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Railway Induced Vibration Abatement Solutions
Collaborative project

Definition of wheel maintenance measures for reducing ground vibration

Deliverable D2.7

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EXECUTIVE SUMMARY

Within the frame of the EU FP7 project 'Railway induced vibration abatement solutions (RIVAS)', abatement measures for ground-borne noise and vibrations for maintenance (Workpackage 2) are studied. Workpackage 2.4 of RIVAS focuses on rolling stock maintenance based on vibration reduction technologies for wheels.

The dynamic component of vertical wheel–rail contact forces generated by wheel irregularities (wheel out-of-roundness, OOR) is an important source to ground vibration and ground-borne noise, see for this e.g. the RIVAS deliverables D2.2 and D5.4.

Chapter 2 is showing: The EN 15313 applies as a maintenance base for secure interoperability of the wheelsets. It is primarily concerned with the organizational aspects and the management of the wheelset maintenance, contains the geometrical limits for safe interaction of wheel / rail or wheelset / track, shows pictures of damage to wheels and axles and contains mandatory requirements for wheel/wheelset geometry and wheel damages. Overall, the impression appears that the EN15313 is imprecise regarding the permissible errors at the wheel treads. Railway Group Standard GM/RT2466 specifies limits on wheel wear and general crack conditions that may be found on the tread of a wheel. By the application of GM/RT2466 it is common practice for train operators to turn the wheels at short enough intervals to avoid either crack length or cavity length limits being reached.

Different condition monitoring systems are used to detect out of round wheels. Most of the condition monitoring systems for railway vehicles are focused on the wheels and bogies since these are the parts that have the largest impact on the performance and are also the mayor cost drivers in maintenance. There are track based detection systems and workshop based detection systems. The difference is, that track based detection systems are installed in lines and are working without speed restriction. By using wheel impact detectors structural health monitoring trends can be observed based on the wheel impact data which indicate the actual condition of the wheels. Those trends can indicate the critical wheels that actually need to be removed, while at the same time allowing wheels that aren't critical to remain in service. Track based detection systems in long-time commercial use are for example DafuR in Germany and GOTCHA in Netherlands.

Workshop based detection systems allow the detection of different wheel/wheelset data (cracks, wheel profiles, out-of-roundness, wheel diameter, wheel tread defects) but they are situated in the vicinity of a workshop. The monitoring requires reduced train speed or stand still. A sophisticated workshop based monitoring system is for example ARGUS. It is important to share data from measuring devices directly with the rolling stock owner. The direct data transfer allows the vehicle owner to take immediate remedial actions. On the other side, if different alarming-levels are implemented in such devices, it allows the vehicle owner to pass from corrective maintenance to conditional maintenance.

In practice, e.g. wheelsets of high-speed trains require regular attention on a wheel lathe to remove tread defects before the depth is more than 0.5 mm. Research of real practice showed that OOR of up to 2.5 mm are removed by the ground wheel lathes.

A methodology for establishing reprofiling strategies uses a two-stage process. The first step involves tread defect frequencies and wear rate statistics from the raw data gathered as part of normal wheelset maintenance activities. The tread defect and wear data are then used as the input to a probabilistic computer simulation specifically designed to explore the impact of different wheel

lathe operating strategies on wheelset maintenance costs. This simulation has to investigate the effect of a number of different aspects of a wheelset maintenance strategy (Re-profiling policy, Parity rules, Planned turns). Another approach is based on systematic preventive maintenance. Instead of applying condition based maintenance with the scope to maximise the reprofiling intervals with the consequence of cutting depth of 6 to 7 mm the wheels are reprofiled in short terms (e.g. about all 70’000km) with a cutting depth of around 1 mm. As a consequence wheelset overhaul (lifetime) can be extended significantly due to this “reprofiling philosophy”.

Chapter 3 summarizes some of the European experiences in maintenance: The wheels of most vehicles in the European railways are still monitored by standard measurement equipment and visual inspection. Reporting is in use for locomotives by drivers and for passenger cars by conductors or by passengers. Especially for high speed applications (France, Germany, Spain, Switzerland, etc.) monitoring systems are applied.

In Chapter 4 the Table 4.1 lists the different failure types on wheels/wheelsets and on wheel treads which can cause a reprofiling procedure. Technology Assessment is based on a failure mode effect analysis (FMEA) where the different failures in Table 4.1 are treated in a systematic way. Based on this analysis mitigation measures are defined. These measures can be located for example in the field of design, of system maintenance, of workshop based monitoring, of track based monitoring and in the area of improved wheel material properties.

The entire wheel set, depending on the technical solution, consists of different components. There is a difference if the wheelset is used in a freight car, with a coach or in a driven vehicle. If for the reduction of wear of wheel and rail also additional elements are used (equipment for steering the wheelsets, lubrication, etc.), these must be taken into account in wheelset maintenance. In addition it is known that faults on the driving surfaces of the treads can lead to stress on components in the unsprung part of the bogie (springs, connection rods, earthing brush, speed sensors, etc.). They can also cause damage to track components (rails, sleepers, ballast). They also affect the environment (noise, vibration, etc.). To avoid damage to “overstressed” elements, additional expenses have to be taken into account in the wheelset maintenance. The resulting savings are difficult to quantify. They can be estimated based on experience, test results, theoretical investigations, etc.. As long as these different costs of the overall system are not known, LCC has to be established in a pragmatic way taking into consideration durability diagrams as a basis for the calculation. Based on these durability diagrams it can be verified if the reprofiling philosophy is correct or if it should be modified. The LCC is the sum of costs for reprofiling, for wheel replacement including required material, for immobilisation of vehicles, and for transfer of the vehicles to the different workshops (wheel lathe, overhaul).

The best approach to improve wheel maintenance plans is to investigate the causes for failures and its effects and have in mind LCC over a reasonable lifetime (e.g. wheelset lifetime). A preventive reprofiling according to the train and track specifications can then be a mitigation solution to reduce vibrations considerably but it has to be checked if other solutions could be more cost-effective.

Next steps:

Maintenance tests will run at SBB in Switzerland for preventive maintenance in the next months.

The technology assessment in Table 4.2, resp. Annex C shall be filled by experience of the RIVAS partners and others and will be included in the RIVAS WP5 guideline (Deliverable D5.5).

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1. INTRODUCTION

1.1 OVERVIEW

It is the aim of the EU to have cost effective mitigation measures for vibration protection. Because of the big influence of OOR (out-of-roundness), wheelsets with high OOR amplitudes are a problem in the vicinity of populated areas. They can be the cause to emit high vibration values. Until now, only few studies address the wheel maintenance as a mitigation measure to reduce vibration, although it has been shown (e.g. RIVAS deliverables D2.2 and D5.4) that OOR have a strong influence on groundborne vibrations.

The aim of this document is to present the wheel maintenance practice and to propose maintenance mitigation measures dedicated to the reduction of vibrations.

To define maintenance it is important to understand the interactions between OOR mechanisms and product qualities (see Figure 1.1).

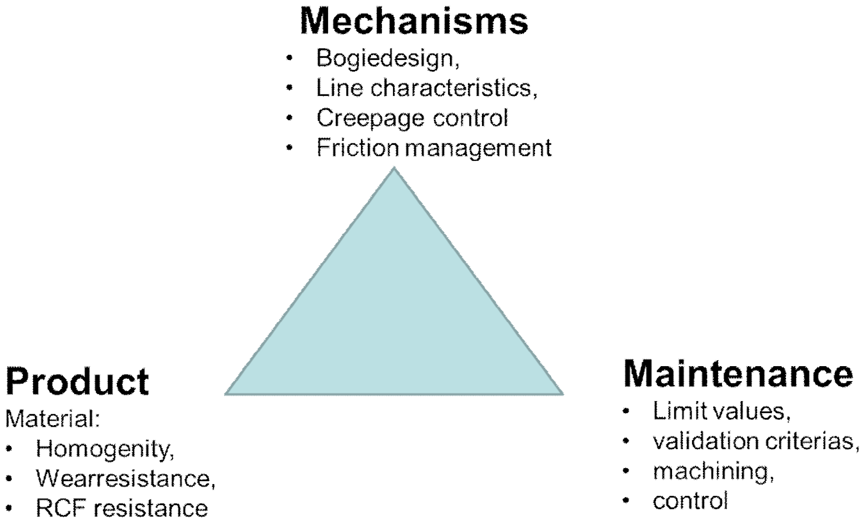


Figure 1.1: Influences for maintenance by product quality and mechanisms.

The strategy for improving wheel maintenance as a mitigation measure is presented in the Figure 1.2 below. An overview study on maintenance of wheelsets was ordered by SBB and is fully integrated in this deliverable D2.7 [1].

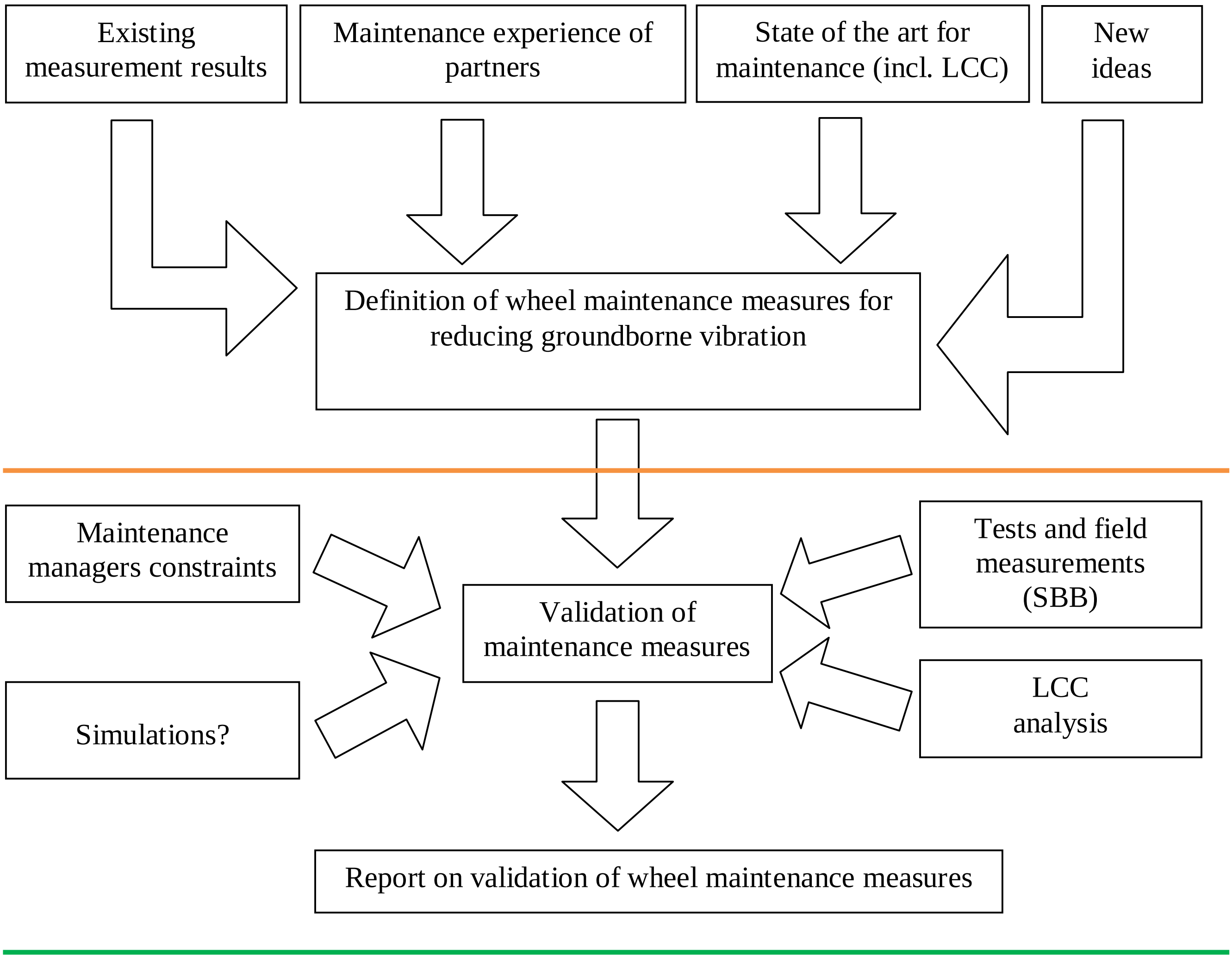


Figure 1.2: Strategy for WP2.4 wheel maintenance project. The first part is covered in RIVAS-Deliverable 2.7, the second part is covered in RIVAS-Deliverable 2.9.

1.2 Definitions of maintenance

1.2.1 Principles of maintenance

Maintenance is the set of all technical activities, administrative and management during the life cycle of a functional unit to maintain or restore a state in which it can perform the required function. Maintenance includes actions such as diagnostics and repair, adjustment, revision, monitoring and verification of hardware equipment (manufactured goods) or even intangible equipment (software). For definitions of maintenance see Figure 1.3

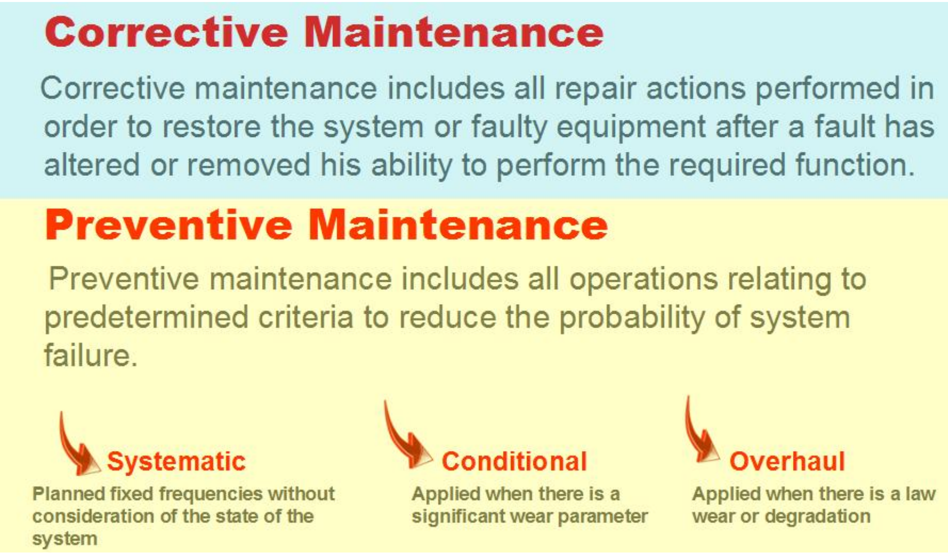


Figure 1.3: Principal definitions of maintenance

The condition maintenance and periodic replacement of railway wheelsets represents a significant cost faced by Train Operating Companies. Railway vehicle wheels wear relatively slowly, and could last for many years (sometimes more than 20 years) based on wear considerations alone. However, they are also subject to tread damage caused by wheel slide events, rolling contact fatigue, flange wear, and tread roll over. Wheels therefore require regular re-profiling by machining on a wheel lathe, which can drastically reduce the expected life. For this reason an optimum strategy for wheel maintenance and lathe operation is required, in order to maintain wheels within operational safety limits at minimum costs.

1.2.2 Definition faults, errors and failures

A **failure** is said to occur in a system when the system's environment observes an output from the system that is not conform to its specification. An **error** is the part of the system, e.g. one of its constituent (sub)systems, which is liable to lead to a failure. A **fault** is the adjudged cause of an error and may itself be the result of a failure. **Hence, a fault causes an error that produces a failure**, which subsequently may result to a fault, and so on (see Figures 1.4 and 1.5).

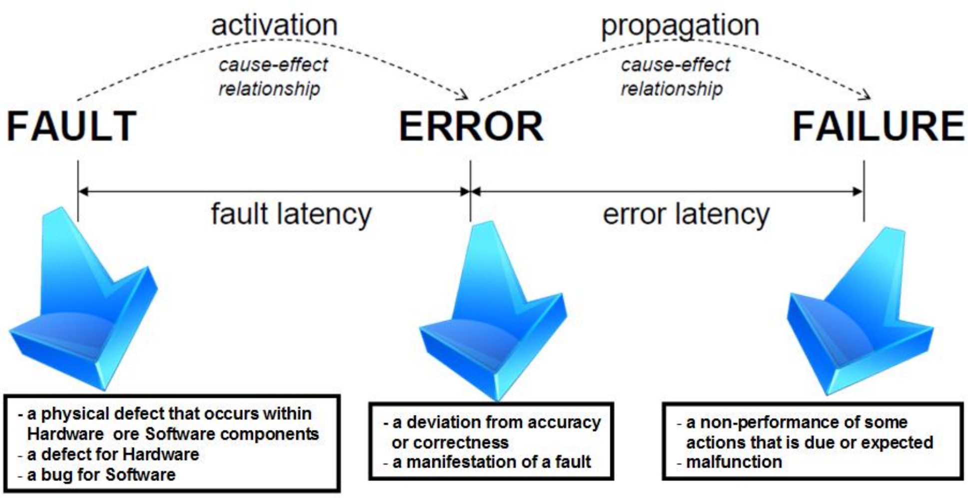


Figure 1.4: Relationship between Fault/Error/Failure

Based on the above, a fault in a system may propagate to the system's environment. A system is called fault tolerant when it can deal with faults and their consequent errors in such a way that it does not violate its specification, i.e. the environment of a fault tolerant system does not perceive a failure of the system. Hence, a fault tolerant system does not propagate faults to its environment. Fault tolerance techniques are practical methods that describe how to detect an error and confine it within a system. The confinement can be based on the restoration of the subsystem on which the error was detected before that error infects other parts of the system, or it can be based on the masking of the error occurrence (e.g. by isolating the subsystem on which the error was detected and using some form of redundancy to deliver the expected output).

