.

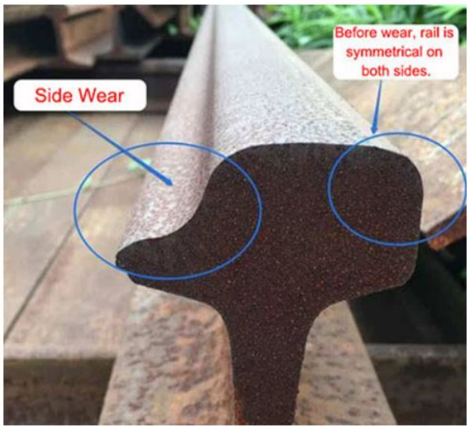

Figure 2.1: Railhead geometry with wear. Figure from [12].

Fatigue

Fatigue is deterioration phenomenon which appears in solid bodies exposed to high alternating load. Rolling contact loads on track and wheels lead to fatigue in rail operations. One of key points in fatigue is that it is a threshold phenomenon. When load (stress) amplitude exceeds a fatigue limit, fatigue lives exponentially decrease as shown in Figure 2.2.

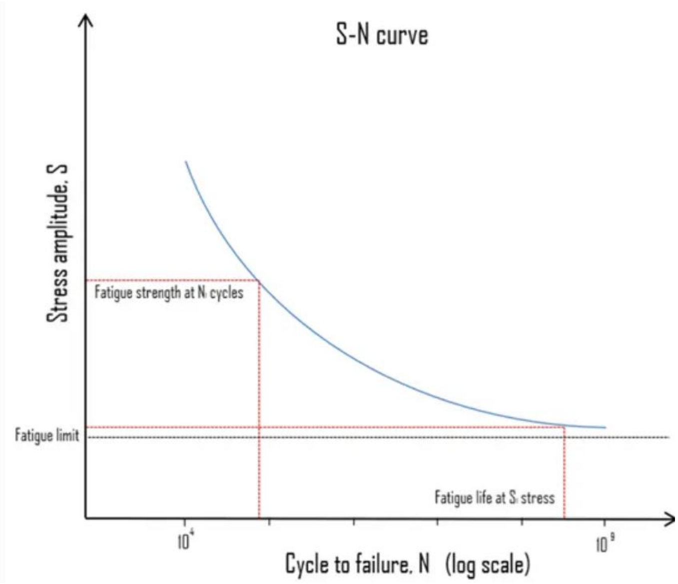

Figure 2.2: Fatigue life S-N curve. Figure from [13].

2.2 Track system

Track components suffer from deterioration due to track forces and creep. The deterioration rate of the track is decided by the total forces acting on the track [11].

2.2.1 Rails

Rolling contact fatigue occurs near the contact patch between vehicle and track while plain fatigue occurs further away from the contact patch. Plain fatigue usually occurs near the rail foot or the lower corner of the rail head where cracks can grow from defects and stress concentrations [14].

High normal and tangential stresses can cause head checks on the rail surface, and together with high dynamic stresses from local irregularities can local cracking, so-called squats, occur. Longitudinal cavities inside the rail head can cause tache ovals, but due to today's steel production they only sometimes occur near welds [11].

Due to the contact forces and the creep forces in curves, gauge corner wear occurs on the outer rail while top surface wear occurs on the inner rail. The track gauge is increased with gauge corner wear [11].

Plastic deformation can occur due to high loading close to free edges and severe contact geometry. The material will be redistributed as well as residual stresses and anisotropy can occur. It can also cause crack initiation [16].

2.2.2 Rail joints

Continuously welded rails are today common. Tensile residual stresses and phase transformations are usually induced in the welding process. It can speed up fatigue deterioration, and may together with material impurities and high load from poor welding cause cracks, and in worse case detachment of the rail [14].

To insulate rail sections electrically, insulated joints are usually used together with continuously welded rails [14]. An older method for connecting rails, and a method for insulating rails, is with fish plates and bolts. This type of rail joint is a weak spot since it is less stiff and contains a gap between the connected rails. The wheels dip down when going over the joint due to the weakness and the gap, and this leads to high dynamic forces affecting both the wheels and the rails [11]. Plastic deformation can therefore occur at the joint which can lead to bridging , so-called lipping, at the rail head over the gap [14].

2.2.3 Switches and crossings

Switches and crossings need to handle different shapes of wheel profiles and the wear state of the wheel will affect the loading. The stresses can be high at switches and crossings which can cause plastic deformation and cracking at for example switch blades and crossing noses. There are also large relative motions between the wheels and the rail at switches and crossings which can cause wear at for example switch tongues and crossing noses [16].

2.2.4 Rail fastenings

The repeated loads from trains can lead to deterioration of the rail pads [11]. Insufficient fastening, due to cracking and detachment, can occur if the rail fastening is subjected to high loads or due to wear of the rail pad [14].

2.2.5 Sleepers

The repeated loads from trains can lead to cracks in sleepers [11]. The cracks can occur and grow from the geometrical irregularities near the fastening holes where the stresses are high. Out-of-round wheels, together with, for example, a high axle load can cause a high impact load on the sleeper that causes it to crack. The ballast support will influence the location of the cracking of the sleeper. With proper ballast support it can be prevented that cracks form in the middle of the sleeper where it is weak [14].

If sleepers and rail fastenings do not work properly it can affect the transferring of loads as well as affect the track gauge. Concrete sleepers are the most common type on the mainlines in Europe and Sweden, but wooden sleepers are still in use in many places [11]. Concrete sleepers provide good stability and have a long service life, while wooden sleepers provide good elasticity and insulation [15]. Ballasted track with concrete sleepers can be seen in Figure 2.3.

Figure 2.3: Ballasted track with concrete sleepers. Figure by the authors.

2.2.6 Ballast

The deformation and vibration from train movements can cause ballast wear [11], and in severe cases cracked ballast stones. This will influence the function of the ballast since the internal stiffness is decreased. Further, wear particles change the stiffness and resistance ability of the ballast. The deformation and vibration from train movements can also gradually lead to ballast settlements [14].

2.2.7 Catenary

The contact wire will wear due to the contact with the pantograph on electric trains [8]. The contact can also cause the catenary to fatigue.

2.3 Rail vehicles

Vehicle components suffer from deterioration due to track forces and creep. High impact forces, and vibrations, between wheel and rail can occur due to track defects. This can lead to further damage on both track and wheel [11].

