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# Holistic procedure for rail maintenance in Sweden

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**Abstract:** The paper discusses a procedure for systematic and holistic (considering most of the factors influencing the rail degradation process) analysis and prediction of rail failures so that rail maintenance can be performed effectively. The current rail maintenance and reporting procedure followed by Banverket (Swedish National Rail Administration) for the Swedish Iron Ore Line is also described. The necessary data required to perform analysis and prediction of failures are discussed along with the improvement areas in Banverket's database management system.

This paper will help the infrastructure managers to better understand the existing rail maintenance procedure, and the improvements which can be incorporated in the existing procedure to make it more effective.

**Keywords:** rail degradation, failure, influencing factors, rail maintenance procedure, data reporting, vehicle–track interaction, rail defects

## 1 INTRODUCTION

Railways are one of the prime modes of transportation in many countries and as they are closely associated with the passenger and freight transportation, they own high risk in terms of loss of human life and damage/destruction of the assets, even though their probability of occurrence is very low. New technologies and stringent safety standards are constantly being introduced, but accidents still occur [**1**, **2**]. The Hatfield derailment (UK) in October 2000 killed four and injured 34 people. The damages in terms of the consequential costs to Railtrack Company (acquired by Network Rail since 2002) were about £733 million [**3**]. The derailment happened because a rail, in which there were multiple cracks and fractures due to rolling contact fatigue (RCF), fragmented when a high-speed train passed over it [**4**].

The German Intercity Express (ICE) train derailment at Eschede on 3 June 1998 took more than 100 lives. The accident was caused by a fatigue fracture which started on the underside of the rim of a wheel separated from the disc connecting it to its axle by rubber pads. The derailment caused one of the carriages to swing out of line and to strike a support of the bridge, prompting its collapse [**2**]. There will always be some risk associated with the derailments and collisions, but it can be reduced by elimination of the root causes by means of effective maintenance procedures and models.

By the beginning of 1990s, many researchers and rail players felt the need for developing models and strategies for rail infrastructure maintenance. Rail expert planning, organization and maintenance (REPOMAN) and total right-of-way analysis and costing system (TRACS) were developed in the early 1990s [**5**–**7**]. REPOMAN was based on maintenance planning while TRACS was based on the track degradation analysis and life cycle costing. Rail players in collaboration with academic/research institutions became actively involved in the development of the rail infrastructure maintenance strategies, which further produced useful track maintenance models like Economical Track (ECOTRACK) [**8**], Integrated Track Degradation Model (ITDM), developed at Queensland University of Technology, Australia [**9**, **10**] and Degradation Cost On Track (DECOTRACK), developed jointly by Damill AB, Banverket and Järnvägstekniskt Centrum (JVTC) at Luleå University of Technology [**11**]. During this

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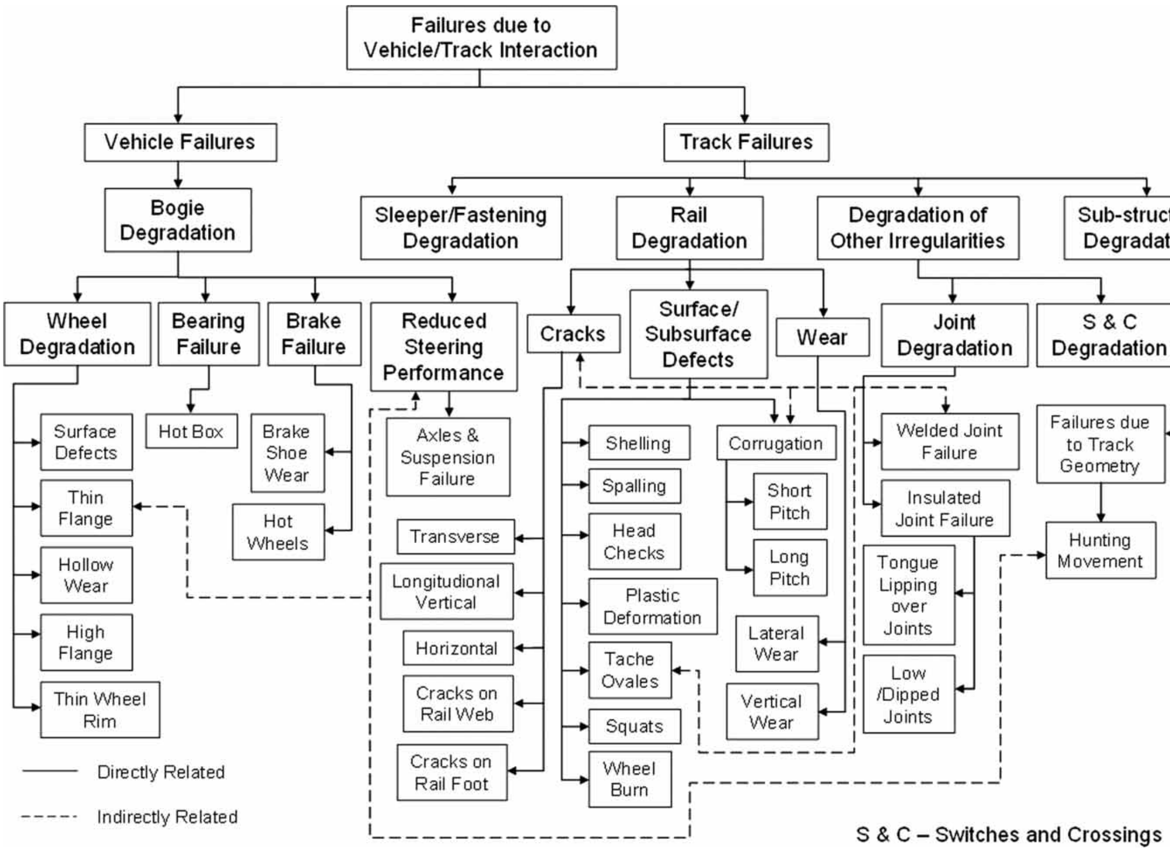


**Fig. 1** Failures occurring due to vehicle–track interaction (adapted from Sroba and Maass [**12**] and Espling *et al.* [**13**])

time, Transportation Technology Center, Inc., a subsidiary of the Association of American Railroads, also developed Integrated Railway Remote Information Service (InteRRIS), a comprehensive, detector-based, internet-communicated vehicle–rail condition and performance monitoring system. InteRRIS acts as a data-warehouse for automatically storing and analysing vehicle performance data.

Most of the above-mentioned models provide efficient and innovative data reporting systems; some of them also analyse these data, however, many of the factors which influence the rail degradation process have not been considered. There is a need for describing an efficient and effective rail maintenance procedure considering these factors which influence the rail degradation process.