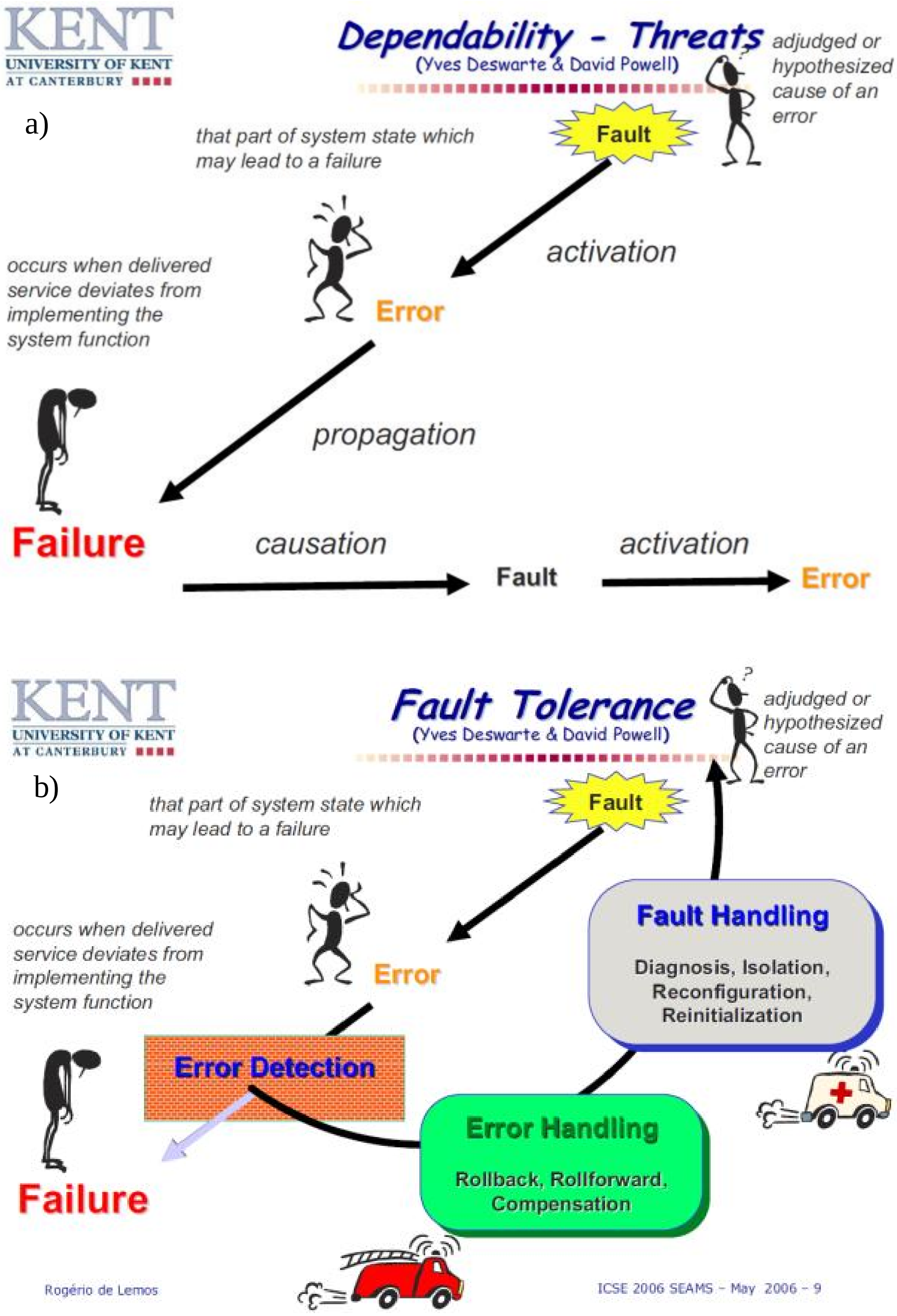


Figure 1.5: a) Dependability (the ability to avoid service failures that are more frequent and more severe than it is acceptable) – b) Fault tolerance (aims at avoiding the failure of the system) [2]

Errors and failures are connected slightly different to the maintenance process. Failures are mostly connected to corrective maintenance, at least on a functional level, but not necessarily on a system service level. Hence errors are often connected to preventive maintenance, such as condition based maintenance in which the condition monitoring equipment is used to discover a developing error and enable the possibility to prevent it. With preventive maintenance, the goal is to detect and prevent errors before they create disturbances in the system. The key factor of preventive maintenance is that it is possible to detect error indications at an early state which makes it possible to determine when the error has to be corrected and also possible to plan the maintenance activities in a proactive way.

1.2.3 Condition-based maintenance

Condition-based maintenance is an approach applied to improve safety and reliability as well as decreasing cost of operation and the need of support during the useful life of a technical system. Condition monitoring can be seen to have been in use for many decades if we count human observations, whereby skilful maintenance technicians were able to estimate the condition using their expertise and knowledge about the equipment. With the help of new technologies there is now the possibility to have continuous observations. The true strength of automated condition monitoring is for example in cases when the development of an error to a failure is very rapid or for example when large numbers of units have to be observed, as in the case with railway with a large amount of vehicles connected in a train set moving over large distances. The technology is also objective in its observations.

When deciding on using a condition monitoring system there are some functional requirements that have to be fulfilled. These functional objectives of the system are:

1. Provide information regarding current condition.
2. Provide forecast of future condition.
3. Detect and diagnose developing errors.

The ability of the system to achieve these stated objectives is dependent on the fundamental elements for condition monitoring and condition-based maintenance.

1. Data collection
2. Data analysis
3. Data interpretation
4. Use of information
5. Maintenance feedback

From this, the three first elements would concern the condition monitoring part and the two last would concern condition-based maintenance, how to actually use the information to support the maintenance management.

1.3 Reprofiling and its causes

Reprofiling the wheels becomes necessary to restore their profiles because of the safety features and comfort after the wheels have been altered due to the outstanding natural wear including RCF

(Rolling Contact Fatigue) or accidental defects by interaction with the rails and brake shoes. For more details see Annex A.

Reprofiling, in the context of this document, means the reconstruction of a NEW profile on a worn wheel. This profile is applied to all the width of the profile by reducing the diameter of the wheel, in accordance with the EN13715 standard.

The partial machining of parts of the wheel profile is a practice sometimes used. Note, however, that these practices can be adopted only when there is not significant wear on the flange, that is to say that the general shape of the flange is not impaired at the time of reshaping. So after reprofiling with weak recovery in diameter (less than 5 mm), the shape of the flange is very close to the form of a new flange. This can only be considered once the worn profile is identified and its evolution between new and used is linear over the active part of the flange and the connecting section.

The observation of normal wear can lead to adopt a different profile (see also Annex A2.2). This profile is then called "wear profile." The adoption of such a profile requires very specific studies and experimental validations what is going beyond determining a strategy for reprofiling maintenance. However, the data recorded by the process of analysing profiles developments for determining reprofiling cycles are a very useful source for determining a wear profile.

2. LITERATURE SURVEY

This literature review starts with a general description of a maintenance procedure. In fact, several maintenance procedures are in use.

2.1 Wheelset maintenance according to EN15313

The EN 15313 applies as a maintenance base for secure interoperability of the wheelsets. The standard prescribes the geometric limits for wheelsets and wheel profiles. It shows possible damage patterns in the components of the wheelset. But it does not distinguish, for example, in the case of the axle between acceptable and unacceptable failures. In addition, the standard specifies that a maintenance plan must be drawn. In this organizational measures shall be maintained, by which on the one hand, the compliance with established, internationally agreed limits will be ensured and on the other hand, the experience is taken into account. The standard does not discriminate between acceptable and unacceptable damage to the axles and the wheels. It leaves the damage evaluation and its findings to the long-term experience feedback in the maintenance. It is apparently assumed that by experience the damages and their impact on the durability of the wheelset can be assessed but this needs proper feedback between the stakeholders and analysis of the data by specialists.

The EN 15313

- is primarily concerned with the organizational aspects and the management of the wheelset maintenance (see section 2.1.1),
- contains the geometrical limits for safe interaction of wheel / rail or wheelset / track (see section 2.2.1),
- shows pictures of damage to wheels and axles, without distinguishing, for example, in the axles between acceptable and unacceptable damage (see section 2.2.2),
- contains mandatory requirements for wheel/wheelset geometry and wheel damages (see section 2.2.3),
- describes the checks, when wheelsets were involved in incidents on the track (derailment, overload, response of stationary detection equipment, collisions, etc.).

2.1.1 Organisation of maintenance

The general organisation of the maintenance must take into account the principle areas listed in the following diagram (Figure 2.1).

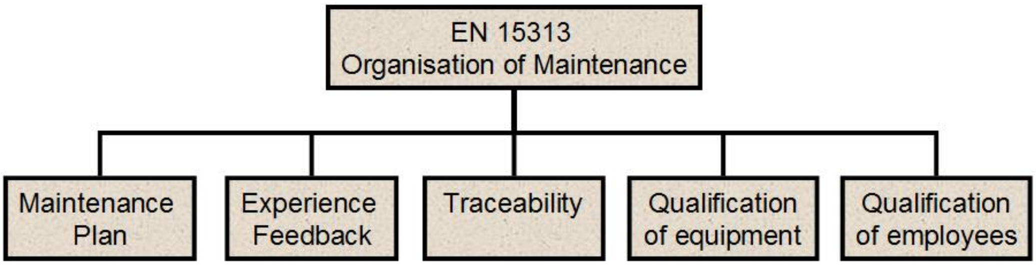


Figure 2.1: Organisation diagram

The maintainer is thus equated with a manufacturer who has to ensure that the product meets its entire life in respect of the art. The impairment of the functions in operational use is allowed to move on an experienced safety factor. The handling and processing at maintenance shall not affect the mechanical strength of the components. If, for example, notches due to mechanical impacts are repaired by grinding, the stresses due to the mechanical loads in service may not be increased in the repaired zones. For this purpose a quality plan for the product to be delivered is required, which must be approved by the authorised representative (engineer). This quality plan shall relate to the quality assurance manual, it must include the specific items for this product. The maintenance plan has the following objectives:

- Description of procedures and quality control for the maintenance engineer to observe the quality of the product to be delivered,
- The quality plan must provide at least the same reliability as the lot by lot acceptance. In the following Figure 2.2, the aspects are included, which are detailed in EN 15313 on the topics of the above.

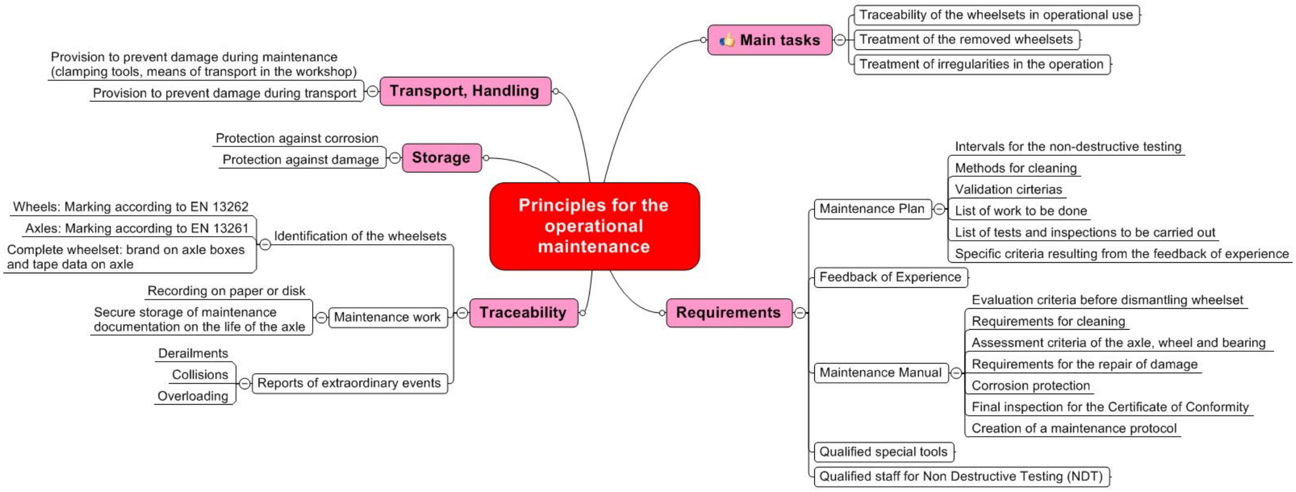


Figure 2.2: Principles for the operational maintenance of wheelsets

The term "wheelsets in operation" includes the entire time after delivery of the wheelsets by the manufacturer until its scrapping. The easiest wheelset consists of the axle, the two wheels, and the axle bearings. These components have different life spans and must be tracked separately. EN 15313 differs between the wheelsets, which are installed under the vehicle on the one hand and on the other on wheelsets which are removed from the vehicle during maintenance. Similarly, the requirements for the inspection and maintenance differ for the two conditions mentioned. Thus, for example on axles of most vehicles only dimensional checks and visual checks are carried out. Non-destructive tests are limited to wheelsets when removed. In some cases, for example in some high speed applications, non-destructive tests are required on not removed wheelsets.

Some main tasks of maintenance are tracking, supervision, and evaluation of the wheelsets in operational use. The observed irregularities during maintenance are examined and validated here. In addition, the treatment of the wheelsets is developed in the workshop. In these tasks are involved:

- the operator of the vehicle: he checks the wheelsets at the scheduled maintenance during operation.
- the competent technical services, which have experience in the maintenance of wheelsets and already have created rules for maintenance,

- a named person of the railway transport companies, which technically is a recognized expert.

The recognized technical expert should be contacted if

- the elimination of damage requires geometry changes to be made,
- changes in the maintenance process take place,
- failures or omissions were noted, which do not conform to the norms and maintenance manuals,
- new types of failures occur, subject to a detailed assessment.

The handling, transport, and storage of wheelsets have to be such that no damage can occur that affects the fatigue properties of the axles and wheels. In particular it has to be avoided that notches are generated and part of the corrosion protection becomes damaged. The requirements for completing the tasks are explained and set out in detail by the operator and maintenance personnel in the management documents. These include the maintenance plan, taking into account the feedback of experience, the maintenance manual, the aspects of quality assurance and traceability.

The maintenance plan contains the intervals for the non-destructive testing, the procedures for cleaning, the assessment criteria, and the list of works, tests, and inspections to be carried out. In detail, the maintenance plan refers to related documents in the maintenance manuals, in which the execution of the mentioned aspects are recorded. The maintenance plan includes the basis of the philosophy of EN 15313, as the name expresses, the planning aspects of maintenance, taking into account the maintenance manual and the feedback of experience. The maintenance manuals contain the description of

- the controls and the assessment criteria to be considered,
- the activities,
- the regulations to be respected,
- the special equipment and their application,
- the unfilled protocols for final checks and thus for the attestation of conformity.

Maintenance is documented on the basis of a test report and other findings are recorded on the basis of a report. The records and reports shall be used in addition to the quality control of the traceability of the wheel and its components (gears, shafts, etc.).

The EN 15313 prescribes a qualification of the maintenance or the maintenance workshop for wheelsets installed under the vehicle on the one hand and on the other hand those which are removed from the vehicle during maintenance. The issues listed in its tables and the quality assurance plan is checked (according to EN ISO 9001, for example).

2.2 STANDARD CRITERIA FOR MAINTENANCE

2.2.1 Geometric limits for geometric interaction of wheel / rail or wheelset / track

A classification of limits on the wheels and axles is defined in the standard EN 15313 [3] (see also figure 2.3). Depending on the field of application this standard defines:

- Mandatory requirements for compliance with specified limits for the geometric and safe interaction. These are minimal or maximum dimensions, for example, limits due to the negotiation of the railway track and in particular the turnouts.
- Binding works, which are carried out and their values for the assessment criteria in the maintenance plan are determined depending on the feedback of experience.