2.3.1 Wheels

Due to the contact forces and the creep forces in curves, together with the wheel angle of attack, tread wear occurs on the inner wheel while flange wear occurs on the outer wheel. High normal and tangential stresses can cause a phenomena on the wheel that corresponds to formation of head checks on the rail. The wheels can also become eccentric due to poor centering during profiling [11].

See also Chapter 2.3.3 for how brakes affect the deterioration of wheels.

2.3.2 Axles and bearing boxes

High load magnitudes can cause the bearing box to deteriorate which leads to heat that melts the axle. An axle can also break due to plain fatigue caused by corrosion on the axle [17].

2.3.3 Brakes

It is common with brake blocks that act on the wheel tread on freight wagons. When the brake block is applied, the wheel tread is roughened. In addition, the wheel can crack due to thermal overloading from the heat energy that is generated. Out-of-round wheels, like wheels with a wheel flat, can occur if the wheel is locked during braking and slides on the rail that also gets affected. Corrugation can arise on the wheel tread during braking when some parts expand and wear due to a higher temperature [11].

Brake blocks and wheels wear when pressed against each other. The respective deterioration rate depends on the material of the brake pads. Brake blocks can for example be made of cast iron, composite materials or be sintered [10]. Brake blocks can be seen in Figure 2.4.

Figure 2.4: Brake blocks. Figure by the authors.

2.3.4 Springs and dampers

Suspension in freight wagons need to handle large variations in payload, since the wagons can be everything from empty to fully loaded. Springs are used to make the vehicle smoother and more isolated to forces on the track [10]. Some common springs on freight wagons are rubber springs of the chevron type, coil springs and leaf springs. The repeated loads that the springs suffer from can cause them to wear and fatigue.

Dampers are used to limit the dynamic motions of the vehicle. Friction dampers get wear on the friction surfaces but they are simple, cheap and robust, and are therefore often used on freight wagons. The friction between the leaves in a leaf spring allows the leaf spring to serve as both a spring and a damper. Rubber springs can provide a damping effect while coil springs give almost no damping [10]. A bogie with leaf springs can be seen in Figure 2.5.

Figure 2.5: Bogie with leaf springs. Figure by the authors.

2.3.5 Buffers and couplers

The buffers and couplers can wear because of the dynamics within the train [8]. The repeated loads can cause the buffers and couplers to fatigue.

2.3.6 Pantographs

The pantograph on electric trains will wear due to the contact with the contact wire [8]. The contact can also cause the pantograph to fatigue.

2.4 Modelling of deterioration

2.4.1 Deterioration models

The rate of deterioration mechanism such as wear, fatigue, and crack depend on the level of the external load. Basically, each deterioration has own threshold and it increases exponentially over the limit. However, deterioration rate is quite slow with small variation of loads. The exponential characteristics may be approximated as linear as shown in Figure 2.6.

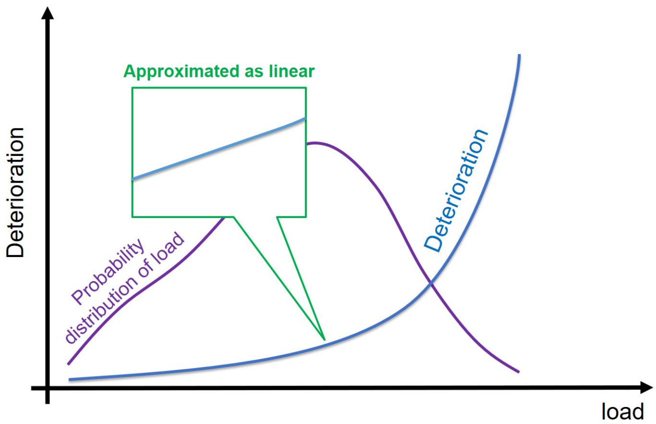

Figure 2.6: General deterioration curve over load. Figure by the authors.

2.4.2 Track system

Linear model
The first step to model track deterioration assumes that it is proportional to amount of tonnage that passes by the track as follows:

$$DQ = k_1 \times P \tag{2.1}$$

in which DQ is a degradation of track quality, P is tonnage on track, usually measured as Million Gross Tonnage (MGT), the coefficient, k_1 is determined from track and vehicle operating conditions [18].

Exponential model
The above linear approximation is applicable with a small variation of loads. However, the track deterioration generally shows exponential behavior as a whole. An exponential model for track quality over time can be expressed as follows:

$$Q(t) = Q_0 \times e^{bt} \tag{2.2}$$

Here Q_0 is initial quality of infrastructure, b is the deterioration rate and t is enlapsed time. The exponential term, e^{bt} describes rate of quality degradation over a longer period [19]. It shows that track quality degrades faster over time without proper maintenance action. Therefore, it is important to forecast future maintenance demands based on trend analysis of train transport.

Deterioration law model
Another quantitative method to estimate track deterioration as function of tonnages, axle load, and train speed is expressed as follows:

$$E = k \times T^{\alpha} \times P^{\beta} \times V^{\gamma} \tag{2.3}$$

where E is deterioration, T is tonnage, P is axle load, and V is speed. α, β, and γ are constants which represent the exponential effect of load parameters on deterioration rates [20].

2.4.3 Rail vehicles

Wheel axle
The life time analysis of railway wheel axle can be based on studies of dependency between number of load cycles and fatigue crack length [21]. The crack growth of the wheel axle shows an exponential increase above a threshold load level, shown in figure 2.7.

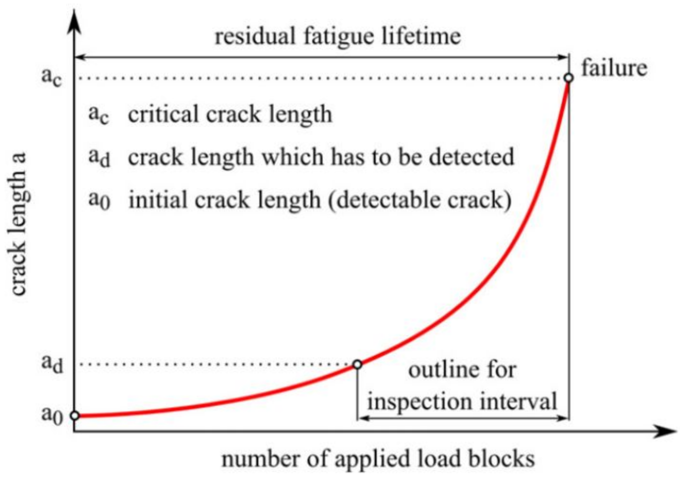

Figure 2.7: Dependency between fatigue crack length and load. Figure from [21].