The outline of this paper is as follows: section 1 describes the need for a holistic rail maintenance procedure and the state of the art. Section 2 describes the rail degradation and defect formation process. Failures due to vehicle–track interaction have also been mentioned in this section. Section 3 describes the current maintenance trend in Banverket. The rail maintenance procedure followed at Banverket's Iron Ore line is described in section 4. Section 5 describes the steps required to develop an effective rail maintenance procedure. Contribution of this paper is discussed in the concluding section.

## 2 DEGRADATIONS DUE TO VEHICLE–TRACK INTERACTION

Maintenance of rolling stock not only increases their life but also reduces rail degradation. As the wheels are in direct contact with the rails, degradation on the wheel surface and profile will effect degradation on the rails. Bogie condition will also influence rail degradation. Figure 1 shows the different kinds of degradation/failures taking place on both vehicle and track due to their interaction. Some of the degradations, defects, or failures (e.g. hunting movement) having influence/being influenced by other failures are also shown in Fig. 1.

A track consists of different components, i.e. rails, switches, fasteners, sleepers, tie plates, ballast, and subgrade [**14**]. Degradation of each of these components together constitutes the track degradation. Many track degradation models have been developed as mentioned above, but still there is a need to develop different component level degradation models so that detailed analysis is carried out at the

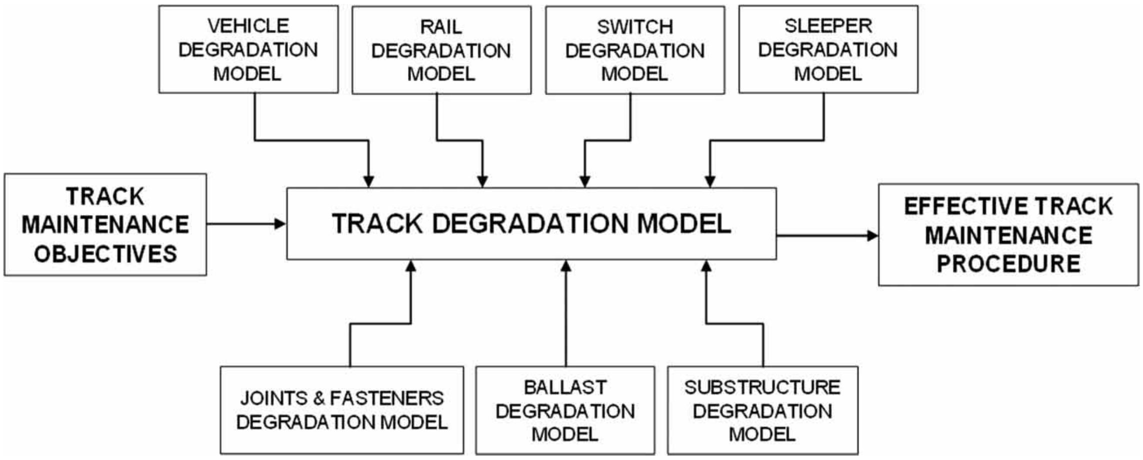


**Fig. 2** Need for an overall track degradation model to develop an effective track maintenance procedure

component level, which together will lead to the development of an overall track degradation model (Fig. 2). This model will help in framing out an effective track maintenance procedure. The track degradation model should be in-line with the track maintenance objectives.

Bad wheel–rail interface is a cost driver and a lot of research is being done in this area [**15**]. Rails, among all the components of the track structure, are subjected to highest stress levels because rails are in direct contact with the wheels. The stress level between wheel and rail is in the order of 30 kN/cm$^2$, which is two orders smaller between rail and sleeper and reduces to around 30 N/cm$^2$ between sleeper and ballast. Finally, the stress between ballast and substructure is only around 5 N/cm$^2$ [**14**]. The scope of the paper is limited to rail degradation and maintenance activities. Description of a detailed and holistic approach for developing each of the track component degradation models is beyond the scope of this paper.

## 2.1 Rail degradation

Wear and RCF in rails are significant problems for the railway industry [**16**]. They are major contributors to rail deterioration depending on the different factors influencing the condition of the rail during its life cycle [**17**]. The rail head is worn away by wheels on its surface and deteriorates due to abrasive contact with the base plate or sleeper on its underside. Corrosion leads to loss of rail material and the surface crack reduces the fatigue resistance of the rail. Increased speed, higher axle loads, increased traffic and freight lead to the surface-initiated cracks on the rail [**18**].

Rail break is the last phase of the crack development process. As the crack continues to increase in length as well as depth, stress concentration also increases and finally the rail break occurs. However, this does not happen in all cases. Sometimes spalling takes place and a portion of rail material comes out as the crack develops. The end result of a crack is governed by its development path. It is very difficult to predict the crack development path as it depends on several factors. Some of the cracks disappear early on in their development as a result of wear and tear, while most of them are removed by grinding operations. Not all cracks pose a derailment risk, but they are the major contributors to rail degradation. A rail break might also be caused due to manufacturing defects, such as formation of blowholes, but they are usually detected by non-destructive testing (NDT) inspection techniques. Detail fractures (a type of rail break) account for about 75 per cent of the rail defects in continuously welded rail track in North America [**19**].

## 2.2 Rail defect formation

The failure rate of the system depends on the condition of the system, which depends on the system being subjected to different kinds to stresses due to fatigue, lateral forces, axle loads, traffic density, etc., any of which causes degradation. Therefore, the system may not fail fully, but can degrade, and there may exist several states of degradation under which the efficiency of the system may decrease [**20**]. In some cases, if the degradation level exceeds a particular limit (for example, a rail defect propagates to form a rail break), the system may not operate successfully; this may be considered as a system failure. Failure is the termination of the ability of an item to perform a required function [**21**]. Rail break is a rail defect that can be considered as the last but definite failure state. A rail break may be defined as any rail which has separated into two or more pieces, or a rail from which a piece of metal becomes detached, causing a gap of more than 50 mm in length and more than 10 mm in depth in the running surface [**22**].

### 2.3 Rail defect classification

Due to the economic pressure there is a world-wide trend to increase axle loads, traffic density, and speed to reduce operating costs and increase the efficiency of railways. This has lead to an increased rate of rail defect formation. Rail defects occur due to a number of causes, which have been used as a basis for rail defect classification by many researchers.

Olofsson and Nilsson [**23**], classified rail defects which occur due to RCF into surface-initiated and subsurface-initiated defects. Surface-initiated defects are formed mostly due to an increase in traffic density and axle load (e.g. head checks and squats). In contrast, subsurface defects are often caused by metallurgical faults (e.g. shelling, tache ovale, and longitudinal vertical crack).

Cannon *et al.* [**24**], divided rail defects into three broad groups:

(a) defects originating from rail manufacture (e.g. tache ovale);
(b) defects originating from damage caused by inappropriate handling, installation, and use (e.g. the wheel burn defect, which is caused by spinning wheels);
(c) defects caused by the exhaustion of the rail steel's inherent resistance to fatigue damage. Many forms of RCF-initiated defects are within this group (e.g. head checking and squats).

whereas Marais and Mistry [**25**], classified rail defects into two groups:

(a) defects related to the rail joints (e.g. flash butt weld defects, thermit weld defects);
(b) defects related to rail quality (e.g. horizontal head cracks, tache ovale).