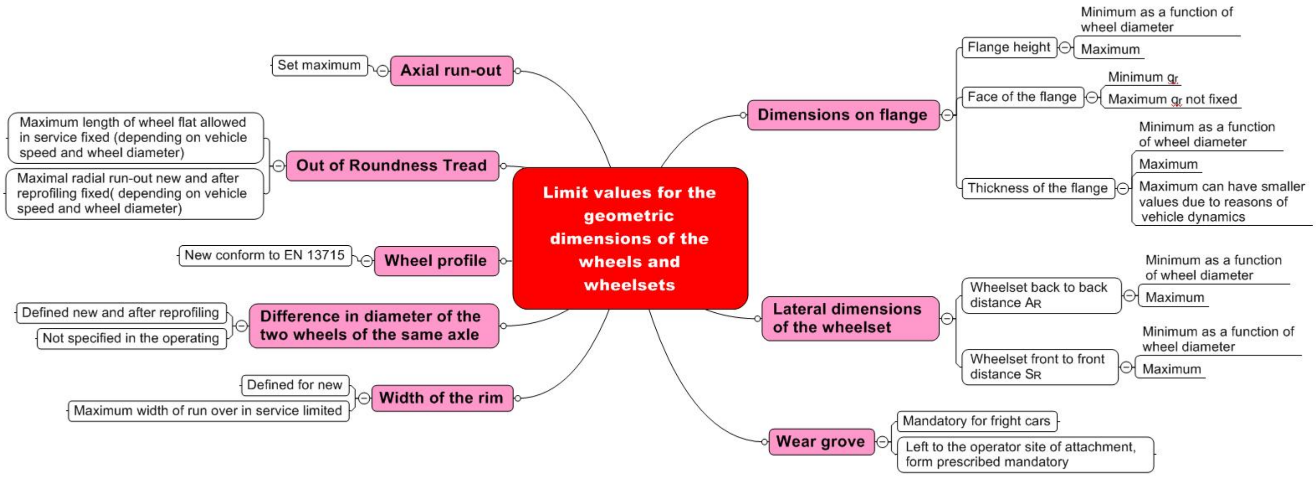


Figure 2.3: Classification of limit values for the geometric dimensions of wheels and wheelsets

For some of the limit values, the standard defines no limits or just limit intervals for operation (e.g. difference in diameter of the two wheels of the same axle, out of roundness of wheels). It leaves it up to experience and thus the feedback of experience of the operators for the corresponding definitions in the maintenance plan.

2.2.2 Damage pattern on wheels

Figure 2.4 gives an overview of the possible damages, which are listed in EN 15313 regarding the wheels. Any type of cracks is not permitted. Notches in the rim, which are aligned in the radial direction and thus result in the formation of cracks at the notch root to break the wheel, are not allowed, unless they can be repaired. With the exception of flats (see table 2.1), which are defined in EN 15313 for wagons to a maximum length of 60 mm, the maximum sizes of the other defects are determined non-binding. It is the responsibility of the operator or maintenance engineer to state limits in the maintenance plan. Even the way of repairing defects is not covered in the standard. These repairs must be described in the maintenance manual. It must be ensured that the mechanical component strength is not reduced by the repairs. If cracks are repaired the accuracy of the repair shall be demonstrated by non-destructive testing (NDT).

M		$M \le 18$			$18 < M \le 22{,}5$				$22{,}5 < M$		
V (km/h)		$V \le 160$	$160 < V \le 200$	$200 < V$	$V \le 120$	$120 < V \le 160$	$160 < V \le 200$	$200 < V$	$V \le 100$	$100 < V \le 120$	$120 < V$
D	$1\,000 < d$	80	60	40	80	60	50	35	X	X	X
	$840 < d \le 1\,000$	60	50	30	60	50	35	25	60	50	30
	$630 < d \le 840$	40	30	25	40	30	25	20	40	X	X
	$550 < d \le 630$	35	25	X	X	X	X	X	X	X	X
	$d < 550$	30	X	X	X	X	X	X	X	X	X

M: ***Axle Load in Tonnes (t)***
X: ***Reserved (no known use)***
D: ***Acutal wheel diameter***

Table 2.1: Boundary lengths of the defects on the tread (flats) according to EN15313

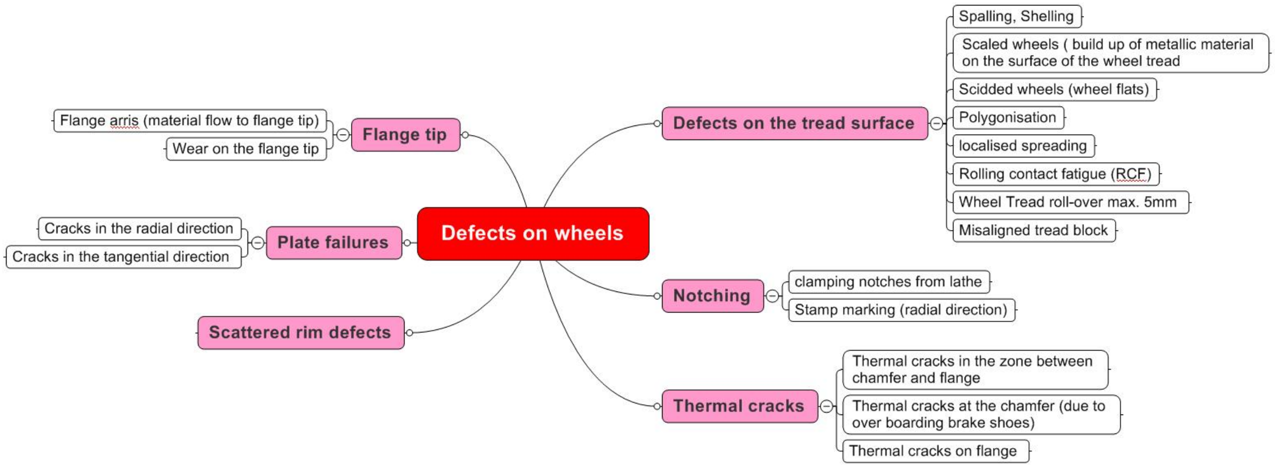


Figure 2.4: Defects of wheels

2.2.3 Mandatory requirements in EN15313

In accordance with the area of application the EN15313 specifies:

- mandatory requirements for all owners (e.g.: minimum and maximum dimensions, dimensions of the wheel-rail interface, etc.),
- binding measures to be carried out, the values of the criteria in the maintenance program are specified as a function of the operating experience.

The requirements have to be observed and the values in Table 2.2 are the acceptable limits for safe rail traffic (see Figure 4.2 for definitions of criterions). In Table 2.3 the permitted (not-binding) out-of-roundness (Δr) is given.

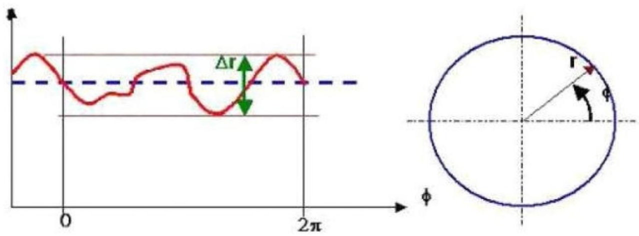
Part of the wheelset	Criterion	Section in EN15313	Diameter of the wheel [mm]	Limit value [mm]	
				Minimum	Maximum
Flange	Flange height	6.6.1.2	$330 \le d \le 630$	31.5	36
			$630 \le d \le 760$	29.5	
			$760 < d$	27.5	

<table>
<tr><th rowspan="2">Part of the wheelset</th><th rowspan="2">Criterion</th><th rowspan="2">Section in EN15313</th><th rowspan="2">Diameter of the wheel [mm]</th><th colspan="2">Limit value [mm]</th></tr>
<tr><th>Minimum</th><th>Maximum</th></tr>
<tr><td rowspan="4"></td><td rowspan="3">Flange thickness</td><td rowspan="3">6.2.1.3</td><td>$330 \leq d \leq 760$</td><td>27.5</td><td rowspan="3">33</td></tr>
<tr><td>$760 \leq d \leq 840$</td><td>25</td></tr>
<tr><td>$840 < d$</td><td>22</td></tr>
<tr><td>Flange angle</td><td>6.2.1.4</td><td></td><td>6.5</td><td>-</td></tr>
<tr><td rowspan="7">Wheelset/
Wheel-rim</td><td rowspan="3">Wheelset back-to-back distance A_R</td><td rowspan="3">6.2.1.5</td><td>$330 \leq d \leq 760$</td><td>1359</td><td rowspan="3">1363</td></tr>
<tr><td>$760 \leq d \leq 840$</td><td>1358</td></tr>
<tr><td>$840 < d$</td><td>1357</td></tr>
<tr><td rowspan="3">Wheelset front-to-front distance S_R (Wheelset external gauge)</td><td rowspan="3">6.2.1.6</td><td>$330 \leq d \leq 760$</td><td>1415</td><td rowspan="3">1426</td></tr>
<tr><td>$760 \leq d \leq 840$</td><td>1412</td></tr>
<tr><td>$840 < d$</td><td>1410</td></tr>
<tr><td>Rim-wheel width</td><td>6.2.1.10</td><td></td><td>135
140</td><td>Tolerance
-2, +1</td></tr>
<tr><td rowspan="11">Defects on axles or their com-ponents</td><td>Defects on the wheel-tread</td><td>6.2.2.1</td><td></td><td></td><td>See table 7 in EN15313 or table 1 in the present report</td></tr>
<tr><td>Thermal cracks</td><td>6.2.2.2</td><td></td><td></td><td>inadmissible</td></tr>
<tr><td>Tread-rollover</td><td>6.2.2.3</td><td></td><td></td><td>≤ 5</td></tr>
<tr><td>Defects on flange back of the rim</td><td>6.2.2.4</td><td></td><td></td><td>inadmissible in radial direction</td></tr>
<tr><td>Defects on the front face of the rim</td><td>6.2.2.5</td><td></td><td></td><td>Inadmissible in radial direction</td></tr>
<tr><td>Circumferential groove of the tread</td><td>6.2.2.6</td><td></td><td></td><td>Sharp grooves are inadmissible</td></tr>
<tr><td>Overhanging brake blocks</td><td>6.2.2.7</td><td></td><td></td><td>Inadmissible</td></tr>
<tr><td>Clamping notches</td><td>6.2.2.8</td><td></td><td></td><td>Inadmissible</td></tr>
<tr><td>Defects on the flange</td><td>6.2.2.9</td><td></td><td></td><td rowspan="3">See text content in the corres-ponding paragraph</td></tr>
<tr><td>Displacement or rotation of a wheel on the axle or of a tyre</td><td>6.2.2.10</td><td></td><td></td></tr>
<tr><td>Defects in the web</td><td>6.2.2.11</td><td></td><td></td></tr>
</table>

Table 2.2: Summary of mandatory requirements of EN15313

Overall, the impression appears that the EN15313 is imprecise regarding the permissible errors at the wheel tread. After all, the Annex I of EN15313 contains further information about the permitted deviations from roundness. However, these are not mandatory.

Wheel diameter — dependent speed	**Permitted Out-Of-Rondness** (Δr)
$D > 840$ mm	
• $v_{max} \le 60$ km/h	1,5
• 60 km/h $< v_{max} \le$ 160 km/h	1,0
• 160 km/h $< v_{max} \le$ 200 km/h	0,7
• $v_{max} > 200$ km/h	0,5
380 mm $< d \le$ 840 mm	
• $v_{max} \le 200$ km/h	0,7
• $v_{max} > 200$ km/h	0,5
$d \le 380$ mm	0,3



Circularity defects
(radial run-out)

Table 2.3: Appendix I, EN15313: Informative values for permitted *Δr:* out of roundness (OOR) and sketch of definition of *Δr*.

2.2.4 Other specifications

In EN 15313 the maximum sizes of the other defects on the tread surface are determined non-binding with the exception of flats.

Railway Group Standard GM/RT2466 [4] specifies limits on wheel wear and general crack conditions that may be found on the tread of a wheel (see also [5]). If multiple cracks occur and one of the cracks exceeds 40mm length, the wheelset must be withdrawn from service within 24 hours. When an isolated crack longer than 30mm is found, the vehicle must be withdrawn from service immediately. When an isolated crack longer than 20mm but shorter than 30mm is found, the wheelset must be withdrawn from service within 24 hours. If the RCF (Rolling Contact Fatigue) should develop to form cavities in the tread of the wheel GM/RT2466 sets limits on the maximum size of the cavity. The wheelset must be withdrawn from service if any single cavity is greater than 15mm in circumferentially length around the wheel or any two cavities separated by less than 50mm have a total length greater than 15mm.

By the application of [4] it is common practice for train operators to turn the wheels at short enough intervals to avoid either crack length or cavity length limits being reached. The turning intervals are adjusted for the different RCF initiations observed on powered axles and the first and last axles in a multiple unit. While preventive wheel turning is successful in reducing wheel RCF problems, it reduces vehicle availability. Where effective inspection and preventive turning regimes are not in place, wheels that have suffered severe RCF are usually identified by wheel impact load detectors and scheduled for maintenance.

2.3 Detection of OOR

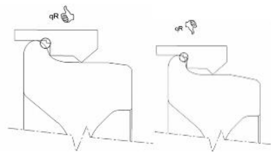
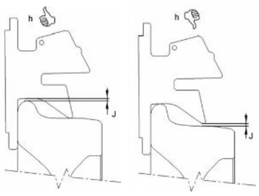
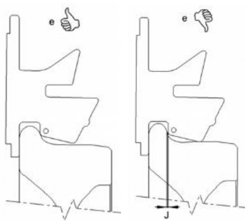
The detection of non-circular wheels cannot be viewed in isolation. Some first analysis can be found in Deliverable D2.2 [6]. In practice, various different methods are used, which are partially embedded in broader maintenance procedures. For example, a non-circular wheel or tread damage certainly can be detected by visual inspection at the scheduled maintenance or by other traditional inspection techniques used in the railway industry, such as drive-by inspections where all of the wheels on the train are glanced at while a vehicle to be inspected drives by. On the other side such inspection techniques are not as accurate and reliable as more rigorous and quantitative inspection methods. Many damaged wheels aren’t found, while many still useable wheels are removed although they could remain in service. By using wheel impact detectors structural health trends can be observed based on the wheel impact data which indicate the actual condition of the wheels. Those trends can indicate the critical wheels that actually need to be removed, while at the same time allowing wheels that aren’t critical to remain in service.

The limit values for OOR for example can be different and varying according to customer requirements. The limit values for OOR in passenger trains due to comfort are lower than those applied for freight trains. For freight trains there exists a lot of experience from heavy haul applications: For example high impact wheels have been observed to increase the surface crack growth rate on a rail by a factor of nearly 100 times than under non-impact loading conditions. Also, it has been shown with numerical calculations that dynamic impacts have a detrimental effect on concrete sleepers health by increasing the risk of crack initiation in the sleepers.

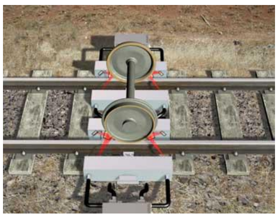
2.3.1 Condition monitoring used for railway vehicles

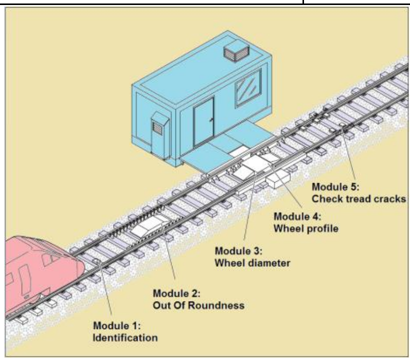
Today there are many commercial products for condition monitoring of railway vehicles. The monitoring technology can be classified either as reactive or predictive. Most of the condition-monitoring systems for railway vehicles are focused on the wheels and bogies since these are the parts that have the largest impact on the performance and are also the mayor cost drivers in maintenance. Table 2.4 contains different methods for wheel and wheelset control (wheel condition monitoring). A distinction is made between

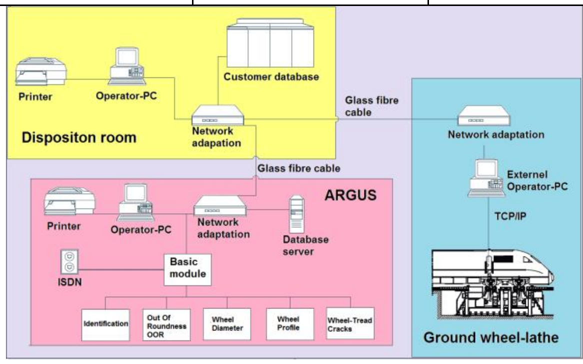
a) simple methods for wheel condition definition (application of templates and visual control),
b) methods for investigation of wheel conditions (Methods for the analysis of new wheel profiles or for detailed OOR analysis. These methods can be applied, for example, to examine the relationship between the shape and amplitude of OOR and these results can calibrate the wheel impact measurement results of automated measuring systems in the track),
c) methods of wheel condition monitoring using installations in the track and
d) methods of wheel condition monitoring using installations in the workshop.