Bearing
SKF (Svenska Kullagerfabriken, Swedish ball bearing factory) estimates bearing life using a rating life formula as follows:

$$L_{nm} = a_1 \, a_{\mathrm{SKF}} \, (\frac{C}{P})^b \tag{2.4}$$

where the L_{nm} is bearing rating life [millions of revolution], a_1 is the life adjustment factor for reliability, a_{SKF} is life modification factor, C is the basic dynamic load rating [kN], P is equivalent dynamic bearing load [kN], and b the exponent of the life equation [22].

According to the the above formula, dynamic loading of the bearing significantly affects the bearing life. In other words, both axle load and dynamic impact due to track condition influence the bearing life.

Wheel wear
In the interview with LKAB [9], it was stated that 80% of their costs were due to wheel maintenance. The maintenance carried out on the wheels is usually reprofiling. Reprofiling of wheels mainly aims to remove surface wear and cracks, and to recover the running part of the thread. Presuming linear deterioration, wear rate can be estimated as follows:

$$SWR_{(n)} = 10^5 \times (\mathrm{DO}_0 - \mathrm{DO}_n)/S \tag{2.5}$$

where the $SWR_{(n)}$ is the service wear rate, expressed in mm $/10^5$ km, the DO_0 is initial diameter of the wheel, DO_n is the diameter after n-th reprofiling of the wheel, S is the running distance of the wheel until n-th reprofiling [23]. Maintenance engineers can plan schedule to exchange wheels based on $SWR_{(n)}$.

3

Maintenance actions

There are two major tasks in railway maintenance: inspection and maintenance work itself. Inspection task includes monitoring the conditions of railway systems and detecting faults. On the other hand, maintenance work implies series of actions to fix failures in railway systems.

Under the interviews with the companies it was clear that different components have different maintenance plans. Much of the maintenance work is determined by planning intervals from historical data to decide the cycles. Other components are handles using a conditioned based maintenance decided from measurements.

3.1 Track system

Trafikverket in Sweden is today in charge of maintaining 14 200 km of railway [24]. The main focus is to make sure that the railway system is safe and available for traffic. In the maintenance plan from Trafikverket [24], it is described that the two main maintenance activities categories carried out are:

Base maintenance

In this category, both supportive maintenance and preventive maintenance are included. It can overall be concluded that the base maintenance aims to keep the railway functioning, without making it better or worse. The supportive maintenance includes matters such as emergencies and unpredictable accidents. This could be for example the signalling system out of order, an animal getting hit by the train or problems related to snow during the winter.

The preventive maintenance is divided into condition based and predetermined maintenance as shown in Figure 3.1. The condition based maintenance is determined thorough inspections and controls, and money assigned to this part is determined thorough historical experiences. The predetermined maintenance is carried out periodically and is planned early in advance.

Reinvestments

Along with basic maintenance, reinvestments is the other major part of the maintenance carried out. This category aims to keep the function quality of the railway in a long term view by replacing parts that are about to pass their expected lifetime.

Trafikverket describes that their goal is to increase the proportion of reinvestments compared to base maintenance, since this will be more cost efficient [24].

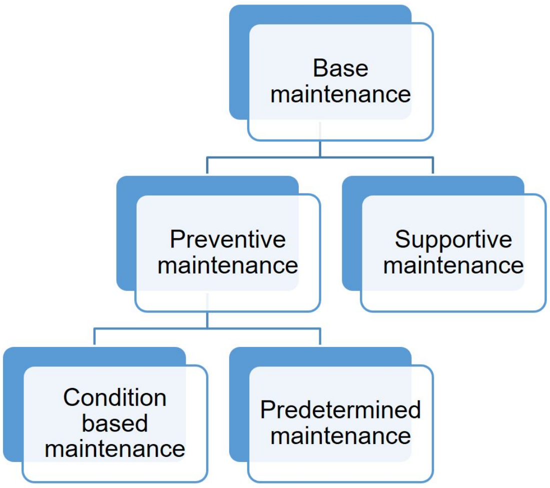

Figure 3.1: Maintenance categories. Figure by the authors.

3.1.1 Detecting faults

It is of importance to be aware of the condition of the track, which is why different methods are used to collect data. This data can then be used to perform condition based maintenance on the track system. To detect geometric faults on the rails, often caused by wear and settlement in the ballast, a measuring vehicle could be used as shown in Figure 3.2. This measures the vertical and lateral deviation for each rail [11]. The distance between the two rails is also measured, both in the lateral and vertical direction. This is then analysed to decide if corrective maintenance should be carried out.

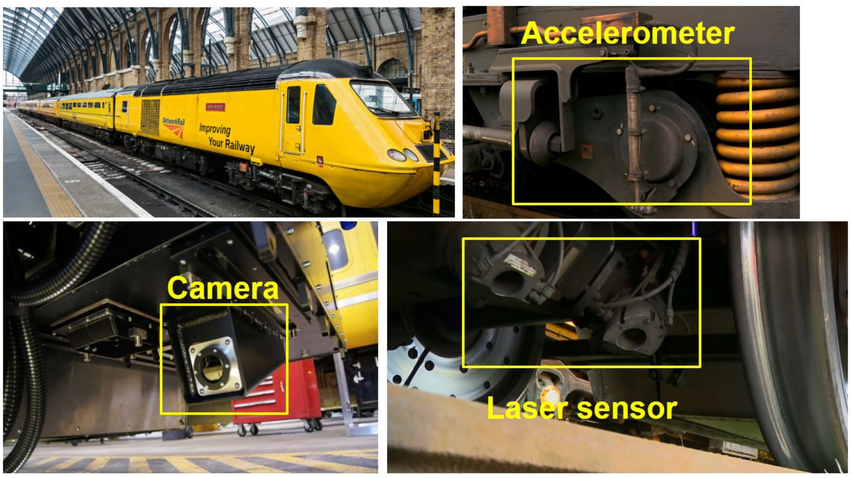

Figure 3.2: Measurement train to monitor track. Figure from [25].

Cracks and other types of damage are often caused by fatigue on the rail such faults can be discovered through ultrasonic inspections or eddy current techniques which are performed by of a measuring vehicle [14]. The rail head profile which can be damaged due to plastic deformation or wear can also be inspected by a vehicle or a measuring trolley. Another example of more monitoring to allow condition based maintenance is the time measurement of a switch to change position. If it repeatedly is taking too long, this will be alarmed and the switch will be lubricated by a worker.