Many infrastructure managers follow the Union International des Chemins de fer (UIC) rail defect classification standard. According to the standard, broken, cracked, and damaged rails are given a code that may comprise up to four digits. The first digit indicates the situation under which the defect occurred, the second and third digit indicates the defect location and pattern, respectively, while the fourth digit indicates additional characteristics and differentiations, if any [**22**]. Standardized information in the form of rail defect code becomes particularly useful while carrying out data reporting, interpretation, and analysis. Scope of misinterpretation of the information intended to be conveyed is considerably reduced by the use of defect codes to clearly explain defect characteristics.

## 3 CURRENT MAINTENANCE TREND AT BANVERKET

The railway operation in Europe has traditionally been integrated as a single entity looking into both traffic and infrastructure. During the last 20 years, deregulation and demands on increasing the effectiveness and efficiency has segregated the railways into traffic operators and infrastructure managers (track owners) in some countries. It has also become common to outsource the maintenance activities concerning both the rolling stock and the infrastructure. Historically, maintenance in the railway sector has been based on time, tonnage accumulation, or operated train kilometres (predetermined maintenance). The current trend within the European Railway sector is to move towards condition-based maintenance. In Sweden this process started in mid-1990s.

The life cycle of an infrastructure facility in Banverket is divided into four stages: operation, maintenance, upgradation, and decommissioning (Fig. 3) [**26**]. According to the Swedish standard [**27**], the maintenance process is divided into preventive maintenance and corrective maintenance. Preventive

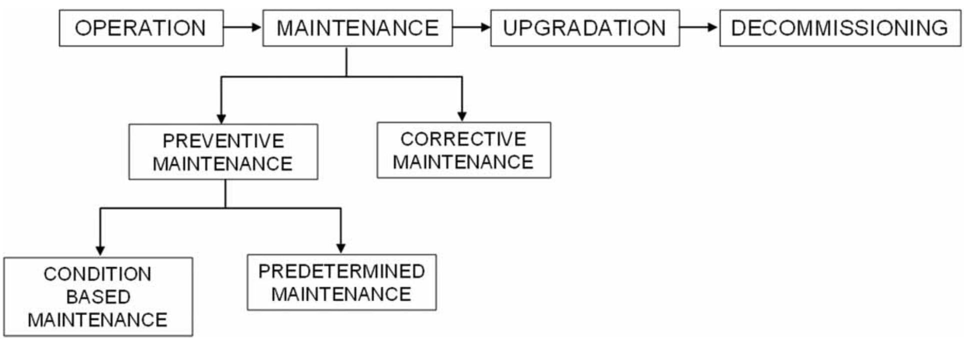


**Fig. 3** Maintenance definition followed by Banverket (adopted from Karlsson [**26**], SIS [**27**], Andersson [**29**], and Åhren [**30**])

maintenance is subdivided into condition-based and predetermined maintenance. The corrective maintenance approach is reactive in nature, whereas preventive maintenance is a form of proactive maintenance activity [**28**].

The current maintenance strategy in Banverket is to minimize the corrective maintenance and as far as preventive maintenance is concerned, predetermined maintenance should, to the extent possible, be changed to condition-based maintenance [**26**]. Banverket's strategy leads to its overall aim of rail maintenance, which is to provide a rail that meets functional demands for frequency of train service and loading capacity, travelling time, comfort, reliability (accessibility and punctuality), safety, and environmental impact; and all these requirements are to be fulfilled as cost efficiently as possible [**31**].

## 4 THE SWEDISH IRON ORE LINE

The iron ore line (Malmbanan) runs from Narvik in Norway, situated on the coast of the Norwegian Sea, to Luleå in Sweden, which is situated on the coast of the Gulf of Bothnia, spanning around 500 km (Fig. 4). The northern branch (Kiruna–Narvik) handles 15 millions net tonnes of ore which is 27 millions gross tons, while the southern branch (Luleå–Boden–Gällivare) handles seven millions net tonnes of ore which is 18 millions gross tonnes [**32**]. The infrastructure managers, Banverket in Sweden and Jernbaneverket in Norway maintain the iron ore line. The line, running north of the Arctic Circle, is characterized by diverse geographical terrain requiring some small radius curves and steep gradients. The line is subjected to harsh climatic conditions such as snowstorms and temperatures close to $-40^\circ$ Celsius in winters and $+25\,^\circ$C in summers. Rail temperature variations over the four seasons are therefore very large. An effect of this is large tensile stresses during winter time, which increase the risk of crack propagation and, at worst, rail breakage.

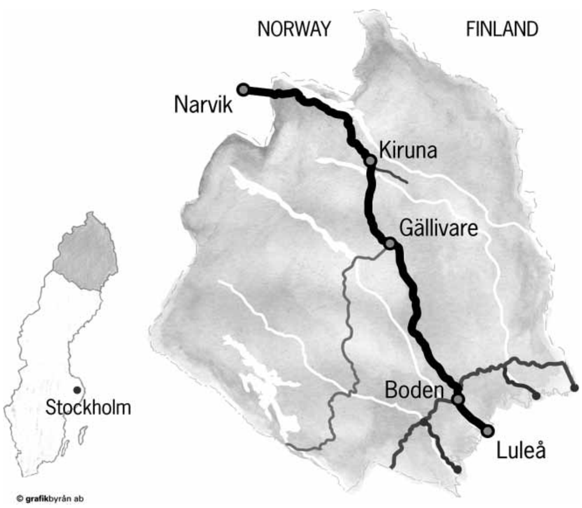


**Fig. 4** The iron ore line from Luleå to Narvik

Work on upgrading Swedish part of the iron ore line is under way, mainly comprising of increasing the number of wagons from 52 to 68, the train length from 470 to 750 m and the train weight from 5200 to 8160 tonnes [**32**]. The line allows mix traffic and has been recently upgraded from 25 to 30 tonnes.

### 4.1 The rail maintenance procedure followed at Banverket's iron ore line

Banverket uses different guidelines for monitoring track and track components. They specify the minimum requirements for the infrastructure maintainer. Monitoring and maintenance include the functions of inspection and testing; assessment of inspection and test results, and the execution of preventive or corrective actions. The objectives are to inspect the critical elements of the track to determine its condition; record defects which might affect, or have the potential to affect the capability of the track to safely perform its required function; carry out assessments to determine the capacity of the track and finally, take actions where the track is unable to carry out the required function safely. Figure 5 shows the track failure data reporting procedure.