Methods	Categories of faults on wheels			
	Wheel profile	Out of roundness	Tread defects	Cracks
a) Simple methods	X (good/bad)	X (limited)	X (limited, dependent on experience)	X (limited, dependent on experience)
Templates	Flange angle  Flange height  Flange thickness 			
Visual control	X (limited)	Wheel flats, localised spreading in advanced state	X	X
b) Methods for investigations	X	X	X (limited)	When measuring by visual control[1]
Miniprof	Wheel profile including sizes of flange and wheelsets 	When measuring by visual control[1]	When measuring by visual control[1]	When measuring by visual control[1] **Table 2.4 continued next page**

[1] When the wheel profile or out-of-roundness is measured, the tread is in direct view of the examiner. It is assumed that the examiner has the experience to perform simultaneously with the measurement a visual assessment of the tread.

Methods	Categories of faults on wheels			
	Wheel profile	Out of roundness	Tread defects	Cracks
Calibri				
Direct measurement of out of roundness	When measuring by visual control[1]		When measuring by visual control[1]	When measuring by visual control[1]
c) Wheel condition monitoring on the track	X	X	X (limited to vertical split rim failures or shattered rims)	X (limited to vertical split rim failures or shattered rims
For example Dafur, see chap. 2.3.3			X (limited to vertical split rim failures or shattered rims)	X (limited to vertical split rim failures or shattered rims
Wheel profile inspection in line	 			
d) Wheel inspection in workshops	X	X	X	X **Table 2.4 continued next page**

<table>
<tr><th rowspan="2">Methods</th><th colspan="4">Categories of faults on wheels</th></tr>
<tr><th>Wheel profile</th><th>Out of roundness</th><th>Tread defects</th><th>Cracks</th></tr>
<tr><td>For example ARGUS system, (see chapter 2.3.4)</td><td colspan="4">



See Figure 2.7 and 2.8.</td></tr>
<tr><td>For example AURA for tests after reprofiling</td><td></td><td></td><td colspan="2"></td></tr>
</table>

Table 2.4: Methods for wheel profile, OOR and tread defects detection

2.3.2 Products in the market for condition monitoring

Many of the products for condition monitoring of railway vehicles are wayside monitoring systems and not directly mounted on the vehicles. In many cases, it still would not be economical to have sensors on every vehicle to monitor the entire vehicle condition because the cost of monitoring would become more costly than handling the faults when they occur. The vast numbers of vehicles that are in use on the railway lines makes it very costly to equip them all and also it is a challenge to both organize and maintain detector technology on every vehicle.

Possibilities exist in the railway sector however due to the fact that the vehicles are track bound and that the vehicles are most often used on specific routes even though they may be used over very long distances. But this makes it possible to monitor the vehicles with equipment standing adjacent to the track. The amount of monitoring systems and detectors can then be limited but still monitor and measure a large number of vehicles.

2.3.2.1 Reactive systems

Reactive Systems detect actual errors at the vehicles; many of these errors are hard to predict or have very short error to failure time. In most cases the information from these systems is not suited for trending, but is of importance to protect the equipment from further damage due to the failure. The systems also have reactive characteristics and they don't use the information in a trending way, even if the information could be used in that way. Some examples of systems and detector technology that are used in a reactive way are:

- *Dragging Equipment Detector:* The dragging equipment detector is a device to detect the presence of objects dragging beneath a moving train.
- *Hot Box Detector and Hot/Cold Wheel Detector:* Hot box detectors have been in use since the 1960s and are designed to detect overheated journals (hot boxes) since a bearing failure can have catastrophic consequences if it happens when the vehicle is in service. Bearings can have defects for a long time and only show small variations in temperature but when they are about to seize there will be a large and rapid increase in temperature. This heat up from a normal state to a catastrophic level can be as fast as 30-60 seconds.
- *Sliding wheel detector:* Sliding wheel detectors are systems that are designed to detect wheels that are sliding or skidding due to the fact that they are not rolling as fast as they should compared to the velocity of the whole vehicle. Mechanical failures or human errors can cause sliding or skidding wheels to occur and if undetected they can result in derailments.

2.3.2.2 Predictive systems

Predictive systems are capable of measuring, recording and trending the ride performance of the vehicles and also specific components. From the collected information it is possible to analyse the condition of the equipment to predict possible failures and errors that may occur in a near or distant future. This makes it easier to plan the maintenance activities ahead and also to utilize the equipment in a more efficient way. Some examples of systems and detector technologies that are used in a predictive way are:

- *Acoustic bearing detectors:* This technology uses microphones to record sounds from the passing vehicles. The monitoring systems that are in use focus on the wheel bearings as it is well known that bearing defects produce vibrations at frequencies that can be connected to the characteristics of the defect. The technology cannot detect all bearing defects but is a more predictive system than the Hot Box detector since the bearings will generate an excessive amount of heat only at a late stage when there is a rapid degeneration of the internal components.
- Vehicle *performance monitoring/ Wheel condition monitoring:* The monitoring systems are used for monitoring the performance of the vehicles, bogies and the individual wheelsets in the track, detecting for example lateral displacement, hunting and angle of attack and wheel tread failures.
- *Vehicle inspections:* Vision technology can be used for monitoring a large amount of applications such as brake pad inspections to get an automated inspection process. It can also be used for detecting defect springs, missing end cap bolts, faulty handbrakes and coupler faults.

2.3.3 Track based detection

Some track based detection systems are described below:

DafuR

The DafuR (german: **D**etektions**a**nlage **f**ür **u**nrunde **R**äder) is a WLC (wheel load checkpoint) used to detect out-of-round wheels [5]. Detection systems of this type are scattered over the German railway network, and each day data from 2 000 – 3 000 trains are collected and transmitted to the vehicle owners (operators). Based on RFID (Radio Frequency Identification) information on vehicle configuration, each measurement can be directly linked to a specific wheelset due to tags on every vehicle. It is the responsibility of the vehicle owner to take action (wheel maintenance or reprofiling) if the measured data exceeds an agreed limit more than once in three different pass-bys measured.

Using a system of strain gauges mounted on the rail, the vertical wheel–rail contact force is measured over a distance of 4.2 m. The system was developed by DB Systemtechnik [6]. A statistical assessment of the continuous force signal is performed to provide for example a dynamic magnification factor (german: dynamischer Beiwert), see Figure 2.5. To determine the type and severity of the wheel out-of-roundness, the measured signal is compared (pattern recognition) with the characteristics of other signals recorded for known wheel geometries.

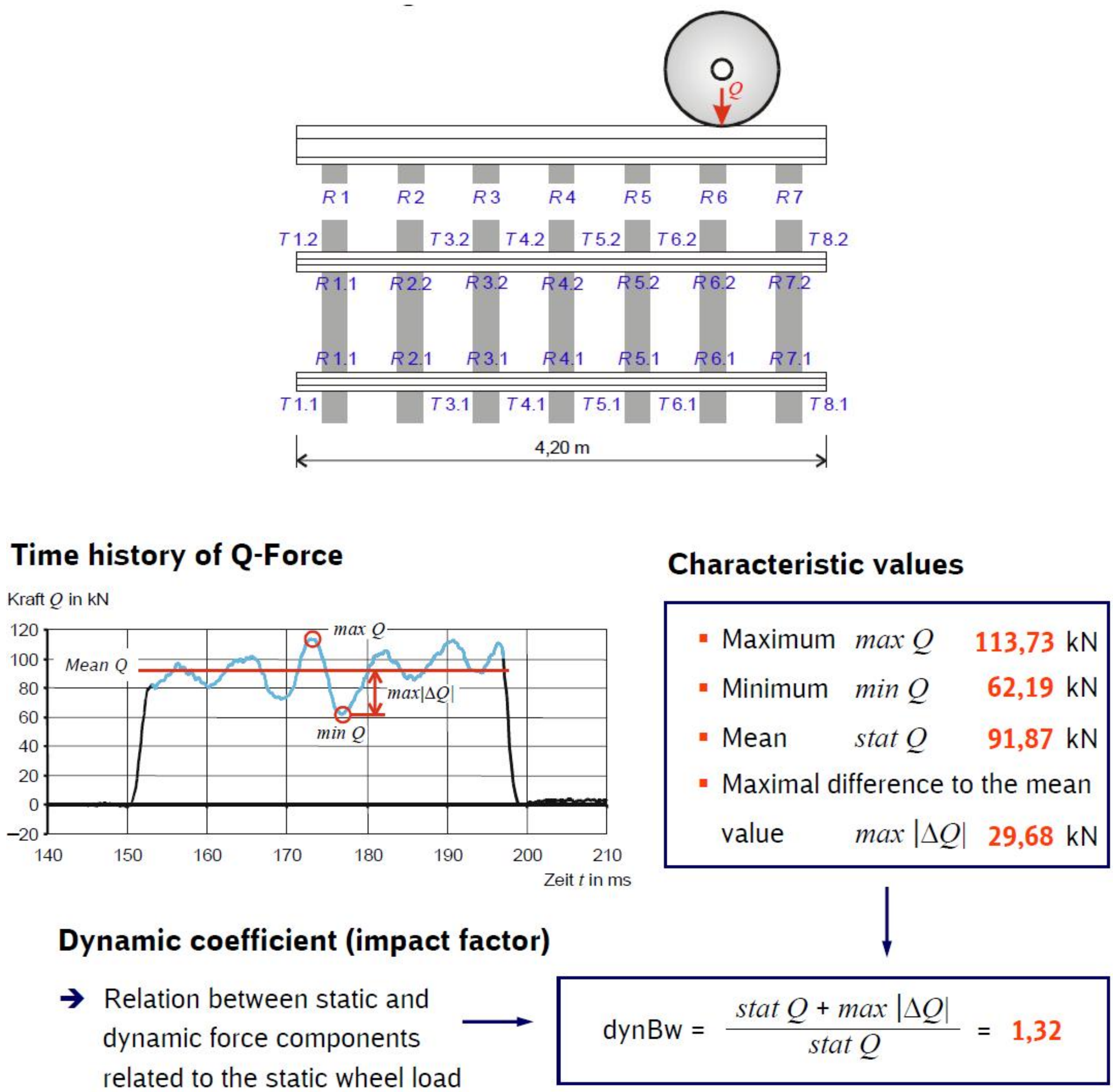


Figure 2.5. Measurement principle of DafuR, time history of a measured vertical wheel–rail contact force and derived quantities. From [6]

Figure 2.6 illustrates four signals measured by DafuR for the same wheel with a flat. At the leading edge of the flat, the vertical force is reduced (sometimes to zero indicating loss-of-contact). The drop in contact force is followed by a severe impact. The pattern recognition method indicates a wheel flat length in the interval 42 – 52 mm. The repeatability of the signal is good. According to German regulations (maximum flat length 60 mm), this wheel flat does not require immediate maintenance. For further information about DafuR, see RIVAS D2.2 [6].

Several other measurement stations based on strain gauges mounted on the rail are referred to as WILD (Wheel Impact Load Detector). This system was developed by the American company Salient (L.B. Foster) [7].

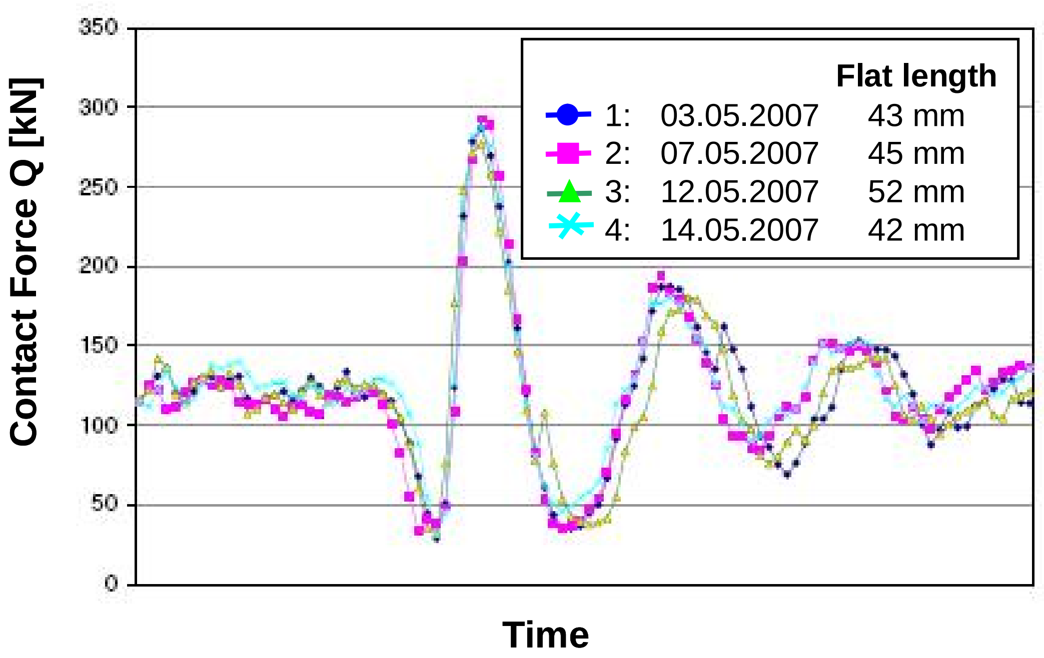


Figure 2.6. Characteristics of vertical wheel–rail contact force measured for a wheel flat: wheel unloading followed by an impulse. From [5,6]

GOTCHA

Another system for track based detection of wheel out-of-roundness is the Dutch GOTCHA system [8]. The system includes optical sensors mounted on the rail to measure rail deflection due to vertical wheel loads. Because of the use of optical technology, the system is not sensitive to electromagnetic influences. A post-processing procedure transforms the measured signal to quantitative measures of the static and dynamic wheel loads. The deflection of the sensor (deflection of the rail) as a result of a vertical load on the rail is dependent on both the frequency and amplitude of the force and the distance between the sensor and the impact location. In the post-processing, the frequency dependence is accounted for by a transfer function to obtain the wheel load.

Using this system, it is possible to distinguish between different types of wheel defects, such as polygonal wheels and wheel flats. A 'defect value' based on the rms (root mean square) value of the registered dynamic wheel–rail contact force (for one wheel turn) is used to determine the severity of the defect. The system of GOTCHA detectors installed on the Dutch railway network is connected to a system for automatic identification of vehicles.

2.3.4 Workshop based OOR measurements

ARGUS II (fixed installation)

ARGUS II is the next step in the development of the ARGUS inspection and test system. It enables not only wheelset diagnostics of full rail-bound train vehicles, but for the first time the diagnosis of tram wheel sets in running operation is possible. When entering the test section, the vehicles are automatically identified and measured. All relevant data are archived in a database. This allows the operator of wheelsets without personnel expense and loss of time to monitor continuously. Based on the collected measurements a wear characteristic can be determined, which will serve as a basis for an economic and environmental-friendly as well as safety-conscious maintenance.

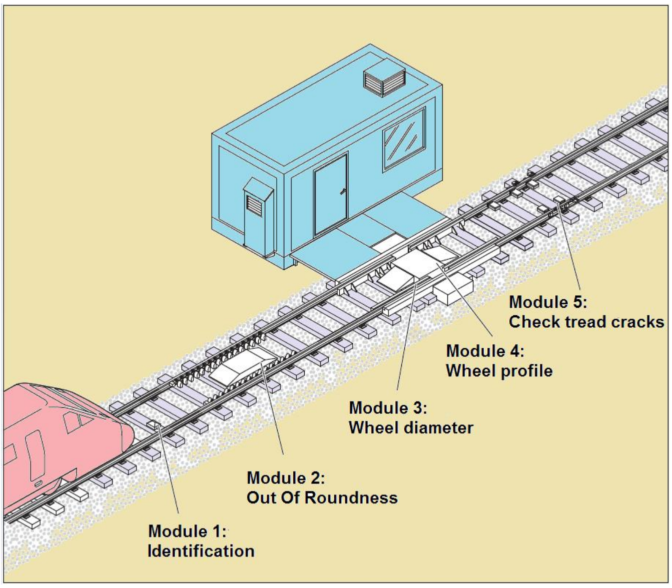


Figure 2.7: Different modules of ARGUS – System

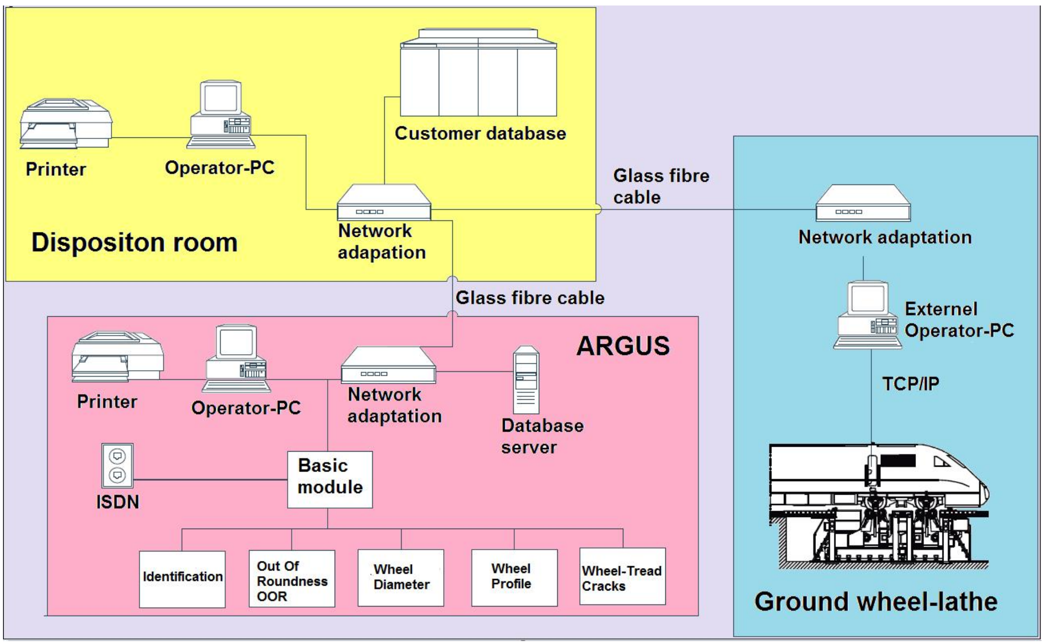


Figure 2.8: System architecture of a modern Ground wheel-late-system

Figure 2.7 shows the different modules of the ARGUS II – System and Figure 2.8 shows the system architecture of a modern ground wheel-lathe-system. The respective modules capture the data listed as follows:

- ***Identification:***

  The identification module is used for the detection and classification of the different trains and axles. Mounted on the train, read by the identification module and transmitted to the database which associates the measurement results of the respective wheel sets.