3.1.2 Maintenance measures

Many forms of corrective maintenance are carried out on the railway. Some are simple, like adding lubrication to a switch, while some require large machines performing the work. Track geometry faults can be fixed by improving the condition of the ballast. This is done by a tamping machine in Figure 3.3, which with the help of force and vibrations push the ballast into the desired position. This restore the track geometry.

Figure 3.3: Tamper and ballast regulator. Figure from [26].

To fix cracks in the rail caused by fatigue, either welding or replacement of the rail can be the solution. When the rail is replaced, usually at least 5 m of the rail is removed and the new rail is welded to the old. Of course, welding is always crucial since it can give rise to problems like thermal cracks related to high tensile residual stresses [16]. A measure used to correct the rail head profile is grinding as shown in Figure 3.4. This is typically done by a grinding train.

Figure 3.4: Rail grinder. Figure from [27].

Another method which helps to decrease the deterioration of the railway track and wheels is to decrease the friction forces. This can be done by lubrication, and is used in narrow curves. Lubrication is added by a device which senses when a train is coming from vibrations. Too much lubrication should not be used, since this can cause braking and traction problems [11].

3.1.3 Challenges

Trafikverket describes in their maintenance plan [24] that an increase in traffic will affect the cost of the maintenance being done. This is due to:

- Increasing traffic decreases the time of coherent maintenance, which creates costs for when the machines and work is standing still.
- Short time slots for maintenance leads to provisional solutions, while waiting for larger operations.
- The total need of maintenance is increased which leads to higher costs of machines and staff.
- Maintenance during day time may cause traffic disturbances, and higher working costs on nights.

3.2 Rail vehicles

As many other types of vehicles, preventive maintenance is carried out on rail vehicles. This is often predetermined maintenance which is planed by specifying what should be done and how often. In the interview with LKAB [9], it was explained that large maintenance works are planned regularly and the cycles are based on historical experience. Condition based maintenance is also performed on the vehicles, this often consist of smaller jobs that need to be done. An example of this is reprofiling of the wheels, which is done about three to five times during the life of one wheel in LKABs case.

3.2.1 Detecting faults

It is possible to detect faults such as wear, fatigue, cracks and out-of-roundness on the rail vehicles to prevent accidents. This is done with the help of both track and workshop based detection to avoid serious accidents like derailment which can have devastating outcomes.

3.2.1.1 Track based detection

It is possible to some extent to monitor the condition of the wheel, axle and the bearing box on the vehicle, which all are critical components which can lead to a derailment if they were to break. Common methods to detect some types of deterioration mechanisms of these components are heat and noise sensors [10]. If there is problem with bearing deterioration this will result overheating, which will be alarmed with the heat sensor. The noise sensor will alarm if any irregularities are detected, like a damaged bearing.

An other way of monitoring wheel out-of-round conditions is to detect wheel–rail contact force on the track as shown in Figure 3.5. The wheel impact load detector can measure dynamic loads for example via rail mounted strain-gauges. The detector can derive quantified impact effects from measurements, which represents wheel out-of-roundness levels. [28]

Figure 3.5: Wheel impact load detector at Sunderbyn. Figure by Matthias Asplund, Trafikverket, from [29].

3.2.1.2 Workshop based detection

The maintenance work for detecting faults is also carried out on the workshop. There may be multiple sensors installed in a wheelset diagnostics system as shown in Figure 3.6. These sensors analyze wheelset conditions such as out-of-roundness, wheel diameter, wheel profile, and wheel tread wear.

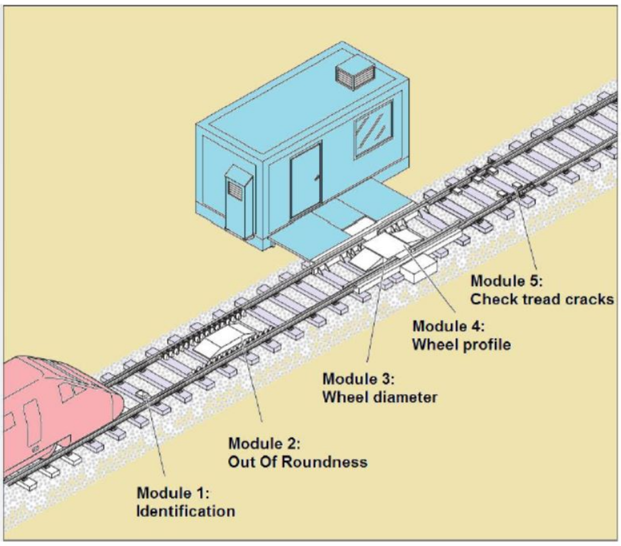

Figure 3.6: The wheelset diagnostics system ARGUS. From [23].

To detect axle deterioration in the form of fatigue, ultrasonic testing can be done [17]. This is important since if an axle was to brake, this can lead to a derailment. Other methods that are used is monitoring the wheels condition, both using of visual inspections and measurements.

In the interview with LKAB [9], it was stated that they can often see wear on all components and they therefore may to decide what components that need maintenance or replacement. Some tests which can help with this is testing the door system, coupling system and computerised break tests for each wagon. They thereby ensure that the train will be able to run until the next service.

3.2.2 Maintenance measures

Different methods to maintain the components are carried out on the vehicles, and according to LKAB, 80% of their maintenance budget is due to the wheels [9]. The method that wheels are maintained is through reprofiling. This will extend the lifetime of the wheel and give a new solid surface. To maintain bearing boxes, lubrication is important, since this otherwise can give rise to melting of the axle in too high temperatures [17]. Replacement of different deteriorated components of the vehicle is an important way of maintaining and the replacement intervals are often decided from historical data.

3.2.3 Challenges

It is crucial to plan vehicle maintenance, since the location of where the maintenance is performed is of importance. If something on the vehicle breaks out on the line, it can be hard and expensive to fix as compared to in a workshop. In the interview with Green Cargo, they expressed their concerns with not having enough workshops, as well as the trains being to long for the intended workshop slot. This means for example that they can only maintain one train at a time, instead of two trains which the slot in the workshop is intended to be able to fit [8].

3.3 Effect of increasing demands on maintenance

Axle load
In rail vehicle maintenance, wheel wear and cracking will significantly grow with higher axle load. Maintenance frequencies for wheels, bearings, and wheel axles are expected to be higher. Maintenance engineers in the workshop need improved inspection systems to check condition of wheel wear.

Operation frequency
Typical relationship between load magnitude and deterioration is exponential as mentioned in Chapter 2. When operating frequency of trains becomes double, deterioration of rail vehicles also doubles.