The rail maintenance procedure used at Banverket is shown in Fig. 6. Banverket currently uses ultrasonic trains (also known as NDT cars), hand-held ultrasonic devices and visual inspection to inspect the rails to identify the possible internal defects [**17**]. To estimate the potential risk, each rail failure detected by the ultrasonic train is verified by hand-held ultrasonic equipment and recorded on the spot by an inspector in the form of a report. Severe defects which the inspectors thinks are of high priority are immediately recommended for corrective maintenance [**29**]. Visual inspection is carried out separately by rail inspectors according to an inspection plan (known as planned visual inspection), recorded in a report and stored in a database. Visual inspection may also be carried out in an unplanned manner by the inspector to check the track condition in between planned inspection intervals. Finally, track inspectors are obligated to report if they detect any deviation from normal rail condition, as they perform their daily maintenance work along the track. These reports are also stored in a database.

The signalling system, with its traffic control safety mechanism, detects any deviation that can be linked to a rail failure. However, signalling system is not used as a maintenance planning/inspection tool; it is a safety system for operating trains. If the signalling system detects any deviation from the norm, traffic control reports this to the maintenance contractor.

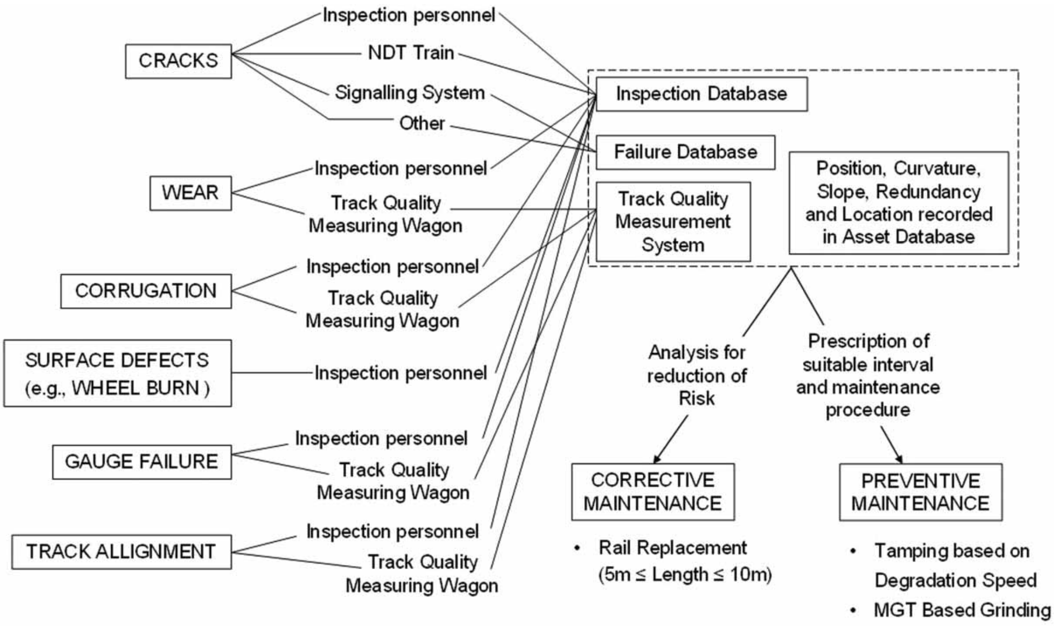


**Fig. 5** Track data reporting and analysis procedure followed in Banverket (adapted from Espling *et al.* [**13**])

The contractor then performs an inspection or repair if necessary, and reports the action to a database.

All data recorded from the different systems are further analysed by an expert. Historical data and information stored in a centralized database is also used to correlate failure patterns. Finally, a decision is made to prioritize these defects. Priority of defects is based on several factors, such as track geometry, traffic type, traffic density, axle load, age of rails, defect history, rail material, curvature, yearly, and total accumulated Million Gross Tonnes (MGT). The consequential costs and risks associated with a particular defect are also taken into consideration, if derailment occurs due to that defect.

Low-priority defects are then recommended for preventive maintenance in the form of, e.g. grinding, minimal repair, rail welding, or rail section rectification/replacement. The kind of preventive maintenance adopted for a particular kind of defect depends on its need and severity. High-priority defects are immediately recommended for corrective maintenance which may be in the form of minimal repairs (mostly carried out during the winter), rail section replacement and/or welding. Immediate maintenance is a procedure whereby emergency measures are either carried out immediately or traffic restrictions are imposed [**29**]. Minimal repairs as a form of corrective maintenance are temporary repairs carried out during the winter. Usually, if a high priority defect/rail break occurs in winter, the segment containing the defect is replaced with a new rail segment. Welding of the rail segments is generally avoided in winter because it becomes very difficult to maintain uniform and correct welding temperatures, which may otherwise effect on weld quality. Therefore, the rail segments are temporarily attached by fishplates (known as minimal repair) which are later on replaced by welding in summer. The defects detected by signalling are generally severe, often in the form of rail breaks or rail breaks in a developing stage and need immediate attention, thus corrective maintenance is carried out to counter these defects [**17**].

Figure 6 also illustrates those areas in Banverket's rail maintenance procedure where there is scope for risk-based analysis.

1. Rail failure prediction can help the maintenance expert to make better decisions as regards recommending a defect for preventive or corrective maintenance by assessing the risk of each defect.
2. A limit for permissible risk can be standardized for defects falling under different specifications. If the risk associated with a particular type of defect is more than the maximum permissible limit, the defect will be recommended for immediate, corrective maintenance and *vice versa*. This requires the development of an effective track maintenance procedure.
3. Similarly, rail failure prediction and risk estimation will help in deciding on cost-effective grinding intervals. Rail failure prediction will also help in cost-effective welding procedures.

Defects left undetected by the above-mentioned inspection tools build up operational risk in rails, some of which may eventually be detected through derailments. However, the percentage of defects leading to