- ***Out of roundness:***

  As a direct geometric measurement in drive-through operation is not possible, a secondary variable is measured, from which the desired information is clearly derived: The calculated measure of this module is the height of the flange deviation. Experience has shown that this deviation is a direct measure of the eccentricity and the shape error of the running circle of a railway wheel. The measuring principle is mechanical. The height of the flange is sampled with probes that are pneumatically pressed during the crossing from below against the wheel flange.

- ***Wheel diameter:***

  The wheel diameter is determined on behalf of the radius of curvature of two arc segments in the area of measurement circle diameter using the light-section method.

- ***Wheel profile:***

  To measure the profile, the light-section method is employed. Both wheels of a wheelset are optically measured from the bottom of the profile cross section. Each wheel rim is illuminated by two laser beams flared.

- ***Wheel tread defects:***

  Two ultrasonic transducers are integrated into the left and right rail. As soon as a wheel is in contact with the probe, it transmits an ultrasonic pulse in the form of a so-called Rayleigh surface wave. This rotates the wheel several times and produces a sequence of current signals in the probe, if the tread is intact. The test is to determine the contact surface to a depth of about 5 mm. If in this range damages in the form of cracks and/or cavities exists, in addition to the current signals additional echoes of the defects will be registered.

ODS (mobile equipment)

To obtain accurate and more detailed information of wheel out-of-roundness (OOR), a direct measurement of the radial deviation from the nominal rolling radius can be performed by mechanical displacement probes. One such measurement device is supplied by Lloyd's Register ODS [9], see Figure 2.9.

The system is designed to measure surface roughness as well as OOR. The surface roughness of a wheel is directly linked to the radiation of noise from the wheel/rail contact and is consequently an important parameter to control. Three probes in mechanical contact with the wheel tread measure the radial deviation from the nominal wheel radius. The wheel is lifted and is rotated by hand. The radial deviation is measured with a sampling distance of 0.5 mm along the wheel perimeter. The amplitude resolution is 0.06 µm which allows measurement of roughness levels less than -20 dB.

The three measurement probes are mounted side by side along a virtual line in the axial direction, i.e. across the wheel/rail contact running band. The axial location of each probe can be adjusted depending on which part of the wheel surface shall be measured. By taking repetitive measurements with the three measurement probes at different axial locations it is possible to obtain an accurate 3D measurement of the wheel shape or a particular defect, for example a wheel flat.

Figure 2.9: Equipment for direct measurement of wheel out-of-roundness. The three probes in mechanical contact with the wheel tread are shown together with the small wheel for measurement of the distance around the circumference. Photo by Magnus Melin

MARPOSS (mobile equipment)

The equipment MARPOSS (product of company MARPOSS, Belp, Switzerland) used by SBB is another sensor system which measures the out-of-roundness of the wheel by turning the wheel 360 degrees [6]. The accuracy of the measured unevenness is 1 µm. Data is sampled at about every 2.2 mm of the wheel circumference (1800 data points for a wheel circumference of 3900 mm).

A standard protocol for direct measurement and analysis of wheel out-of-roundness was suggested in the ACOUTRAIN project [10]. The procedure is closely based on the procedure for rail roughness measurement described in EN 15610:2009.

2.3.5 Wheel based detection systems

An alternative to track based detection systems, such as DafuR, WILD and GOTCHA described in the section 2.3.3, is to mount a condition monitoring system on (a selection of) individual bogies or even individual wheelsets. For example, on the urban railway network in Copenhagen, a wheel monitoring system (WMS) based on measurements with accelerometers is used. A description of the system, together with a discussion of its economic advantages, is given in [11].

Another method for detecting out-of-round wheels is based on measurements of wheel axle bearing temperatures and vibrations, see [12]. The SKF ("Svenska Kullagerfabriken", international techno-logy group) multilog online system includes several modular sensors for continuous monitoring of a range of bogie operating conditions including those of the wheels and axlebox-bearings. To monitor wheel conditions (wheel shape) and to detect wheel flats, the axlebox-housing can be equipped with a multifunction sensor system, see Figure 2.10. Axlebox vibration sensors integrated in the axlebox (or mounted on the housing) can be used to measure the status of the rollers.

Figure 2.10: SKF Axletronic sensor installed in the housing. From [13]

2.4 MACHINING TECHNIQUES

2.4.1 Introduction wheel lathe

In practice, wheelsets require regular attention on a wheel lathe (see Figure 2.11) to remove tread defects and to restore excessive deviation of the tread profile from any given profile (normally the standard profile 'S1002') due to wear. The efficiency of this process has considerable cost implications for both the vehicle owner and the train operating company.

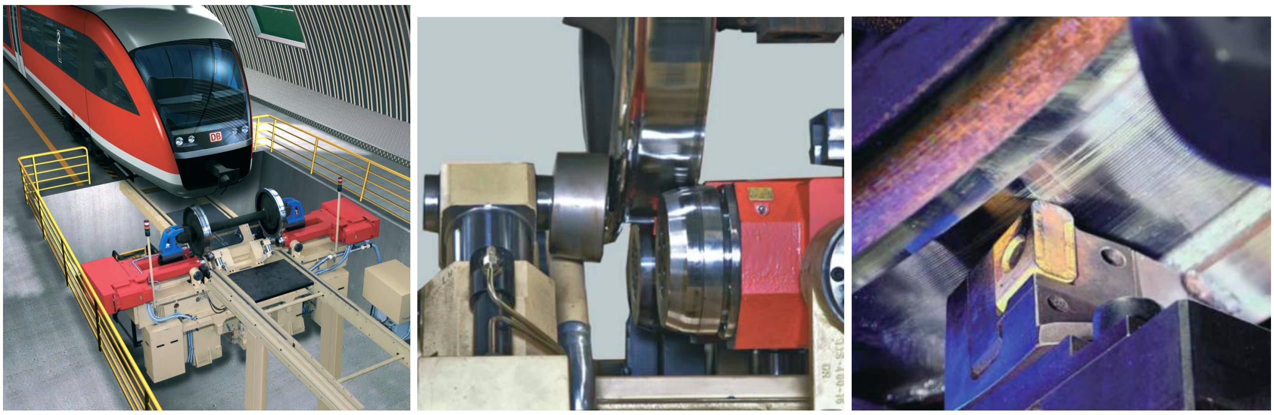


Figure 2.11: Wheel lathe

In RIVAS WP5 Deliverable D5.4 [14] two important observations were made:

1) Another mitigation measure envisaged from the literature is to improve the process of machining for wheel profiling. For example, it has been concluded that clamping the wheel by a three-jaw chuck during reprofiling could lead to the generation of an initial periodic OOR with order 3 [15].

2) Also, minimizing the initial wheel roughness by better precision of the machining tools will delay the roughness growth.

Instead of a wheel lathe it is possible to grind the tread of the wheel , but up to now this is practiced only by SBB. For tramways this method seems more often used, especially when only little material has to be removed (e.g. Zurich tramways for small differences in diameter with big influence on vehicle reactions). SBB has installed a grinding machine in Erstfeld to be able to enlarge the capacity to turn locomotive wheels and because a grinding machine was considerably cheaper at those times.

2.4.2 Introduction research

Research [16] responded to concern within the industry that ground wheel lathes might not be able to adequately remove ovality during re-profiling, because the wheel is supported on the tread, rather than entirely at the wheel centre. The project investigated whether or not ground wheel lathes are capable of adequately removing out-of-roundness or ovality during reprofiling. Lathe types, other than ground wheel lathes, rely on the wheelset being separate from the vehicle or bogie, and can readily be centred at the axle centres, hence guaranteeing accurate re-profiling.

2.4.3 System description of wheel ground lathe for tests

There are two main suppliers of wheel lathes in the UK, namely Hegenscheidt and Atlas Rail. The lathes produced by these manufacturers are of similar design. The Hegenscheidt literature refers to the two steel wheels that drive each of the wheels on a wheelset being machined, as floating friction rollers. Hydraulic rams in the horizontal and vertical planes provide a frictionless three-point bearing arrangement, which directs the lathe power into the wheelset. The rollers, due to constant hydraulic pressure, are able to follow accurately any discontinuities on the wheel profile, whether the wheel has been:

a) just placed on the lathe with problems such as flats etc.,

b) partly machined, or

c) machined to provide a smooth contour.

These rollers are positioned towards the underside near rail level and are equidistant from the vertical centreline of the wheelset and thus push upwards, providing a lifting or unloading force on the wheelset. To counteract this and the forces generated by the cutting tool which makes contact with each of the wheels at bottom dead centre, axlebox support and/or holding-down arrangements are utilised.

2.4.4 Conclusions

- Measurements before reprofiling show OOR of up to 2.48mm and 2.205mm respectively for the Class 170 (DMU, excessive tread wear) and Class 91 (high-speed locomotive, experienced tread problems in the past), the wheel ground lathes effectively removes these abnormalities

- The incidences of significant OOR above 1.0mm is small: 5% and 7% respectively for the Class 170 and 91 vehicles. Therefore the percentage for fully developed out-of-roundness in the present case is very small.
- Wheels turned with assistance of part or full hold down facility are effectively turned about the axle centre and the potential for retention of any OOR is negligible.
- There is no evidence from scrutiny of records relating to Classes 170 and 91 that a OOR abnormality has been retained following reprofiling.

2.5 PROPOSAL OF A REPROFILING STRATEGY

2.5.1 Introduction

In order to better understand and thereby optimise the cost of maintaining wheelsets, a probabilistic methodology for evaluating and comparing the effect of different maintenance strategies on the rate of consumption of wheelsets across a whole fleet can be applied. The advantage of this approach over a method of wear prediction based on first principles is that the data required already exist, as wheel exam reports and wheel lathe records. For any fleet of vehicles operating at a given utilisation on a given route, the average wheel wear behaviour is likely to be stable and well defined. The use of a retrospective approach means that existing data can be used to evaluate the cost benefit of different potential operational strategies without the delay associated with carrying out experimental monitoring.

The proposed methodology uses a two-stage process:

- The first stage involves deriving tread defect frequencies and wear rate statistics from the raw data gathered as part of normal wheelset maintenance activities. The raw data have to be compiled from two main sources
    - the wheel condition sheets,
    - the heavy repair wheel sheets.
- The tread defect and wear data are then used as the input to a probabilistic computer simulation (different software in use) specifically designed to explore the impact of different wheel lathe operating strategies on wheelset maintenance costs (see also chapter 4.3 and Annex B).

The outputs from the simulation include probabilistic profiles of wheelset lives and of the temporal proximity to safety limits, and the whole fleet costs associated with each lathe operational strategy.

2.5.2 Wheelset usage data

These wheelset usage data is normally gathered in the wheel maintenance as EN15313 is asking for traceability.

2.5.2.1 Wheel condition sheets

These are completed when the units are examined at depot and record the following:

- Date
- Mileage
- Unit Number

- Coach Number
- Flange Height
- Flange Thickness
- Tread Condition

The flange height, flange thickness, and rim thickness are all recorded to within 1mm. The tread condition is scored from 1 to 3,

- 1 representing good condition,
- 2 needing attention and
- 3 being unsuitable for use.

2.5.2.2 Heavy repair wheel sheets

These are completed when the unit is sent to the wheel lathe. These sheets record:

- Date
- Mileage
- Unit Number
- Coach Number
- Wheel diameter before attention
- Wheel diameter after attention

There are also a number of tick boxes presented to record the reason for the heavy repair wheel attention. The following options for heavy repair attention are offered:

- Lathe Turn
- Wheel Change
- Parity Turn
- Other – to be specified.

2.5.2.3 Data reduction

The data for all vehicles have to be entered into a master spreadsheet for each class of vehicle and may be separated when vehicles are in service on different lines characterised by different curve distributions. For each vehicle, the spreadsheet allows the condition of the wheelsets to be easily visualised as a function of time. The spreadsheet computes the statistical variations of:

- Tread condition (1, 2, or 3)
- Amount of material removed on the lathe
- Tread wear rates
- Flange wear rates

2.5.3 Results

2.5.3.1 Tread conditions

The frequency of recording a tread condition 3 in each month can provide interesting information. For example,

- The majority of severe tread defects (flats) occur in the winter months during and following the leaf fall season, when track adhesion is expected to be low.
- Spalling occurs more frequently in hot weather periods, where the friction coefficient wheel/rail is expected to be high.

The seasonal variation can also be apparent in the number of lathe visits per month.

2.5.3.2 Material removal on the lathe

The reduction of rim thickness associated with a lathe event can be calculated using the 'before' and 'after' data from the Heavy Repair Wheel sheets. Based on the data distribution the conclusion could be

- the majority of turns correspond to less than a x mm radial reduction, but
- there is a small number that are significantly larger than this. These are likely to have been caused by extreme parity turns, removal of very bad tread defects, or in matching a replacement wheelset.

2.5.3.3 Tread and flange wear rates

Tread and flange wear rates can be calculated for each wheelset on each vehicle from the flange height and thickness measurements. The wear rates should be averaged over time, to cancel out errors caused by measurement accuracy. Based on the data distribution the conclusion could be, that the resulting average wear rate distributions are

- tread wear rates x mm/year and
- flange wear rates y mm/year respectively.

2.5.4 Wheelset life model

2.5.4.1 Methodology

The wheelset life prediction model uses the data for tread wear rates, flange wear rates, and frequency of lathe visits. The model can for example run a time-stepped Monte Carlo analysis for all four wheelsets on a single vehicle. The amount of material lost to wear in each time step can randomly be sampled from the input populations. The probability of a unit visiting the lathe within each month is sampled from the population and can be shown by numbers.

At regular intervals, the condition of each wheelset is checked to see whether a defect is predicted to have occurred, or one of the wheel tread profile limits has been exceeded. If this is the case, that vehicle is 'sent to the lathe'. All wheelsets on the vehicle are then assessed using a set of rules for maintaining parity of wheel sizes between neighbouring axles and between neighbouring bogies, and re-profiled accordingly. The parity rules and the amount of material removed in restoring the profiles are controlled by discrete user inputs to the modelling process.

The model has to simulate the consumption of wheelsets on a single vehicle over the duration of two heavy maintenance (reprofiling) intervals. By running a single iteration for a single vehicle, the use can be represented with a predicted variation in wheel diameter and tread dimensions throughout an x-year period. By sampling over much iteration, the statistical behaviour of a whole fleet of vehicles may be built up, and overall performance measures may then be calculated. These performance measures include the overall costs of wheelset maintenance per vehicle per heavy maintenance, the statistical variation in new and used wheelset lives, and a probabilistic measure of the proximity to safety limits.

2.5.4.2 Maintenance strategies

The simulation has to be used to investigate the effect of a number of different aspects of wheelset maintenance strategy:

- Reprofiling policy;
- Parity rules;
- Planned turns.

These aspects have to be assessed in combination with each other to provide a matrix of different options for operating the wheel lathe. The options are ranked against each other in terms of cost, in order to indicate the optimum method of operation. Metrics describing the probability of developing a tall or thin flange are also calculated as a measure of the proximity of the whole fleet to the safety limits, to ensure that the most cost-effective strategies do not compromise safety.