Speed
With faster trains, the wheel–rail contact loads will have a larger scatter in magnitudes leading to wheel and rail damage. Faster trains are also more sensitive to different defects resulting in higher requirements of maintenance [4]. Figure 3.7 shows that faster trains generate more high magnitude load events, which accelerate deterioration.

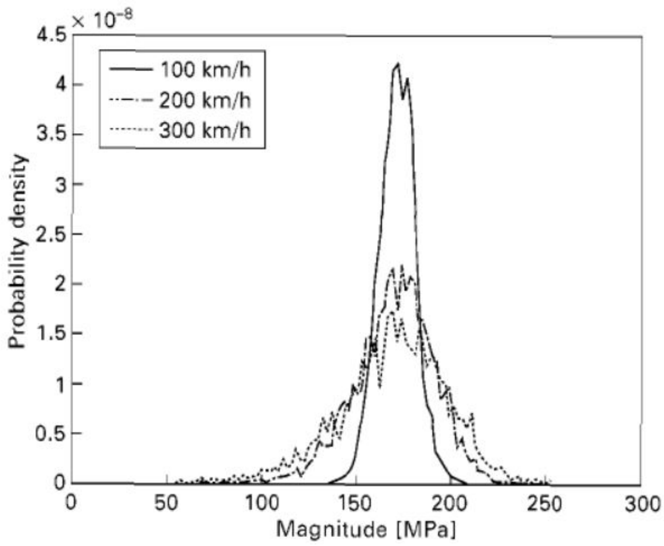

Figure 3.7: Impact load distribution regarding the influence of speed. Figure from [30].

4

Decreasing needs of maintenance

4.1 Track system

4.1.1 Ballasted and slab track

Heavy axle loads and high speeds put demands on the track. To keep a high safety and a low track deterioration, ballasted tracks need to be designed after the demands with components of high performance. High performance track can for example have continuously welded rails attached with pandrol fastenings to concrete sleepers, while low performance track can have rail with joints attached with spike fastenings to wooden sleepers [11]. The choice of components will affect how well the track meets the demands from the traffic. If the track is subjected to higher demands than what it was built for, it will deteriorate too quickly and thus it will also affect the need for maintenance.

Slab track is, compared to ballasted track, more stable and can withstand geometrical irregularities better. There is also no need for ballast actions, such as completion and cleaning, making it possible to save up to 70 percent in maintenance cost. On the other hand, it should be mentioned that the construction of slab track is far more expensive than for ballasted track, as well as the reparation of arisen track damage and wanted track changes are more complicated, time-consuming and costly [11].

4.1.2 Rails

Track of continuously welded rails gives less wheel and rail wear, since they provide a more gentle transition, and do not need as much inspection and maintenance as track that is not continuously welded [11].

To reduce gauge corner wear, premium grade rails with higher tensile strength can be used [11].

4.1.3 Managing friction forces

Lubrication can be used to reduce the friction forces, and hence to reduce wheel and rail damage, with the constraint not to give the train problems with traction and braking [11].

4.2 Rail vehicles

If the upgrade of capacity is done without changing the fleet of wagons, the wagons will have a faster degradation since they will have more loading per time unit [4].

4.2.1 Tare mass

The weight of the wagon is related to the maintenance [11]. With less tare mass, the payload can be increased without the need of increasing the axle load. For example, aluminium has a lower density than steel, but unfortunately it has a lower fatigue strength. To overcome this kind of characteristics, maybe some type of sandwich structures or composites, if they get economically competitive and capable to withstand higher loads, can be possible in the future [10].

4.2.2 Rigid-frame and bogie wagons

Wagons with bogies can cope with more payload, since it will be distributed on four axles instead of two axles, without exceeding the maximum permitted axle load. Bogie wagons can also be longer than rigid-frame wagons since their axles can rotate more vertically. However, weight is added with bogies. In addition, complexity is increased, making the wagons with single axles better weight-wise, cheaper and easier to maintain [10]. A rigid-frame and a bogie wagon can be seen in Figure 4.1.

Figure 4.1: Rigid-frame and bogie wagons. Figure by the authors.

4.2.3 Angle of attack

The creepages and creep forces, related to wear and rolling contact fatigue, can be high due to a large angle of attack that occurs when the train travels through a curve. The angle of attack can be reduced with an increased curve radius, a less stiff wheelset suspension and a shorter wheelbase. For bogies with radial steering, flange wear can decrease but tread wear can increase leading to hollow worn wheels [11].

4.2.4 Tread and disc brakes

Brake blocks, that act on the running tread, are common on freight wagons due to their low weight and simpleness. To avoid roughening of the wheel tread, and the risk of thermal overload of the wheels, disc brakes can be used. Disc brakes consists of brake pads that act on separate discs on the axle or the wheel. The performance of the disc brakes is usually better than tread brakes [11] since the friction is less speed dependent. But on the other hand, tread brakes clean the running surface and small roughening can improve the adhesion. The disc brakes are also more costly, heavier and harder to maintain. But they are also less noisy and the brake pads have a relatively long life-time before they need to be changed [10].

4.2.5 Material of brakes

The material of the brake blocks is also affecting the wear. For example, with cast iron blocks there will be more wear on the blocks, since the steel of the wheel is harder. With composite materials and sintered blocks, which have low block wear, there will be more wheel wear. It should also be mentioned that composite materials blocks increase the risk of thermal overload in the wheels and that sintered blocks are expensive. These two alternatives are also better when it comes to cleaning of the wheel tread as well as they are less noisy and less friction dependent than cast iron blocks [10].

4.2.6 Managing locked wheels

Anti-slip devices can make the wheels rotate during braking and thus prevent them from getting locked which can lead to wheel flats [10].

4.3 Avoiding complexity

If wagons and track are simple, there are less things that can break and less to maintain. The need of maintenance can be decreased if there are few parts that are to be handled. For example, the handling by the customer is very small for tank wagons since they only connect a hose to the wagon. The tank wagon does not have any doors or similar things that can break, meaning that the maintenance can be focused on wheels and brakes of the tank wagons [8]. On the track reduced complexity to avoid too many switches near train stations where many trains pass, brake and accelerate.

See also Chapter 4.2.2 for how rigid-frame and bogie wagons affect the complexity, Chapter 4.2.4 for how tread and disc brakes affect the complexity, and Chapter 5.2.3.2 for how sensors affect the complexity.