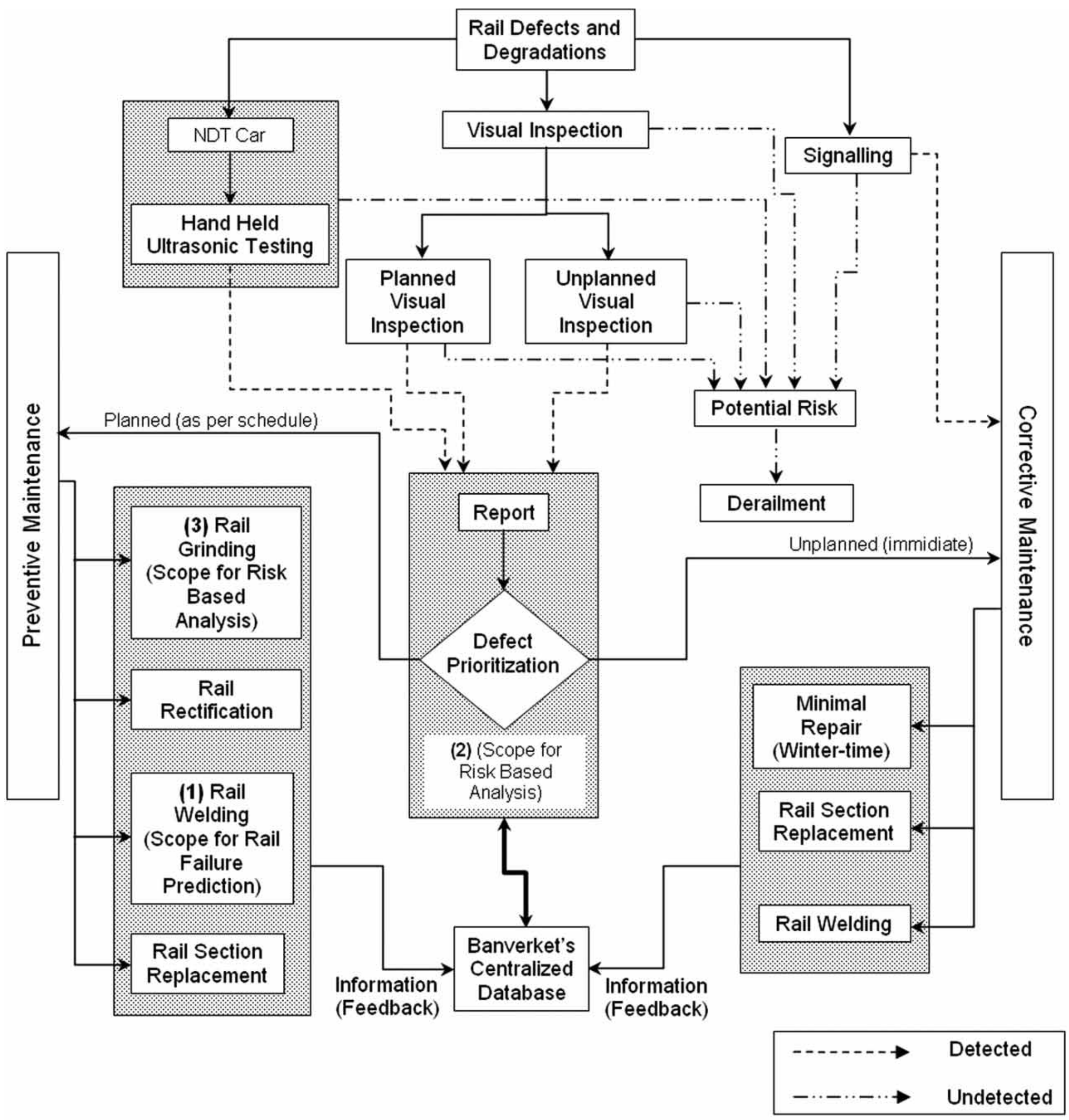


**Fig. 6** Banverket's rail maintenance procedure

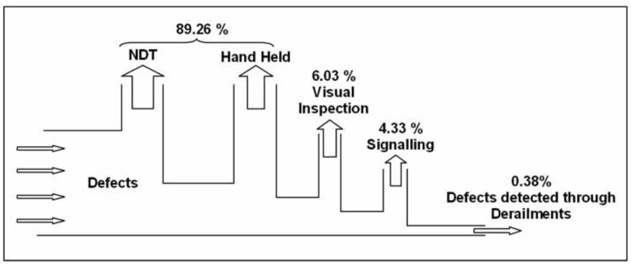


**Fig. 7** Percentage of potential rail breaks detected by the use of different inspection tools [**17**]

derailments is very small as shown in Fig. 7. The figure gives an idea of the percentage of defects detected through various inspection tools used on the Swedish iron ore line. The figures are based on the inspection data collected from section 111, Malmbanan between the years 1997 and 2005 [**33**].

## 5 THE PROPOSED PROCEDURE

In order to predict rail failures considering most of the factors influencing rail degradation, it becomes essential to develop a well-defined procedure. The procedure should be explained to the contractor so that he/she knows what to collect/record and the reason behind it. The initial step of the procedure should be to identify the different factors influencing the rail degradation process. After these factors have been identified, the rail failure data needs to be collected and categorized depending on the conditions under which the failure occurred and the factors which played a dominant role to cause that failure. If there is a deficiency of field data, modelling of the actual conditions followed by simulation can be done to generate data. Once appreciable sample size of data under a particular category is available, trend test should be carried out followed by failure prediction using the most suitable failure distribution. Thereafter, based on analysis and interpretation of the results, maintenance budget is allocated during the decision-making process, the aim of which is to develop an effective rail maintenance procedure. The following subsections have dealt with the steps described above.

### 5.1 Identification of factors influencing rail degradation

The identified factors responsible for rail degradation have been described by Ishikawa diagram in Fig. 8 [**17**].

Four broad classification areas denoting the different phases (design, manufacturing, operation, and maintenance) of rail life have been identified while constructing the Ishikawa diagram. During the design stage, selection of rail/wheel material type, rail size, and rail profile depends on the required operating conditions such as axle load, speed, traffic type, traffic density, etc. Similarly, track is constructed according to the requirements of track geometry (elevation and curvature). Better track design will lead to less degradation and longer rail life. Defects may be generated during rail manufacturing. Other manufacturing aspects along with many of operational and maintenance factors will also influence the rail degradation.

### 5.2 Data collection

The track inspectors should be very careful while reporting the information into the databases. Often confusing data/remarks in the databases lead to misinterpretations. In order to get a holistic picture of where the failures are located and what are the dominant factors causing failures, more structured databases are required having the complete information. For this, the infrastructure managers should know the parameters which are required to be measured; often this is not the case. Different databases should be linked with each other so that more detailed information is available in less time.

While reporting a defect, the type of defect along with the conditions under which the defect occurred should also be reported. Often, analysis of track failure data requires long spread sheets to correlate the factors responsible for the failure. In Banverket, corrective maintenance data is reported in a paper reporting sheet but often not reported completely in the databases, which makes it difficult to trace back while doing analysis. For example, a rail break is reported in the failure system and the required action has also been performed, but the exact location of the rail break is not reported in the database; a segment of rail has been replaced but not reported back in the asset management system. Thus it remains unclear whether left/right or high/low (in case of curves) rail was replaced.