A) Reprofiling policy

A1) Current railway practice

Current railway practice for wheel reprofiling is to recover the complete standard wheel profiles S1002 or P8 every time a wheel is sent to the lathe, as dictated by the specification. This should not be entirely necessary, as clearly the large extent of the material removal required to recover the full profile from a typical worn wheel can be illustrated by several examples. It is potentially more economical to remove only sufficient material to recover the running part of the tread, leaving a flange that is slightly worn but still well within specification. To explore this possibility, a different reprofiling strategy can be considered in the model: Minimum radius reduction. (This recovers the flange height but not necessarily the full flange thickness, however the resulting flange thickness will be within the safety limit).

A2) Application of „wear profile"

The observation of normal wear can lead to adopt a different profile than the profile NEW when reprofiling. This profile is then called "wear profile." The adoption of such a profile requires very specific studies and experimental validations that go beyond determining a strategy for reprofiling maintenance. On the other hand, the data recorded by the process of analysing developments of profiles for determining reprofiling cycles are a very useful source for determining a potential wear profile.

Definitions and Terminology

CDW: Criteria for Determinant Wear. This is the limit that is reached by the wheel profile during normal wear and triggers the reprofiling of the wheel.

WMP: Wear Margin of Profile (or margin recoverable of profile). This is the difference between the rate for a new profile and limit reshaping established for each reprofiling criterion.

SWS: Speed of wear in service. This is the speed at which one of the criteria for reprofiling is achieving reprofiling limit. SWS is expressed in mm/100'000 km.

RWS: Rate of wear in service. This is the rate already used of WMP.

SWR: Speed of wheel wear by reprofiling. That corresponds to the diameter difference in cumulative reprofiling divided by the mileage achieved at last reprofiling.

Methodological approach

Phase 1: Observation of normal wear (and excluding accidental cases)

The first phase of the process is to observe the wear in the operating system stabilized. During this phase, one should consider that the wheel reshaping subject of investigations (test) should intervene only when the safety limits of wear is reached. These limits are listed in Table 2.2.

Phase 2: Analysis of reductions in diameter by reprofiling

At each reprofiling, because of normal wear or accidental faults, the profile is restored turning away still available material in the worn profile. This leads to a reduction in the wheel diameter (D0).

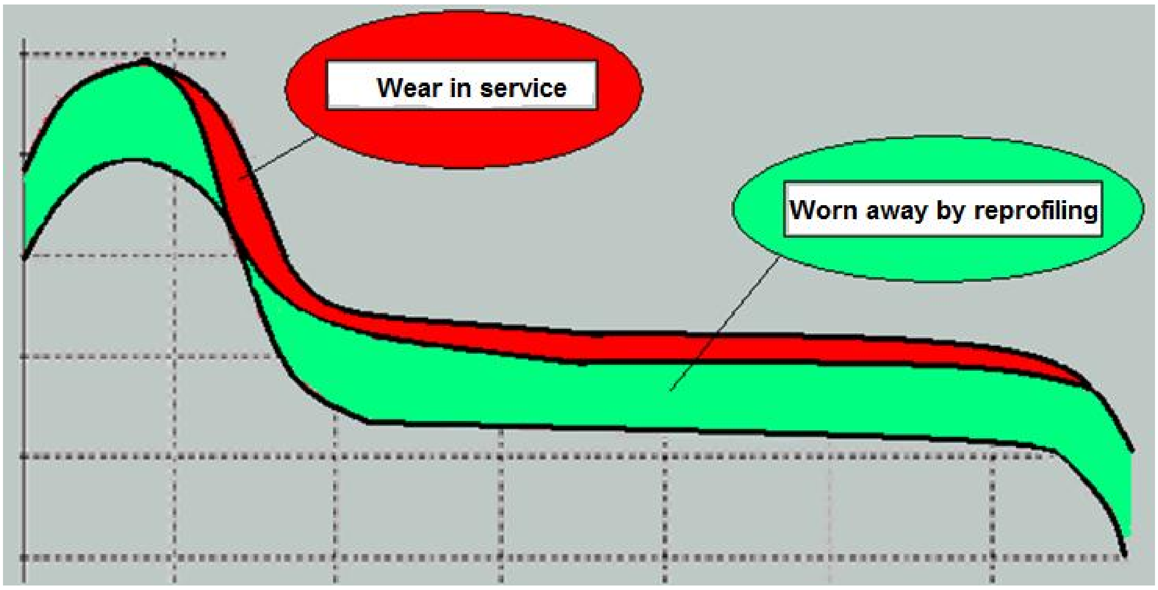


Figure 2.12: Definition of wear in service and wear produced by restoring the new profile

The service wear rate of the diameter at the reprofiling (SWR) is calculated as follows (the formula states the proportionality between diameter reduction and distance travelled):

$$SWR_{(n)} = 10^5 \times \left(D0_{(0)} - D0_{(n)}\right) / \, Kilometer \quad with$$

$D0_{(0)}$: The initial diameter D0 of the wheel

$D0_{(n)}$: Diameter D0 after the n^{th} reprofiling of the wheel

Kilometer: Is the distance travelled by the wheel since its circulation until the n^{th} reprofiling

SWR is expressed in mm/10^5 Kilometer. This parameter is used to calculate the potential of the wheels, especially the residual potential at a given time to schedule the exchange of wheels. This parameter must be calculated for all the wheels of the fleet. Thus, it takes into account not only the effects of normal wear, but also those of accidental wear. At best, this parameter can be validated by the end of the first reprofiling.

Because of the profile shape, the diameter reduction to grant to restore a profile strongly depends on the criterion for reshaping. Indeed, a correction for reshaping a light flat consumes less of the diameter than an insufficient thickness of the flange. It is therefore useful to correlate the reduction in diameter due to reshaping with the extent of Criteria for Determinant Wear (CDW) limits.

Phase 3: Determination of criteria for reprofiling

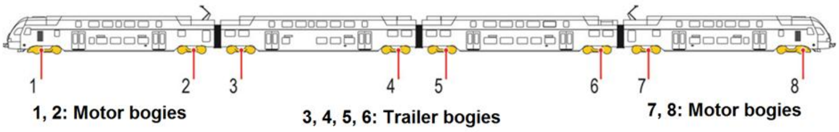
The criterion for determining wear, CDW, is established as the first parameter for which the statistical average RWS reached 90%. It is recommended to have a more nuanced view of the available samples. It is very rare indeed that a strategy of reshaping can be validated before completing two reprofilings for all tested wheels. In case of inconsistency between the results before the first reshaping and those in the second, the second has to be held.

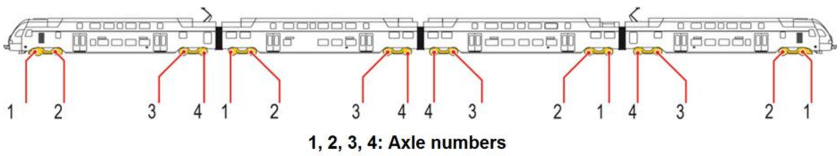
Once reprofiling made a significant part of the park costs, it is possible to determine the optimal limit at which reprofiling is afforded according to partial results validated in Phase 2.

B) Parity rules

The vehicle maintenance instruction defines parity limits that specify the permissible deviation of a wheel diameter from its neighbour on the same bogie, and also from the two wheelsets on the other bogie on the same vehicle.

Figures 2.13 and 2.14 demonstrate examples for maximal admitted diameter differences for a double deck train and for a cargo locomotive. If the diameter differences may move only within narrow limits, this must be taken into account when reprofiling. Depending on the operating experience, the diameters at the reprofiling are reduced of the same diameter (parity) or to similar dimensions (for example half-parity).





Vehicle	Driven Wheelsets		Trailer Wheelsets	
	Maximal admitted diameter difference			
	Between the two driven wheelsets of a bogie [mm]	Between the two driven bogies [mm]	Between the two trailer wheelsets of a bogie [mm]	Between the tow trailer bogies [mm]
Limit value at maintenance	8	Not required	8	Not required
Limit value in service	10	Not required	10	Not required

Figure 2.13: Maximal admitted diameter differences for a double deck train

Vehicle	Driven Wheelsets	
	Maximal admitted diameter difference	
	Between the two driven wheelsets of a bogie [mm]	Between the two driven bogies [mm]
Limit value at maintenance	4	38
Limit value in service	6	40

Figure 2.14: Maximal admitted diameter differences for a Cargo Locomotive

Also some diesel multiple unit (DMU) powered bogies with mechanically linked driven wheelsets across a bogie require a minimal diameter difference between the wheelsets to prevent damage to the drive train.

Turning all wheels on a minimum material removal basis would cause a parity infringement to be more likely to develop in service, and there is therefore the potential that it is more cost-effective overall to consider one of the following alternative strategies:

- Always turn the wheels back to parity limits;
- Turn the wheels back to half the parity limits;
- Turn all wheels to the same diameter.

C) Planned turns

C1) Common feature of wheel maintenance

Planned turns are a common feature of wheel maintenance regimes, where the wheels are reprofiled once, twice or more during the R1 maintenance interval (R1 is the interval for overhaul of the bogie and normally for driven wheels of their replacement), regardless of tread condition. Clearly planned turns have the potential to have a significant impact on the cost of wheel maintenance. Three different interesting planned turning strategies can for example be considered in the model, as follows:

- No planned turns;
- Turn halfway through the R1 interval;
- Turn twice during the R1 at equal intervals;
- other strategies.

A typical diagram for lifetime at this example for a vehicle containing four wheelsets is shown in Figure 2.15. The diagram shows wheel wear due to the contact wheel/rail on one side, wear due to reprofiling on the other side. To understand the magnitude for diameter reduction at reprofiling this diagram has to be accompanied with diagrams containing the associated increases in flange height and decreases in flange thickness. Based on this information the predicted whole fleet flange height and thickness statistics for an individual maintenance strategy comprising a reprofiling policy, set of parity rules and planned turn can be established. If the Criteria for Determinant Wear (CDW) are flange height and thickness (excluded systematic failures due to RCF) the reprofiling limits can be established. These limits may differ from the service limits according to the regulation rules.

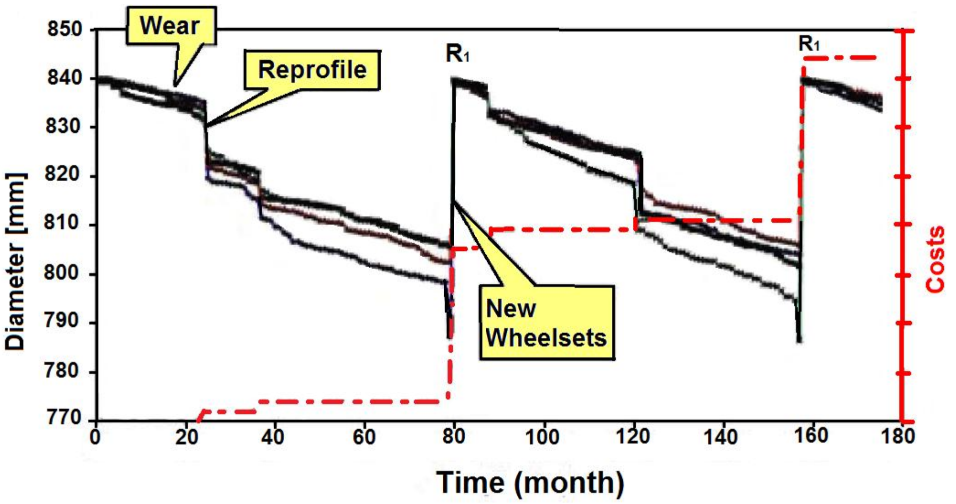


Figure 2.15: Lifetime of four wheelsets showing wheel wear and cost

C2) Reprofiling strategy due to RCF

According to [19] since the 1990's the fleet of the Dutch Railways showed a dramatic decrease in wheel tyre life. This lifetime reduction led to an unacceptable increase in life cycle costs. On some types of intercity rolling stock, cracks have been found left and right of the wheel running surface. These cracks are caused by rolling contact fatigue (RCF) and are strongly related to head checks (gauge corner cracking) found in curves in the track. On wheels these cracks are a reason for reprofiling the wheel tread. Because the cracks sometimes occur as soon as the first short term maintenance interval, this significantly influences the wheel tyre life. To increase wheel tyre life Lloyd's Register Rail has developed a new wheel profile to best match the track conditions.

Therefore Lloyd's Register Rail has proposed to NedTrain to investigate the possibilities of improving the wheel tyre life. The life of wheel tyres is influenced by a large number of parameters, but most parameters cannot be altered by the maintainer. The following three important parameters, which can be influenced by the maintainer, were selected by Lloyd's Register Rail:

1. Wheel profile
2. Wheel tyre material (currently B5T is used for most tyres)
3. Maintenance strategy

Three improvements were determined as most promising and relatively easy to achieve:

- profile optimisation for RCF reduction,
- selection of improved wheel tyre materials,
- optimisation of the maintenance strategy.

An alternative, preventive maintenance regime has been developed. With this scraping regime, during short term maintenance every wheel is turned. Higher mileages are reached and savings on life cycle costs up to 50% and more have been achieved. Unplanned maintenance goes down with 30-60%.

The condition based maintenance at NedTrain was developed to maximise the reprofiling intervals. This does not necessarily lead to the maximum wheelset mileage and minimum life cycle costs because more material has to be removed during the reprofiling. Especially during the last part of the degradation accelerated wheel tread degradation was normally observed. During condition based maintenance, the average cutting depth was 6 to 7 mm. With the Gotcha system [20] the wheel quality of the trains is measured at least once per day during normal operation. If the wheel quality gets below a certain level, wheelset maintenance will be planned. Within a predefined time the train will be sent to the wheel lathe.

The scraping principle belongs to the preventive maintenance category. At every short term maintenance all wheels are turned, with a cutting depth of around 1 mm. The result is that wheels remain round and consequently the dynamic load during their life cycle is lower. Defect initiations like small cracks and pitting are removed in an early stage. Relative large cutting depths due to damage accumulation are prevented. Using a small cutting depth, the work hardened layer is not removed and this results in a slower development of out of roundness. The scraping principle is shown in Figure 2.16.

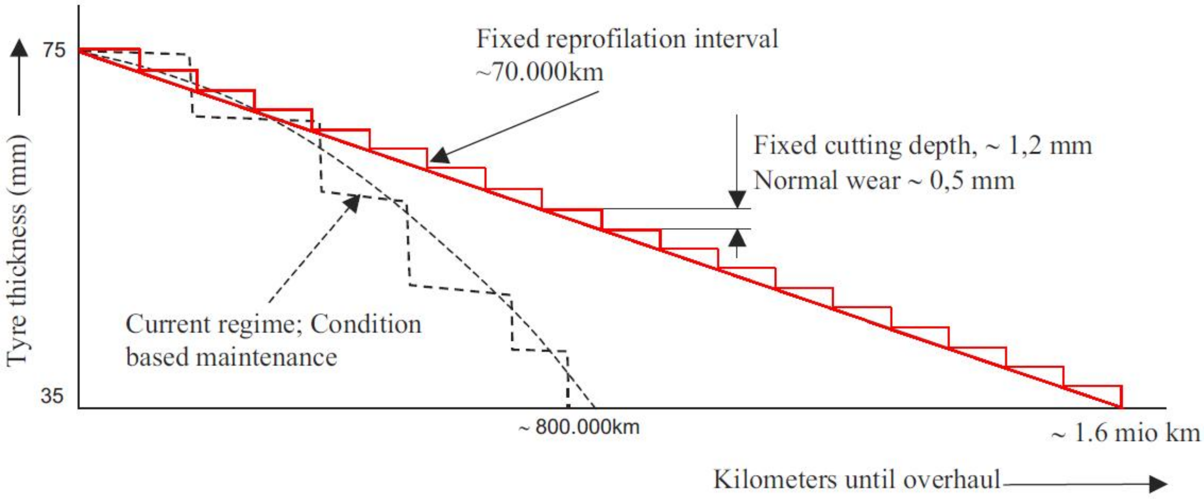


Figure 2.16: Scraping principle (red line) according to [18]

2.5.5 Costs

The model incorporates the following costs, which capture the major financial incentives for the train operating company:

- Cost of replacing wheelsets within a R1 (in R1 among other works the wheelsets are replaced);
- Cost of non-availability during a lathe visit and R1;
- Cost for inspection of wheels and wheelsets.

The operational costs of running the lathe are considered here to be a fixed overhead, although this would not be the case for all train operators.

2.6 CONCLUSION

The EN 15313 applies as a maintenance base for secure interoperability of the wheelsets. That standard is primarily concerned with the organizational aspects and the management of the wheelset maintenance, contains the geometrical limits for safe interaction of wheel / rail or wheelset / track, shows pictures of damage to wheels and axles, and contains mandatory requirements for wheel/wheelset geometry and wheel damages. Overall, the impression appears that the EN15313 is imprecise regarding the permissible errors at the wheel treads. Railway Group Standard GM/RT2466 specifies limits on wheel wear and general crack conditions that may be found on the tread of a wheel. By the application of GM/RT2466 it is common practice for train operators to turn the wheels at short enough intervals to avoid either crack length or cavity length limits being reached.