5

More efficient maintenance

5.1 Maintenance strategies for increasing demands

5.1.1 Stricter maintenance intervention

Maintenance actions for high track quality can not only extend track lifetime but also be economically sustainable in the long term. For instance, tamping work with a stricter intervention level increases maintenance frequency in short term. However, higher track quality results in reduced a need for tamping and expands the lifetime of the track in the long term [31]. This can also be applied to rail vehicle maintenance.

In other words, it is necessary to reinforce short-term maintenance such as monitoring wear, damage, and fatigue. More frequent short-term maintenance can save costs and extend the life-time of wagons, resulting in reduced needs for major maintenance.

5.1.2 Field maintenance outside workshop

Based on the interview with Green Cargo, main issues of increasing maintenance demands relates with maintainability of workshops [8]. If current maintainability remains same without improvements, it can lead making workshops crowded.

One of solutions to this problems could be maintenance work for wagons outside the workshop. Those wagon maintenance works are under operation named 'R0' to prevent larger deterioration [8]. Wagon maintenance work outside of workshop can consist of detecting faults and wear in wheel sets. Those preliminary checkups become fundamental information to maintenance decision in workshops.

This solution requires portable detecting devices/sensors which maintenance engineers can install outside workshops. Therefore, it will primarily need technological support to realize the solution.

5.2 Automation and digitalisation

5.2.1 Digital twin

The resources and activities that are needed to maintain the railway infrastructure can be more effectively utilised, optimised and developed with the help of digital twins [32].

5.2.1.1 Simulation

With a digital twin, and the data from information systems, it is possible to simulate and study for example maintenance operations and changes. It can then be seen if the operations and changes are suitable and how they should be handled before making them on the physical system. This makes it possible to improve the performance of maintenance, as well as the impacts on the trains can be examined and better prepared for. Thus, a digital twin can save both money and time [32] since simulations make it possible to see the effects faster and in advance, which enables an optimisation of the intended activities.

It can also be desirable to simulate the effects on availability of a vehicle if a maintenance parameter is changed. For example, it may be possible to simulate the effects on the number of reprofilings each year, the needed size of the wheel pool and the need of machines if the maximum allowed flange height is decreased by one millimetre.

5.2.1.2 Prediction

Unreliable elements and the planning of maintenance can be identified with the help of constantly updated diagnostics [32]. The railway can be carefully examined and the condition of the operating elements can be predicted in real time with a digital twin. This makes it possible to predict the need for maintenance work. Also, potential problems can be caught before they impact traffic [33].

5.2.1.3 Safety and efficiency

With the possibility to monitor the track remotely, less manual track inspection will be needed, at the same time as the work is done in a more controlled environment, which increases the safety for staff. It also improves maintenance efficiency [33]. For example less travel time is needed for maintenance staff to do inspections.

5.2.2 Maintenance planning

The scheduling of maintenance can be improved with automation and digitalisation. Scheduled maintenance is generally safe and the standard practice today. The scheduled maintenance can be done according to the safest maintenance periods based on historical performance and estimations from manufacturers, making it imprecise [34].

With scheduled maintenance, a lot of unnecessary maintenance is done since it is generally based on cases close to the worst, meaning that some parts will be changed earlier than required. However, early failure of components may arise due to manufacturing faults, assembly mistakes or reparation mistakes. In the worst case these are not caught because they are happening between the scheduled maintenance [34].

5.2.2.1 Condition based maintenance

Condition based maintenance can be scheduled and made according to data from sensors that give an understanding of the actual condition of the track or rolling stock. This makes it more precise than ordinary scheduled maintenance. With condition based maintenance, less unnecessary or too early maintenance is done which overall lowers the amount of needed maintenance. Additionally there is a larger probability that early failures due to manufacturing faults, and so on, will be detected and caught in time [34].

Condition based maintenance with too low or too strict limits before maintenance is triggered must be avoided. Some kind of foresight and possibility to plan maintenance before worst case failures occur is needed to keep a constant and manageable flow in the workshops. It is not good if the workshops are overfull one day and empty the next day.

5.2.2.2 Predictive maintenance

Physical modelling, artificial intelligence and machine learning programs can work on the collected data from sensors, by comparing them with a limit state, to be able to predict when maintenance is likely to be required. With predictive maintenance, the maintenance resources of operators can be better scheduled in advance and allocated. This improves the management of the resources and reduces the down times [34].

5.2.3 Drawbacks

5.2.3.1 Vulnerability

With an increased automation and digitalisation, the risk of cyber attacks is also increased and it becomes more important with cyber security [35].

5.2.3.2 Complexity

A freight wagon is a fairly simple mechanism [8]. The complexity of the wagon will increase if it gets equipped with sensors to collect data, at the same time as sensors need power to operate. It can also be too much complexity if every wagon in the fleet is equipped with the measuring system. This will also introduce more components on the wagon that can fail or break down [9]. It may therefore be more suitable to measure the condition of the wagons from the track, instead of from the wagons. One sensor from the track can thus measure the condition of all the passing wagons, as well as there perhaps may be less sensors to take care of.

5.2.3.3 Amount and quality of data

A lot of data can be collected with sensors, but it also needs to be quality ensured, evaluated and stored somewhere. Sometimes quality is better than quantity, and for the data to be valuable and useful, it needs to be trustable with few uncertainties.

For example, the measuring tools may have to be calibrated to present the correct values. Further, trains during braking, accelerating and curving probably give different values than trains with constant speed at straight track.

It may be possible to get a confirmation that there is something wrong with a wagon if the sensors at the track that measure the condition of the wagons are located rather close to each other and signals for the same problem. With too few sensors at the track or with sensors in the wagons, it may be more unclear if it is something wrong with the sensors or with the actual wagon.

5.3 Simplify for maintenance

If the track and the rolling stock are simple to maintain, it can lead to that they also become faster, cheaper and safer to do maintenance on. The availability of track and rolling stock will be higher if the maintenance can be done faster.

See also Chapter 4.2.2 for how rigid-frame and bogie wagons affect the simplicity of maintenance, Chapter 4.2.4 for how tread and disc brakes affect the simplicity of maintenance, Chapter 4.3 for how avoiding complexity affects the simplicity of maintenance and Chapter 5.2.3.2 for how sensors affect the the simplicity of maintenance.

5.3.1 Design for maintenance

A wagon, for example, can become easy, cheap and fast to maintain if the maintainability has a high priority during the development. It can result in that a bogie can be taken apart and put together within ten minutes by an experienced worker [9].

5.3.2 Modularisation

To make the maintenance more effective, a wagon or a switch, for instance, can be divided into modules that can be swapped against identical modules if needed. Every subsystem can have its own deterioration limit. For a wagon, it can then for example be possible to change the door system, the coupler system, the wheels or parts in the bogies at once [9]. For a switch, it can for example be the switch blades or the crossing nose.