Parameters such as traffic type, speed, tonnage, wheel condition, etc., should also be reported. One of the problems associated with tonnage can be overloading of the wagons by customers. For example,

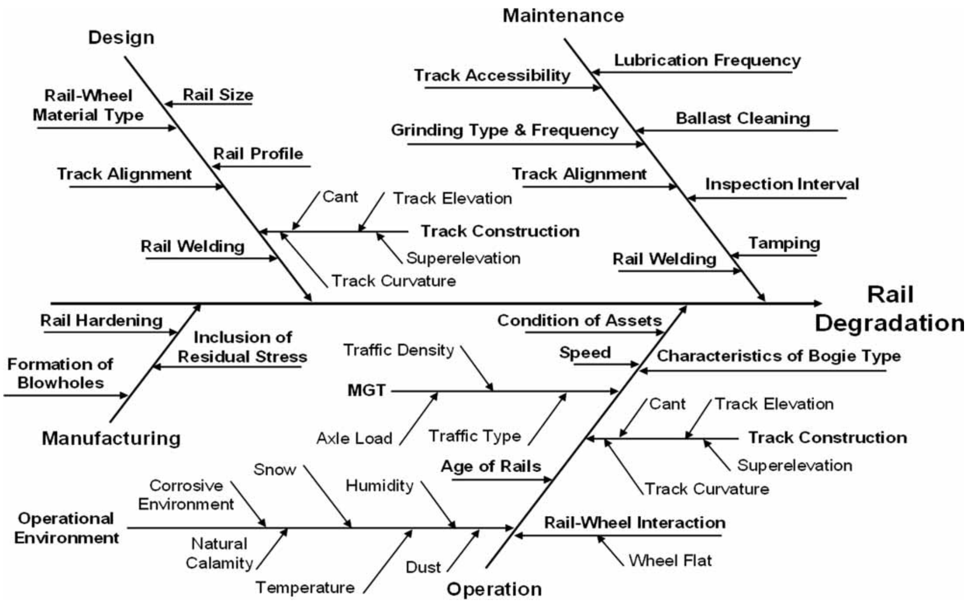


**Fig. 8** Ishikawa diagram (cause and effect diagram) for the factors influencing rail degradation

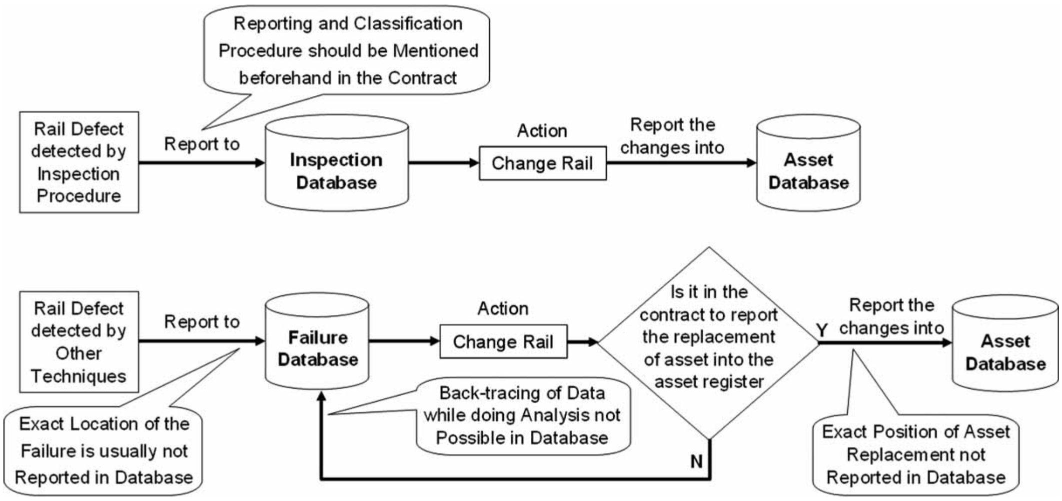


**Fig. 9** Scope for improvements in the data reporting and classification system

when a weight-in-motion system was installed in ProRail, it revealed that 20 per cent more tonnage was carried by the infrastructure than was previously assumed [**34**].

## 5.3 Data classification

Rail break data can be classified according to all the factors identified in Fig. 8. The different levels of the classification framework will be governed by the dominance of the factors influencing rail degradation under a particular condition and the availability of data under that classification. This indicates that the classification framework for the Swedish iron ore line will be different from that of the Australian or American heavy haul lines, for example.

Data availability plays a crucial role in the development of a classification framework. It is important to have a good record of data measuring the effect of various factors influencing rail degradation as shown in Fig. 9. If the required data is not available or is difficult to measure, then modelling and thereafter simulation of the actual conditions under which degradation is taking, place should be done. Figure 9 describes the improvement areas in Banverket's database management system, especially when track inspection, maintenance, reporting, and classification activities are outsourced.

## 5.4 Analysis and prediction of rail failures

After data collection and classification according to the different factors influencing the rail degradation process (Fig. 8), data should be analysed to predict rail failures. However, before analysing the data sets or choosing an appropriate model for each of them, one must proceed for serial correlation and trend test. If failure data are independent and identically distributed (i.i.d.), they do not indicate any correlation and trend. The test for independence can be done by plotting $i$th time to failure against the $(i-1)$th time to failure, where, $i = 1, 2, 3, \ldots, n$ and checking if there is any correlation among the plots. The test for identical distribution can be done by plotting cumulative number of failure against cumulative time to failure. If the plotted points lie on a straight line, there is no trend in the failure data and *vice versa*.

If no evidence of trend is found in failure data, then stationary models such as homogeneous Poisson process or classical distributions can be used for data analysis (e.g. exponential, Weibull, normal, and lognormal distribution). A goodness-of-fit test is used thereafter, to determine an appropriate distribution. If evidence of trend is concluded, a non-stationary model such as non-homogeneous Poisson process (NHPP) must be fitted (e.g. Power law process) [**35**].

For example, Figs 10 and 11 shows the plots for serial correlation and trend test of the failure data for defect type 211, respectively. The description of the defects and their corresponding defect codes (according to