The detection of non-circular wheels cannot be viewed in isolation. In practice, various different methods are used, which are partially embedded in broader maintenance procedures. For example, a non-circular wheel or tread damage certainly can be detected by visual inspection at the scheduled maintenance or by other traditional inspection techniques used in the railway industry, such as drive-by inspections where all of the wheels on the train are glanced at while an inspection vehicle drives by. By using wheel impact detectors structural health monitoring trends can be observed based on the wheel impact data which indicate the actual condition of the wheels. Those trends can indicate the critical wheels that actually need to be removed, while at the same time allowing wheels that aren’t critical to remain in service. Today there are many commercial products for condition monitoring of railway vehicles. Most of the condition monitoring systems for railway vehicles are focused on the wheels and bogies since these are the parts that have the largest impact on the performance and are also the mayor cost drivers in maintenance. Many of the products for condition monitoring of railway vehicles are wayside monitoring systems and not directly mounted on the vehicles. It is important to share data from measuring devices directly with the rolling stock owner. The direct data transfer allows the vehicle owner to take immediate remedial actions. On the other side, if different alarming-levels are implemented in such devices, it allows the vehicle owner to pass from corrective maintenance to conditional maintenance.

There are track based detection systems and workshop based detection systems. The difference is that track based detection systems are installed in lines and are working without speed restriction. Workshop based detection systems allow the detection of different wheel/wheelset data (cracks, wheel profiles, out-of-roundness, wheel diameter, wheel tread defects) but they are situated in the vicinity of a workshop. The monitoring requires reduced train speed or stand still. Track based detection systems in long-time commercial use are for example DafuR in Germany and GOTCHA in Netherlands. A sophisticated workshop based monitoring system is for example ARGUS.

In practice, wheelsets require regular attention on a wheel lathe to remove tread defects and to restore excessive deviation of the tread profile from the nominal standard profile due to wear. Research showed that OOR of up to 2.5 mm are removed by the wheel ground lathes.

A methodology for establishing reprofiling strategies uses a two-stage process. The first step involves tread defect frequencies and wear rate statistics from the raw data gathered as part of normal wheelset maintenance activities. The tread defect and wear data are then used as the input to a probabilistic computer simulation specifically designed to explore the impact of different wheel lathe operating strategies on wheelset maintenance costs. This simulation has to investigate the effect of a number of different aspects of a wheelset maintenance strategy (Re-profiling policy, Parity rules, Planned turns). Another approach is based on systematic preventive maintenance. Instead of applying condition based maintenance with the scope to maximise the reprofiling intervals with the consequence of cutting depth of 6 to 7 mm the wheels are turned in short terms (e.g. about all 70’000km) with a cutting depth of around 1 mm. As a consequence wheelset overhaul (lifetime) can be extended significantly.

3. REVIEW OF EUROPEAN RAILWAYS

3.1 DB

Generally trains in Germany will be inspected nearly daily to weekly visually by a technician expert checking bogies and wheels with regard to observable abnormalities which would lead to an immediate inspection.

If trains (short distance, long distance, freight, locomotives) are not conspicuous with respect to out-of-roundness-behaviour during the daily operation, usually out-of-roundness-effects will occur after a service performance of much more than 30.000 km. In fact there are explicit values for service performance in km for particular train types when wheels must been inspected concerning out-of-roundness (30.000 km to 100.000 km by motor train sets, 200.000 km to 400.000 km by railway passenger cars, partly more than 400.000 km by freight wagons), but there are furthermore other more frequent inspections concerning the brakes and the bogies where there is a special look to the wheels, too. Thereby wheels will be checked whether there are flat spots with a critical deepness and/or length. So the values stated above after which service performance a special check of out-of-roundness-effects is required are rather theoretical values in the real railway operation.

If out-of-roundness-effects will be noticed in motor train sets or railway passenger cars by train conductors or passengers reporting such “felt abnormalities” to the conductor, there will be an entry in the logbook of the train (of course only if it is a minor OOR-effect. Otherwise an immediate inspection will be arranged). The bordbook of a train will be checked by special technicians in frequent intervals depending on the train type (partly at least after a service performance of 10.000 km or even earlier if there are special notes) so that OOR-effects can by refinished and cured shortly.

In the route network of Deutsche Bahn in Germany there are installed specific arrangements/facilities to measure dedicated parameters like dynamic load factored of trains by pass-bys (so called “DafuR”). When certain critical values are detected, the train (or wagon) will be taken out and conducted to the necessary inspection.

ICE-trains will be inspected by the DafuR-arrangements all-over Germany so that an OOR-occurrence will be detected daily and the ICE-train will be conducted immediately to inspection if necessary.

Depending on separate regional aspects there are other trains under control with the DafuR-arrangements. So for example the double decker coaches in the region of Aachen are nearly daily controlled by DafuR-arrangements during rail operation so that OOR-effects can be detected daily and can be conducted immediately to inspection if necessary.

If double decker coaches are not conspicuous by critical values obtained with DafuR-arrangements or notes of passengers and train conductors, there are regular inspections of the wheels concerning OOR at least every six months.

For freight wagons there are also special inspection intervals to check the wheels with respect to OOR at least every six years. But as mentioned above the existence of significant OOR will be noticed much earlier by visual inspection of the technician staff or by routine inspections of bogies and brake systems. The situation of freight-locomotives is similar to freight wagons. Significant OOR will be recognized and reported by the locomotive driver shortly so that the “official inspection intervals” have a theoretical character similar to freight wagons.

3.2 SBB

SBB has started a strategic approach towards a preventive maintenance by using wheel load checkpoint (WLC) data.

Out-of-roundness wheels generate higher Q-forces while rolling. Nowadays Q-forces are already being monitored by about 20 wheel load checkpoints all over the Swiss railway network. But there is no systematic correlation done between measured data and actual maintenance data.

Especially the SBB Re 420 is subject to wheel faults respectively flats and cavities. In addition to that, there is a restricted capacity in maintenance, therefore capacity allocation should be optimized. There is an approach to set up a systematic correlation between the maintenance data sets and the WLC-data to distinguish an ideal warning limit with the goal to avoid the parking of railway vehicles by using the SBB Re420 as an example.

The used data-sources are explained within the following pages. Figure 3.1 gives measurement results of some axles of a train, that has been measured by a wheel load checkpoint. The grey boxes display the nominal value of the wheel load, the red boxes display the maximum wheel load of all sensors. The wheel set of axle 59 is subject to an error as this axle shows much higher wheel load than the adjacent axles. Figure 3.2 shows the gradients of the wheel load checkpoints. Figure 3.3 focuses on gradient Nr. 4 which displays the abnormality. The measured force is the sum of the static and dynamic Q-force. The given sketch on the right in Figure 3.3 shows that there is a connection between the out-of-roundness form and the wheel load level.

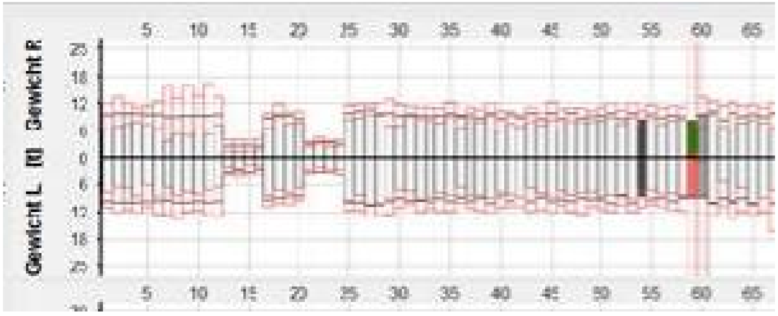


Figure 3.1: WLC-Output: Wheel load of every axle (L: Left, R: Right, max values in read)

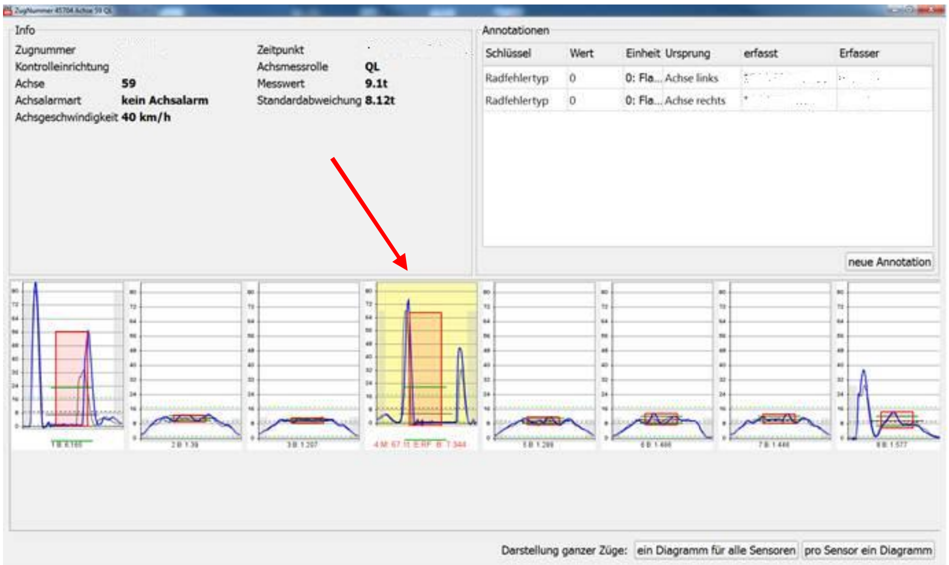


Figure 3.2: Wheel load curve of one axle (left wheel) at different measurement points.

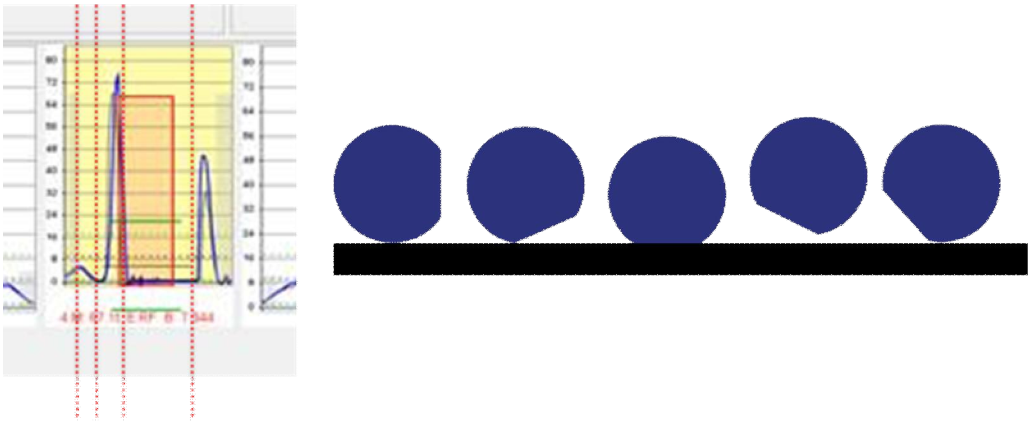


Figure 3.3: WLC-Output: Detail of wheel load, wheel flat brings wheel to fly (wheel load measured for a certain time = 0 t).

Maintenance using ground wheel lathe

SBB has two ground wheel lathe (Zurich & Geneva). In Figure 3.4 the measurement principle of OOR can be seen. The vehicle is lifted and the tread datum is measured before the relevant part is turned away. A higher reading occurs in the case of a material loss, a lower reading occurs in the case of a metal build up.

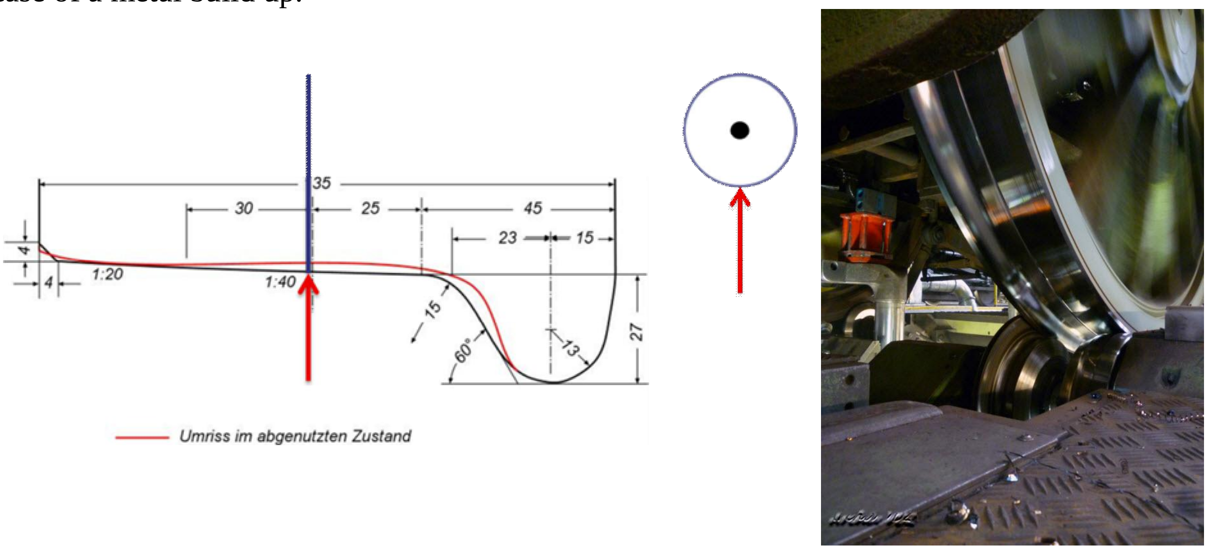


Figure 3.4: Schema of ground wheel lathe OOR measurement and picture of ground wheel lathe.

Wear-monitoring using ARGUS (Geneva)

The vehicle passes ARGUS at 10 km/h. During that pass-by the difference between the flange tip and the tread datum is measured.

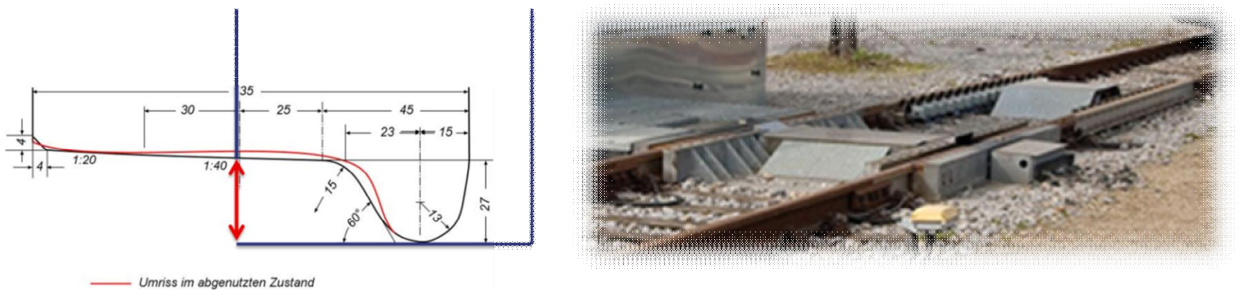


Figure 3.5: Schema of ARGUS OOR measurement and picture of ARGUS measurement system

Centralized Wheelset-Database

The gained data is transferred to a centralized database (see Figure 3.6).

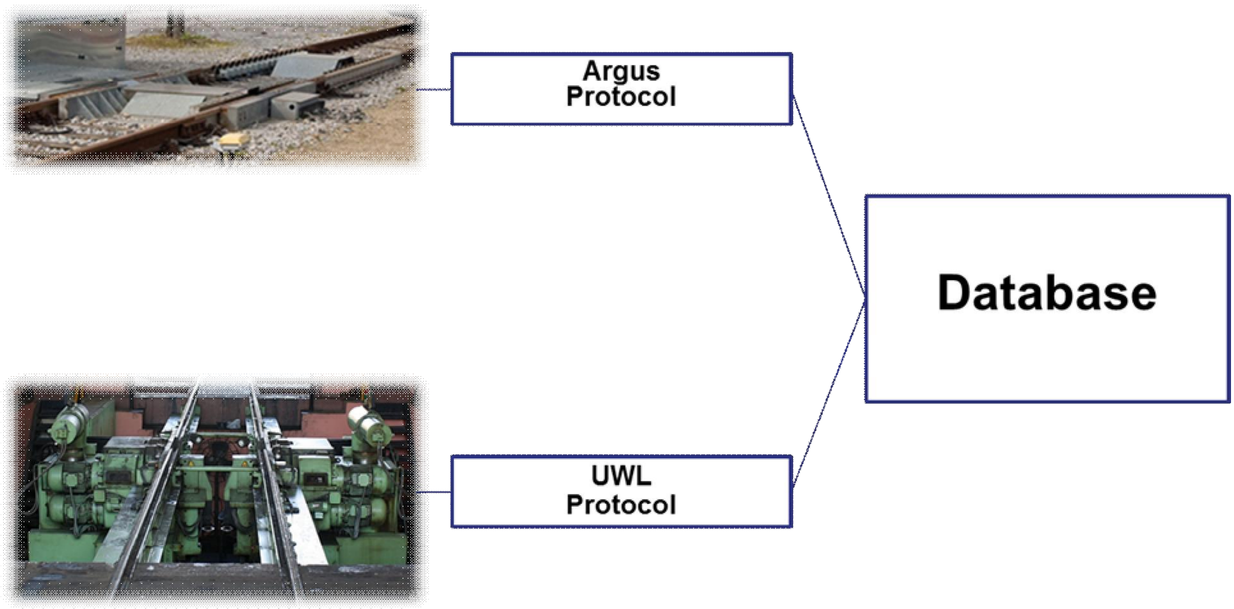


Figure 3.6: Schema of centralized database

3.3 ALSTOM

Measurements will be done, as much as possible, at quasi fixed amount of km of service. The amount of km of vehicle service between two measurements depends on:

- type of train/tram (maximum speed, axle weight,…)
- type of service (passenger, freight,…)
- type of wear problem previously observed.