5.3.3 Standardisation

Standardisation can perhaps make it possible to have the same type of parts or modules in for example different kind of switches or different type of wagons. This can lead to that less unique parts or modules have to be stocked in the workshops.

5.4 Track system

5.4.1 High speed measuring

There are rail maintenance machines that can measure the condition of the track during normal scheduled operations, without having to close down the track. Different maintenance scenarios, including costs, can then be determined from the interpreted data of the measurements that have been taken [36].

5.4.2 Measuring with locomotives

To not make the measuring machines take up time slots in the track, the locomotives of the trains can be fitted with measuring instruments for those measurements that can be done at normal speeds during normal train operations. This can make the track more available either for train operations, with for example freight, or for maintenance work to be done. Also, measurements can be gathered more frequently which may lead to an increased understanding and an easier planning of the maintenance of the track.

5.4.3 High speed grinding

Rail grinding can be done in the form of high speed grinding with machines that operate at speeds up to 80 km/h. This means that it can be scheduled to any slot in the timetable without much need for track preparations or closures. Beside removing small and medium rail defects, the high speed grinding machines also prevent the growth of new defects which extends the service life of the rail with up to 100% [36].

5.5 Rail vehicles

5.5.1 Change in maintenance plans

The maintenance can be optimised by changing maintenance plan if parts that still have a long lifetime left are encountered. This can be good both for the maintainer and the customer of the train since the maintainer does not have to change the part and customer does not have to pay for it [37].

5.5.2 Collect maintenance needs

The service of the wagons can be maximised if the components of the wagon that have roughly the same degradation are collected and changed at the same time, instead of taking the wagon to the workshop every now and then to change a component [9]

5.5.3 Increase preventive maintenance

One way to make the maintenance more efficient can be to increase the maintenance tasks of preventive maintenance and thereby making the trains come to the workshops less frequently [37]. This can increase the availability of the trains since they will have more consequent time in traffic before they return to the workshops again.

6 Conclusions and future recommendations

Many interesting inputs from the industry have been received during the interviews in this project. Comparing the differences between them can give an even better idea about the challenges with freight trains. During the interview with LKAB, it was clear that their main goal is to increase the axle load rather than increase the frequency or speed of the trains. When speaking with Green Cargo, their plan of increasing their freight demands was to increase the frequency, and not increase axle load. These two companies operate under extremely different conditions. Whereas LKAB have a very uniform freight and path, Green Cargo operates with different forms of freight and many different paths in the country. What this implies, is that there is simply not one solution that will fit all, and that needs to be considered when approaching solutions.

During the project, the deterioration depending on the load and frequency have been looked into. What can be concluded is that increasing the load will in theory make the deterioration grow exponentially. Increasing the frequency of train will in contrast show a linear increase in deterioration.

One of the key parts of efficient maintenance is to avoid carrying out maintenance on components which does not need it. This is one of the risks with preventive maintenance, being that the condition of the component which is maintained or replaced is good, even though historical data of similar cases might be different. Condition-based maintenance is therefore preferable. What needs to be considered though, is that measurements with sensors which have to be calibrated and maintained can become even more expensive than having to replace or maintain the component. Of course, the cost is not always what has to be considered either since sustainability is a key factor. Replacing parts which do not need replacement is therefore not preferable, even though the sensors affect on sustainably also have to be considered.

According to what has been discussed above, knowing the condition of the vehicle and track is important to be as efficient as possible. During this project, both research and interviews with professional staff have been carried out. What seems to be an area that is interesting to develop further is combining the measuring of track condition, with the trains that are already running instead of having special vehicles to perform this. This will open up more slots on the track for freight and passenger trains, while also making the detection of faults more efficient. What also has been discovered, mainly under the interviews, is the need of being able to predict the condition of both vehicles and the track even better. This can be done by collecting even more data and developing evaluation and prediction tools that later will decrease the need of manual inspections.

During the project, different approaches of increasing capacity have been considered. Increasing the load and speed of the train are two effective ways of increasing the freight capacity. They, however need very careful analysis and inspection since they are likely to form a larger deterioration than having more frequent trains.

Reducing complexity of the wagons and locomotives can be an important matter when it comes to maintenance. This often makes the wagons more simple to maintain in comparison with the locomotive, since the latter has more components included, which creates a larger risk of something failing. As discussed in the report, it is therefore beneficial to have sensors measuring the condition of the wagons and locomotive track based, as a sensor on each wagon leads to a bigger complexity.

Short interval maintenance is critical in monitoring the condition of locomotives and wagons. Stricter maintenance intervention can initially require more human resources and facilities. However, in the long-term perspective, it is likely to have advantages and benefits in economical and sustainable effects.

References

[1] Energimyndigheten. *Koldioxidavskiljning och lagring (CCS)*. (2022, March 11). Retrieved April 06, 2022, from https://www.energimyndigheten.se/klimat--miljo/ccs/ (Swedish)

[2] Statista Research Department. (2022, April 14). *Amount of freight transported by rail in Sweden from 2006 to 2020*. Statista. Retrieved April 6, 2022, from https://www.statista.com/statistics/435305/sweden-tonne-kilometres-of-freight-transported-by-rail/

[3] Carlier, M. (2022, April 20). *Rail freight transport as a percentage of total inland freight transport in Sweden from 2005 to 2019*. Statista. Retrieved April 6, 2022, from https://www.statista.com/statistics/694290/sweden-rail-freight-share-of-inland-transport/

[4] Paulsson, B., Ekberg, A. and Elfgren, L. (2018, April 16). *Upgrading of freight railways to meet operational and market demands*. Proceedings of 7th Transport Research Arena TRA 2018 Vienna. Retrieved April 19, 2022, from http://dx.doi.org/10.5281/zenodo.1491480

[5] Lindberg, F., and Söderbaum, F. (2021, June 23). *Bantrafik 2020*. Trafikanalys. Retrieved May 25, 2022, from https://www.trafa.se/globalassets/statistik/bantrafik/bantrafik/2020/bantrafik-2020.pdf (Swedish)

[6] Larsson Kråik, P. O. (2022, April 4). Trafikverket. Interview.

[7] Rail Ninja. (n.d.). *High-speed train tickets in Sweden*. SWEDEN TRAINS. Retrieved May 24, 2022, from https://www.swedentrains.com/

[8] Nordh, B., Larsson, H., and Dahlqvist, A. (2022, May 4). Green Cargo. Interview.