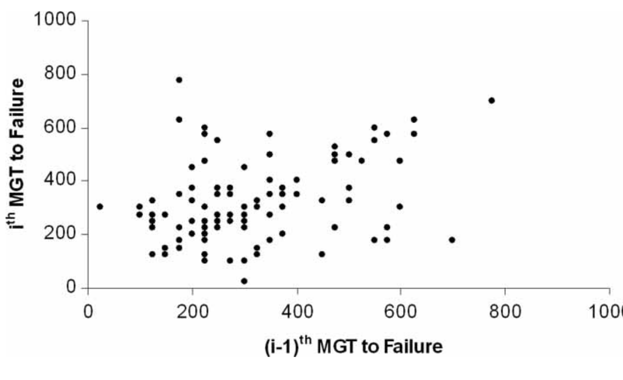


**Fig. 10** Test for serial correlation of defect type 211

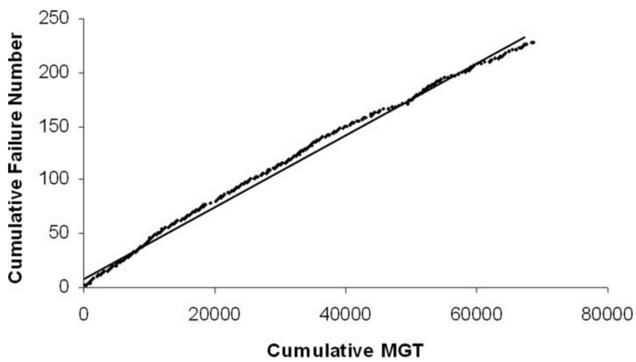


**Fig. 11** Trend test for defect type 211

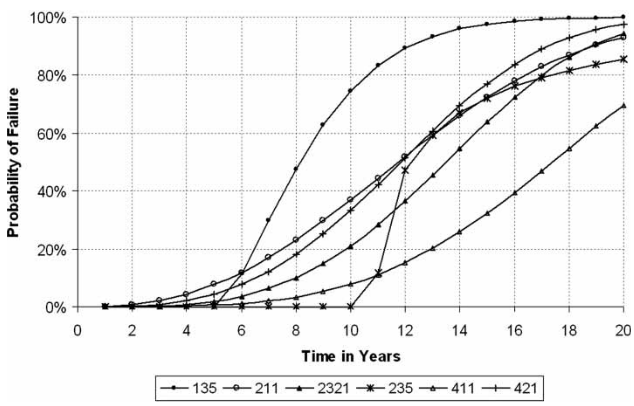


**Fig. 12** Probability of failure for different defect types at different time intervals

UIC standard) considered to exemplify the trending and analysis procedure is given in Table 1. Real data of the frequently occurring defects on the rail section under study (section 111, of the iron ore line, Fig. 4) from the year 1997 to 2005, were taken [**36**]. In this paper, the different defect types assigned by defect codes are considered as failure states. As ageing in rails takes place due to tonnage accumulation on the track resulting from traffic movement, rail defect data analysis is based on MGT of traffic flow. As per Banverket's inspection and failure databases, rail replacements and ageing is estimated by assuming 25 MGT per year of traffic flow on the Swedish iron ore line. The age of rail segments having a rail defect is calculated by multiplying the annual MGT of traffic flow with the difference between the year the rail segment was inspected for a rail defect and the year it was last replaced.

It is evident from the two plots (Figs 10 and 11) that the failure data are i.i.d. Similar results were obtained when this test was further carried out for the other defect types [**36**]. The best-fit test was carried out using ReliaSoft's Weibull++6 software [**37**]. For most of the defect types (defect code 211, 411, 421, and 2321 (Table 1)), two-parameter Weibull distribution was the best fitting distribution where as three-parameter Weibull distribution was the best fitting distribution for defect types having defect codes 135 and 235. The analysis was done using maximum likelihood estimation. The probability of occurrence of failures at different intervals of time (i.e. at different tonnage accumulation) for the failure data sets of each of the considered defect types is calculated. Figure 12 shows the probability of occurrence of failure for each of the defect types considered at different time intervals. For prediction of the risk involved with each defect type, their severity and probability of detection should also be known. This has been discussed in detail by one of the authors in a submitted paper [**36**].

The failure behaviour of different defect types also depends on a number of factors influencing the degradation rate as shown in Fig. 8. Some of the factors play a more dominating role on the failure behaviour of a particular defect type compared to others.

Figure 13 shows an approach to predict rail breaks. The different factors which are being monitored and recorded by Banverket have been underlined. Appropriate measuring techniques need to be designed or incorporated to measure and record other factors in order to get more precise analysis results and failure predictions. Furthermore, development of a priority list of different factors affecting the rail degradation process is currently under study at the Luleå railway

**Table 1** UIC rail defect code and its description [**22**]

| UIC defect code | description |
|---|---|
| Defect code 135 | Star cracking of fishbold holes, this defect consists of progressive cracks that radiate from the fishbolt hole. They are mostly located near the rail ends |
| Defect code 211 | Progressive transverse cracking (kidney-shaped fatigue crack), this defect develops from a defect inside the rail head from an internal horizontal crack or deep shelling of the gange corner |
| Defect code 2321 | Horizontal cracking at the web-head filler radius. Thus crack initially develops in the rail web, parallel to the web-head fillet radius and may curve either upwards or downwards as it progresses |
| Defect code 235 | Cracking around the holes other than fishbolt holes, this defect has the same appearance as that of defect code 135, but they occur away from the rail ends |
| Defect code 421 | Transverse cracking of the profile, this is a welding and resurfacing defect occurring in near the thermal welding |
| Defect code 411 | Transverse cracking of the profile it's a resurfacing defect occurring in electric flash-but welding. The crack develops in the weld cross-section either from an internal defect of the head in the weld or from a defect located in the foot of the rail |

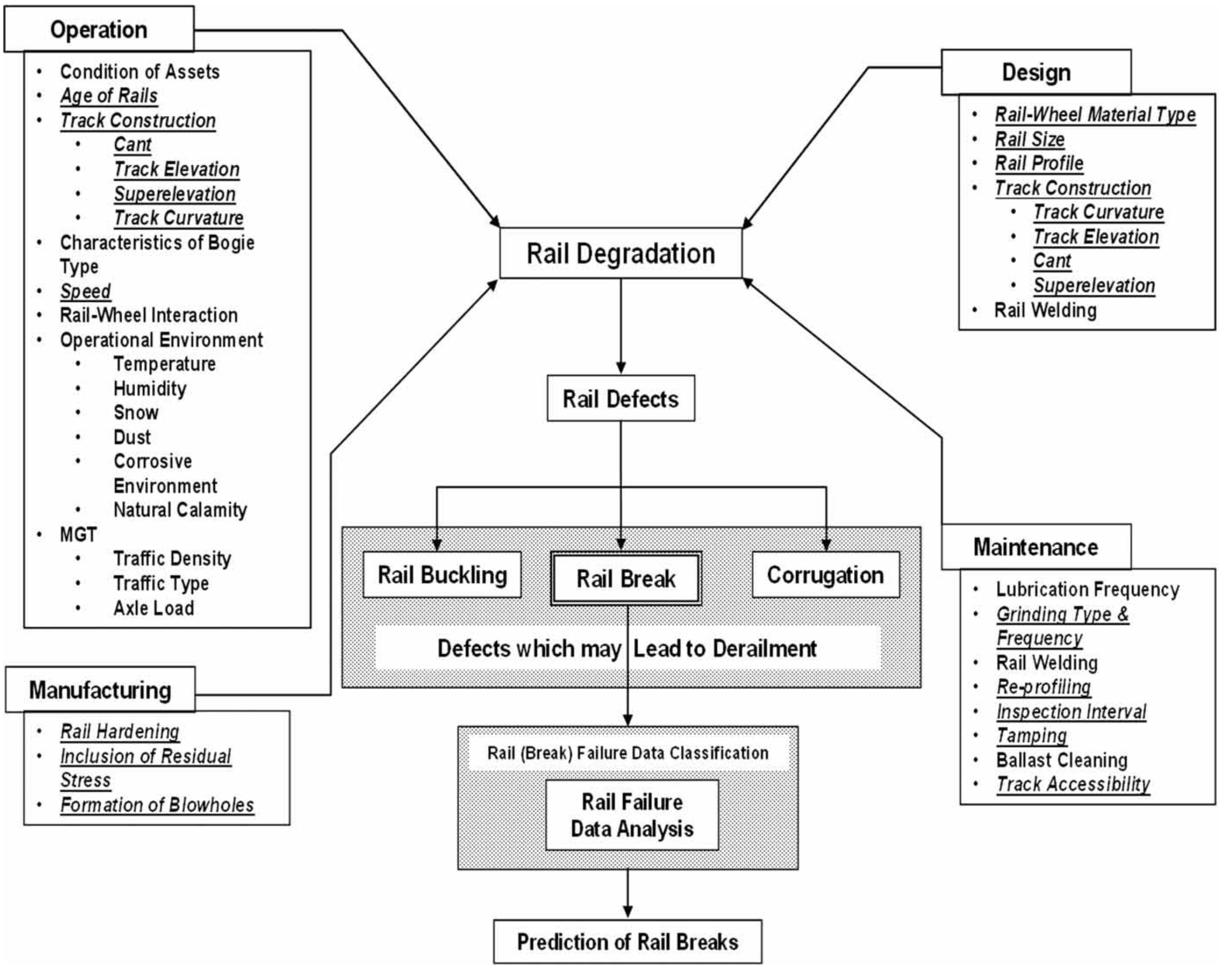


**Fig. 13** An approach for rail break prediction

research centre within the scope of 'the maintenance thresh hold limit project' (http://jvtc.project.ltu.se/).

### 5.5 Maintenance decision making process

Rail players have well-defined business objectives based on stakeholders' demands which in turn create a foundation for the track maintenance objectives. Rail maintenance objectives can be considered as a part of the track maintenance objectives. Track reliability, availability, and reduced risk of derailments can be achieved by reducing the rate of rail degradation (rail maintenance objective) which requires a well-structured and effective rail maintenance procedure (Fig. 14).

Prediction of the failure rate for a rail section helps in proper scheduling of maintenance activities (inspection, grinding, rectification/replacement, and/or welding) in an optimal way. Predicting the failure of a degrading rail section will facilitate risk estimation as shown in Fig. 14. Therefore, rail failure rate prediction is a requirement for the development of an effective rail maintenance procedure.

There are many examples showing the effect of rail maintenance in terms of reduction in the failure/accident rates or increment in rail life [**38**, **39**]. Some of the research studies carried out at Luleå railway research centre has also shown that effective grinding and lubrication can increase rail life [**16**, **40**]. Effective implementation of track maintenance and renewal activities by MRS Logistica, Brazil has reduced the accidents per train per million kilometres from 60.2 in 1996 to 7.0 in 2006; more specifically effective rail grinding and lubrication has increased the rail life from 750 MGT in 2002 to 1500 MGT in 2006 [**41**]. The annual grinding campaigns on Malmbanan have also improved the rail life and quality of the track significantly. For example, in the 1990s about 10 km track needed to be changed annually on the northern branch of Malmbanan. During the last years the respective amount has been only 400 rail meters [**32**].

Generally, a trade-off is made between maintenance budget and the cost associated with the risk involved with rail degradation. It is a cyclic process and continues until an effective rail maintenance procedure is finally developed.

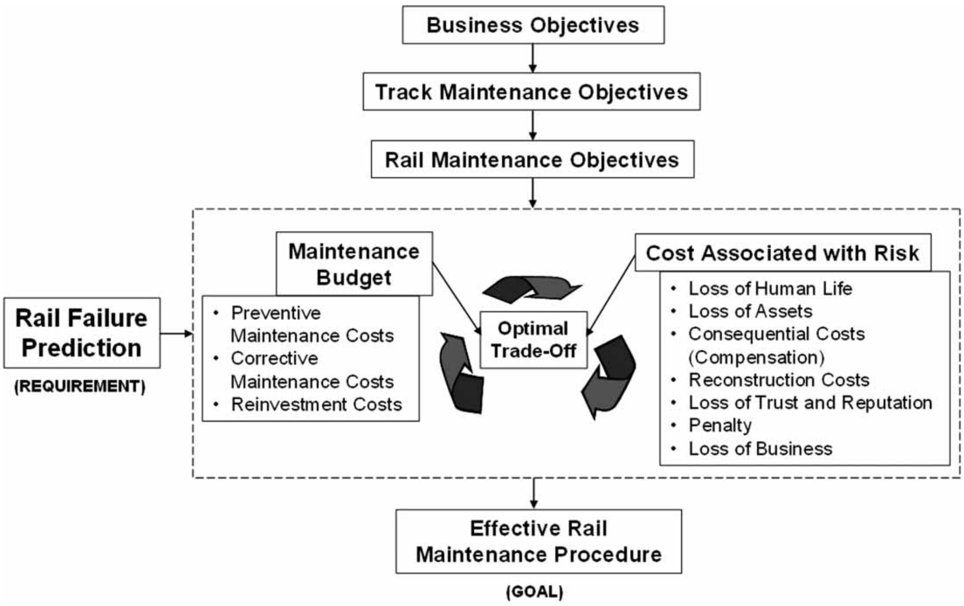


**Fig. 14** Process of developing an effective rail maintenance procedure

If a maintenance procedure is not well-structured and effective, proper maintenance action may not be taken within the required time or a defect may be left uninspected, as a result, rail degradations and defects may develop into rail breaks. A rail break can cause derailments which may have catastrophic consequences.

In order to avoid the consequences and the probability of derailment, stringent safety standards have to be followed, which require massive rail maintenance investments. The investment limit depends on the availability of funds and the level of risk acceptable under the given operating conditions. An effective maintenance procedure should be able to strike the optimum balance between the cost associated with risk and the required maintenance budget.

## 6 CONCLUSION

Effective rail maintenance can be achieved through a well defined holistic (considering many of the factors which influence rail degradation process) maintenance procedure. This paper describes a procedure to collect and record useful data and classify them based on the identified factors influencing rail degradation and further analyse the data and predict the failure rate so that rail maintenance can be performed effectively. Data gives valuable information which delivers knowledge. The infrastructure managers and contractors should know what to collect/record and why it is important. Knowledge of the rail degradation and defect formation process can help the infrastructure managers to understand the kind of information required under specific conditions. The cost implications during the development of an effective rail maintenance procedure are described during the maintenance decision-making process.

The paper also describes the current maintenance trend at Banverket. A case study of Banverket's rail maintenance procedure for its Iron Ore Line is presented. The paper also discusses the improvement areas in Banverket's database management system. Implementation of the suggestions and the described procedure can considerably improve rail failure data analysis and prediction.

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