[9] Pallari, R. (2022, April 29). LKAB. Interview.

[10] Andersson, E., Berg, M., Stichel, S. and Casanueva, C. (2018). *Rail Systems and Rail Vehicles: Part 2: Rail Vehicles*. Stockholm: KTH Royal Institute of Technology.

[11] Andersson, E., Berg, M., Stichel, S. and Casanueva, C. (2018). *Rail Systems and Rail Vehicles: Part 1: Rail Systems*. Stockholm: KTH Royal Institute of Technology.

[12] AGICO GROUP. (n.d.). *How to Ensure Train Track Security and Keep It Stay Away from Steel Rail Wear?*. Retrieved April 30, 2022, from http://www.rail-fastener.com/train-track-safety-steel-rail-wear.html

[13] Material Properties. (2020, July 31). *What is Fatigue Life – S-N Curve - Woehler Curve - Definition*. Retrieved May 20, 2022, from https://material-properties.org/what-is-fatigue-life-s-n-curve-woehler-curve-definition/

[14] Ekberg, A. and Kabo, E. (2021, March 10). *Key parameters and requirements for track health prediction*. CHARMEC, Chalmers University of Technology.

[15] AGICO GROUP. (2019, July 19). *Comparison Of Railway Sleepers*. Retrieved May 24, 2022, from http://www.railway-fasteners.com/news/comparison-of-railway-sleepers.html

[16] Kabo, E. (2021, November 29). *Railway deterioration - track. MMS180 Railway Technology*. Gothenburg; Chalmers University of Technology. Lecture.

[17] Ekberg, A. (2021, December 2). *Deterioration of running gear. MMS180 Railway Technology*. Gothenburg; Chalmers University of Technology. Lecture.

[18] Paulsson, B., Thunborg, M., Nelldahl, B. L., Ferriera, T., Escriba Marin, S., Roderiges Placa, M., ... and Larsson Kråik, P. O. (2017, September 1). *Upgrading of infrastructure in order to meet new operation and market demands*. CAPACITY4RAIL. Retrieved April 18, 2022, from https://capacity4rail.eu/IMG/pdf/c4r-d1.1.5_upgrading_of_infrastructure_in_order_to_meet_new_operation_and_market_demands_final_.pdf

[19] Veit, P. (2013, July 8). *Sustainable Track*. online.tugraz.at. Retrieved May 20, 2022, from https://online.tugraz.at/tug_online/voe_main2.getVollText?pDocumentNr=371375

[20] Esveld, C. (2001). *Modern railway track* (Vol. 385). Zaltbommel: MRT-productions.

[21] Náhlík, L., Pokorný, P., Ševčík, M., Fajkoš, R., Matušek, P., and Hutař, P. (2017). Fatigue lifetime estimation of railway axles. *Engineering Failure Analysis*, 73, 139-157.

[22] SKF. (2017, June). *Bearing damage and failure analysis - SKF*. Retrieved May 20, 2022, from https://www.skf.com/binaries/pub12/Images/0901d1968064c148-Bearing-failures---14219_2-EN_tcm_12-297619.pdf

[23] Müller, R., Gratacos, P., Mora, P., Nielsen, J., Feng, J., and Cervello, S. (2013). Definition of wheel maintenance measures for reducing ground vibration. *RIVAS (SCP0-GA-2010-265754): Deliverable, 2*, 87.

[24] Honauer, U., and Ödeen, S. (2021, March). *Trafikverkets underhållsplan för åren 2021-2024*. Trafikverket. Retrieved April 24, 2022, from http://trafikverket.diva-portal.org/smash/get/diva2:1548209/FULLTEXT01.pdf (Swedish)

[25] Network Rail. (2021, December 7). *New Measurement Train (NMT)*. Retrieved May 15, 2022, from https://www.networkrail.co.uk/running-the-railway/looking-after-the-railway/our-fleet-machines-and-vehicles/new-measurement-train-nmt/

[26] Network Rail. (2019, July 11). *Infrastructure insights: track maintenance and renewal*. Retrieved May 15, 2022, from https://www.networkrail.co.uk/stories/infrastructure-insights-track-maintenance-and-renewal/

[27] KiwiRail. (n.d.). *Rail Grinder*. Retrieved May 11, 2022, from https://www.kiwirail.co.nz/how-can-we-help/rail-grinder/

[28] Nielsen, J. (2009). Out-of-round railway wheels. In *Wheel–Rail Interface Handbook* (pp. 245-279). Woodhead Publishing.

[29] Nielsen, J. C., Abrahamsson, T. J., and Ekberg, A. (2022). Probability of instant rail break induced by wheel–rail impact loading using field test data. *International Journal of Rail Transportation*, 10(1), 1-23.

[30] Ekberg, A. (2009). Fatigue of railway wheels. In *Wheel–rail interface handbook* (pp. 211-244). Woodhead Publishing.

[31] Marschnig, S., Neuper, G., Hansmann, F., Fellinger, M., and Neuhold, J. (2021). Long Term Effects of Reduced Track Tamping Works. *Applied Sciences, 12*(1), 368.

[32] Verkhovykh, G. (2021, July 16). *The development and use of digital twins for the maintenance and repair of railway infrastructure.* Retrieved April 26, 2022, from https://www.globalrailwayreview.com/article/122490/digital-twins-maintenance-railway-infrastructure/

[33] Robinson, E. (2022, April 21). *HS1 Complete UK's first 5G-enabled Augmented Reality Digital Twin Trial.* Global Railway Review. Retrieved April 26, 2022, from https://www.globalrailwayreview.com/news/133727/hs1-complete-uks-first-5g-enabled-augmented-reality-digital-twin-railway-project/

[34] Oberle, K. (2022, March 10). *The steady train to automation.* Global Railway Review. Retrieved April 26, 2022, from https://www.globalrailwayreview.com/article/132547/the-steady-train-to-automation/

[35] Berger, M. (2022, April 21). *It's lights out for aging rail infrastructure.* Global Railway Review. Retrieved April 27, 2022, from https://www.globalrailwayreview.com/article/133604/its-lights-out-for-aging-rail-infrastructure/

[36] Vossloh AG. (n.d.) *Discover easy maintenance - An innovative portfolio that sets new standards.* Retrieved April 22, 2022, from https://media.vossloh.com/media/en/01_product_finder/vrs/smart_maintenance/Productflyer_Maintenance_EN.pdf

[37] Nalovski, I. (2022, April 5). Atkins. Interview.

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