A general rule could be to make the first flange measurement at ‘point zero’ (all the wheels turned at the same moment) and then after all turning actions.

In the following tables 3.1 and 3.2 it has been summarized for the different types of trains and services, the main reprofiling equipment and periodicity:

	HST			REGIONAL				LOCOMOTIVES	
	AVE	ALARIS	KTX	ITALY	WCML	CHESTER	UT-447/UT-450	BNSF	MEXICO
Wheel lathe	Hengelsheidt	TALGO			Wheel lathe			Wheel lathe	
Main reprofiling trigger	km	km			Distance covered			Parameter measure-ments	
Reprofiling periodicity	115.000 km	150.000 km			312.800 km			77.500 km	
Profile measuring tool	Miniprof	EVA system	Qr meter	Multi-function tool "Capecchi"	Miniprof and ViewSystem	BR gauges	RIFTEK	Manual gauges	Winchester gauges W601 &601A

Table 3.1: Main reprofiling equipment and periodicity for different train types

	METROS			CITADIS				
	METROREX	MERVAL	SANTIAGO L4	DUBLIN	STRASBOURG	BARCELONA	ORLEANS	VALENCIENNES
Wheel lathe						Sculford		
Main reprofiling trigger		qR		Sd		km	qR	qR/flats
Reprofilin g periodicity		Condition only (avoid qR = 6,5mm)		70k red line, 90k green line		20.000 km	20.000 km	20.000 km
Profile measuring tool	Manual gauges Miniprof	Miniprof	Miniprof	GO/No-GO gauges	Manual gauge	Miniprof	Automatique t/f	Qr meter

Table 3.2: Main reprofiling equipment and periodicity for different train types

In the Table 3.3 below, the main wheel reprofiling strategy parameters for a characteristic train of different kinds of services are presented:

	HST	**Regional**	**Locomotives**	**Metros**	**Citadis**
	AVE	UT-447 & UT-450/1	MEXICO	JUBILEE Line	DUBLIN 401
Wheels					
D	920/850 [mm]	890/820 (UT-447) & 1020/940 (UT-450/1 M) & 840/790 (UT-450/1 R) [mm]	new wheel: min 40" - max 40-35/64" worn wheel: 36"	770/710 (MB) & 770/690 (TB) [mm]	590/530 [mm]
L	135 ± 1 [mm]	135 ± 1 [mm]	5.5 ± 0.125"	125 ± 1 [mm]	110 [mm]
Ei	1.357 ≤ Ei ≤ 1.363 [mm]	1.594 -0 / +2 [mm]	min 53-3/16" - max 53-1/4"	1 359 ± 1 [mm] Not measured	1380 ± 1 (M1 & M2) & 1379 ± 1 (MIC & IC) [mm]
Ea	1.401 ≤ Ea ≤ 1.428 [mm]		Not measured	Not measured	
Sd	22 ≤ Sd ≤ 32,5 [mm]	25 ≤ Sd ≤ 32 [mm]	15/16" ≤ Sd ≤ 1-17/64"	Sd10 = 28 to 28,61 [mm]	22,2 [mm]
Sh	28 ≤ Sh ≤ 36 [mm]	28,25 ≤ Sh ≤ 36 [mm]	1" ≤ Sh ≤ 1-3/8"	28,7 [mm]	25,5 [mm]
Qr	6,5 ≤ Q_r [mm]	6,5 ≤ Q_r ≤ 11,06 [mm]	Not measured	Qr10 = 8,38 to 8,60 [mm]	

lubrication	Yes oil on the 4 wheels of the end TB of the end trailer vehicles	Yes	No lubrication	Stick Lube	Outside & inside wheel flange lubrication by oil on 1 axle of NP trailer bogie
sanding	Yes sand in the 4 wheels of the 4 MB	Yes	Automatic sanding when a wheel slip is detected by the speed sensors, the locomotives have 8 sanding devices	No	Sanding on each axle of motor bogies (2 LHB MB & 1 Arpège MB)
Reprofiling					
criteria for reprofiling	At every reprofiling activity, as less material as possible is machined to be taken away to restore the flange thickness, with the flange high ("Sh") to be = 32,5 mm (at the first reprofiling time), ≥ 30,5 (at the second reprofiling time) and ≥ 28,5 (at the third reprofiling time)		Measure every 92 days The criteria for reprofiling are the Sd = 1-7/64", Sh = 1-5/6", vertical flange and any others defects on the wheel tread (flat wheel, peel off, etc...) Change wheel when ring thickness = 1-1/8" or 1-1/16"	2+ years or fails gauge	Distance
profile measurement tool	"Miniprof" tool (measuring and checking as "1" and also, in particular, the wheel mean diameter, the wheel ovalisation, the "depression" of the wheel where there is the wheel-rail contact and the conicity difference between the two wheels of the same wheelset)		Winchester gages W601 & W601A	New Gauge	Manual gauge
Wheel profile	Unifié SNCF NF F01-112	RENFE according to DT.14.T00.1017.00	Usually AAR-1B or Unipoint	Wheel proofile LT5 according the drawing 92667	Profile B06
Wheel material	R7 according UIC 812-3 standard	R7T according UIC 812-3 (UT450/1 M) & R7 according UIC 812-3 (UT450/1 R) R8 according UIC 812-3 (UT 447)		R9T	According to the technical specification of exploitation
average metal quantity removed	Average of 3 mm in diameter		3/16" to 4/16" on radius per reprofiling, from 4 to 5 times before wheel change out	4,4 mm per turn	Theoretical 4mm
maint plan reprofiling periodicity	Every 115.000 km	Every 200.000 km	Measure every 92 days Reprofiling every 80.000 km to 100.000 km	18 months	20.000 km adjusted by the Customer
preventive reprofiling	Yes, with this periodicity	Yes, with this periodicity		Yes	
economic reprofiling (partial reprofiling)	Yes, with this periodicity	Yes, with this periodicity & according to RENFE TR-45	No partial reprofiling	Yes	No
Constraints					
reprofiling in train / axle dismounted	Reprofiling in train	Reprofiling in train	Reprofiling in train	Underframe wheel lathe, reprofiling on train	Reprofiling in train
immobilisation time for reprofiling	1,25 hours per bogie (two wheelsets) using a tandem pit lathe	1 day (UT-447) & 2 days (UT-450/1)	From 2 to 3 hours per wheelset (locomotive BB or CC), we reprofile as requiered, both as an average we do the reprofile of 2 sets into a 6 axles locomotive).	1 week	16 hours per trainset
average cost of reprofiling	1,25 hours per bogie (13 bogies)	250 € / axle (UT-447) & reprofiling is done for RENFE (UT-450/1)	Labour ≈ 80 US$ + 20 US$ consumbles + 15 US$ machine depreciation = 115 US$ per wheelset		

Annual mileage	370.000 km	135.000 km (UT-447) & 130.000 km (UT-450) & 200.000 km (UT-451)	36.000 km (Switchers) 65.000 km (Short lines locos) 97.000 km (Road locomotives DC fleet) 126.000 km (Road locomotives AC fleet)	8.300.000 km (fleet mileage for 63 trains) ≈ 131.500 km per train	
Wheel life	1.600.000 km (MB wheel) & 2.000.000 km (TB wheel)	1.200.000 – 1.300.000 km (UT-447) & 1.100,000 – 1.200.000 km (UT-450/1)	400.000 – 500.000 km depending on the track condition and work designation of the locomotive	13,5 years ≈ 1.775.000 km	

Table 3.3: The main wheel reprofiling parameters for different trains

3.4 Lucchini

Instead of more maintenance an optimized wheel material can be a solution, see Lucchini innovations and tests in annex A.4.

3.5 Other Railways

3.5.1 SNCF [21]

With the aim of improving the effectiveness of maintenance and the quality of service to its customers, SNCF developed a system of detection of wheel defects. This monitoring system made of accelerometer sensors is mainly installed on the high speed lines. It is possible to measure with the passage of each train the vibration of the rail generated by the contact of the wheels on the rail. The wheels whose vibrations on the rail are abnormal are identified. This monitoring system allows to follow each wheel and to remove failing wheels before affecting rails. SNCF set up a plan of conditional maintenance based on measures provided by the system.

When trains passing, measurements of accelerometers corresponding to the response of the rail to wheel contact are recorded and processed by a computer located at the edge of the track. Processed measurements are sent to a supervision centre where they are analysed. The following Figure 3.7 presents the system of measurement:

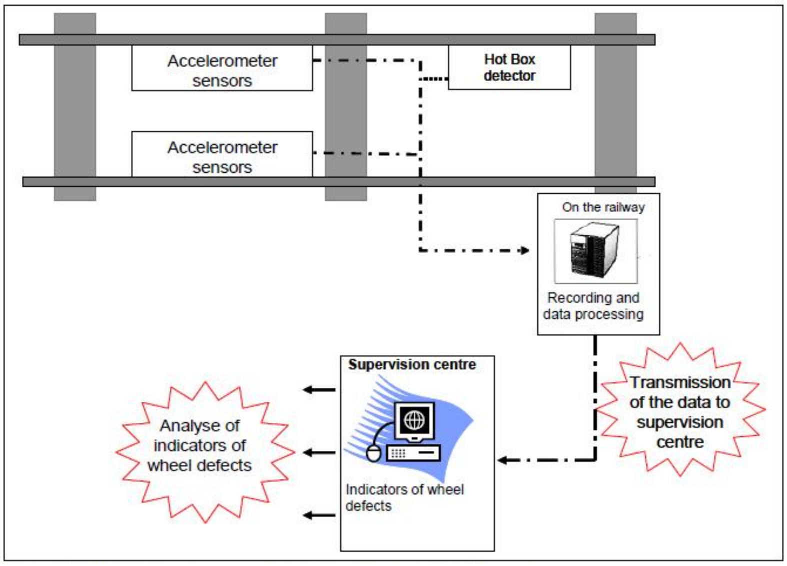


Figure 3.7: Illustration of the SNCF measurement system of wheel defects

3.5.2 Travikverket

Travikverket has wheel-flat detectors. For Travikverket limits are according to wheel-rail force. Infrastructure Manager do not do a classification. The database is available for operators.

3.5.3 ADIF

Also ADIF measures impact loads, out-of-roundness and flats.

3.5.4 Sihltalbahn (SZU)

SZU is a railway company situated in Zürich and is carrying out passenger service on two lines. The curve distribution and the trains used on these two lines can be seen in Figure 3.8.

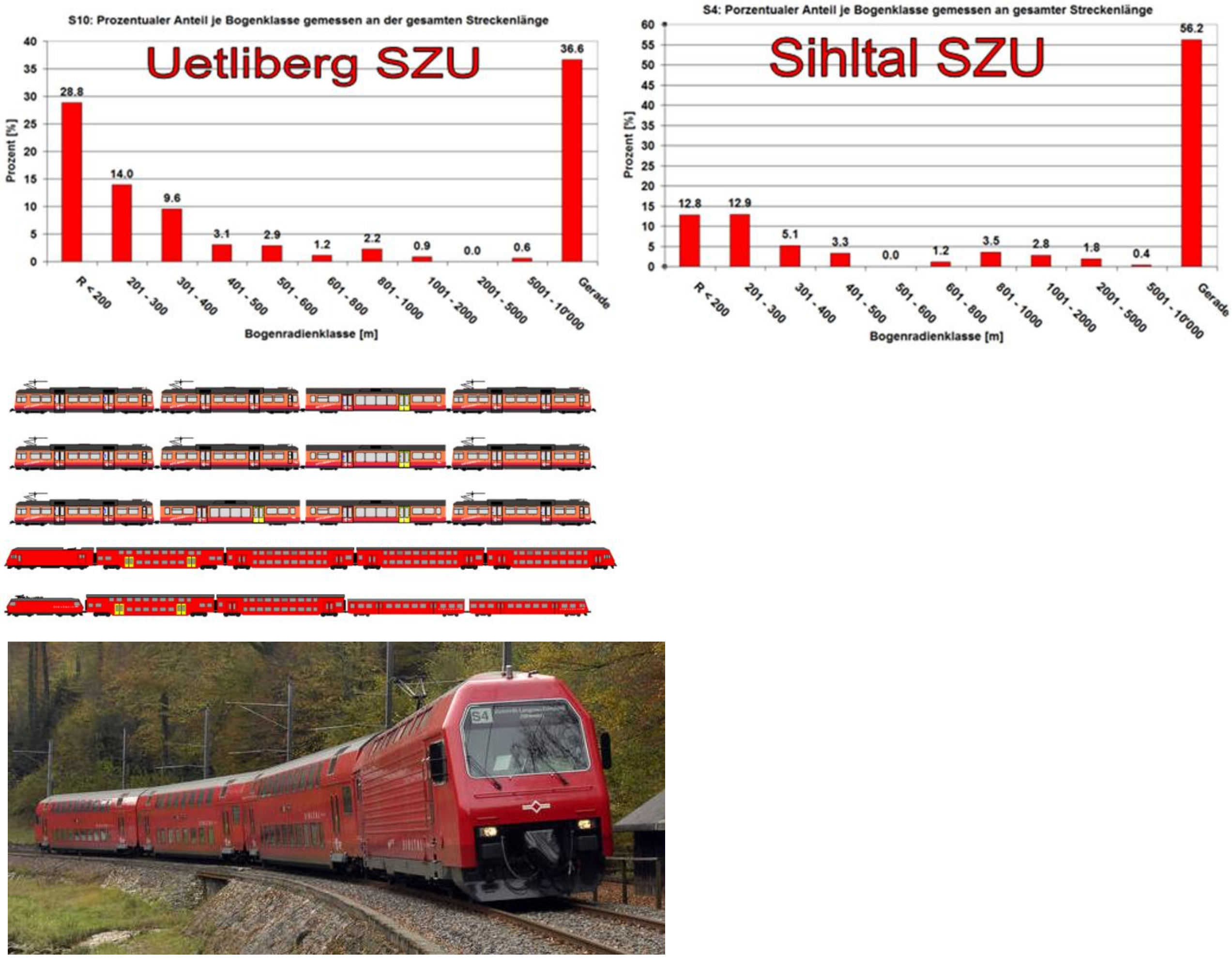


Figure 3.8: Curve distributions and train characteristics of the two railway lines of SZU

The principle difference of the trains in service on these two lines is

- axle load on Sihltal about 17t and on Uetliberg 12t
- axle spacing on Sihltal at coaches 2.5m and at locomotives 2.9m
- axle spacing at Uetliberg around 2m

- wheel materials similar on both lines, different wheel material tests on locomotives of Sihltal

Interesting are the facts that

- on Sihltal there is heavy corrugation on rails in curves with very small radii however on the Uetliberg corrugation has not been observed (on both lines the same steel grade of rail is in use),
- on Sihltal heavy polygons appear at the locomotives and at double-deckers however on the Uetliberg polygons are very seldom observed even so there are more narrow curves.

This example shows that there is a correlation between axle load on the one side and corrugation respectively polygonalisation on the other side. The vehicle characteristics such as steering/primary suspension are similar.

Figure 3.9 shows the different steel grades in test on locomotives of Sihltalbahn. The steel grades are characterized by UTS (ultimate tensile stress) on the vertical axes and the hardness measured on the rims respectively on the tyres. It can be seen that the mechanical characteristics of the different steel grades are significantly different. The experience in service (see also Figure 3.10) is that the steel grades ER7 and S5 show heavy polygonalisation and that the steel grade B6Z shows a better behaviour especially in the first reprofiling interval. Unfortunately, the behaviour of B6Z after first reprofiling is worsened. This is probably due to the fact that RCF is not removed completely on the turning machine. Figure 3.10 shows the durability diagram of the three different steel grades. Further test with modified steel qualities are planned at SZU. The scope of these tests is to

- reduce tendency of polygonalisation and RCF by utilising steel with higher hardness,
- reduce ground vibrations due to wheel tread defects by the application of better steel qualities and optimisation of in line installed detection devices for OOR,
- modificate the reprofiling philosophy to get longer lifetime of the wheels.

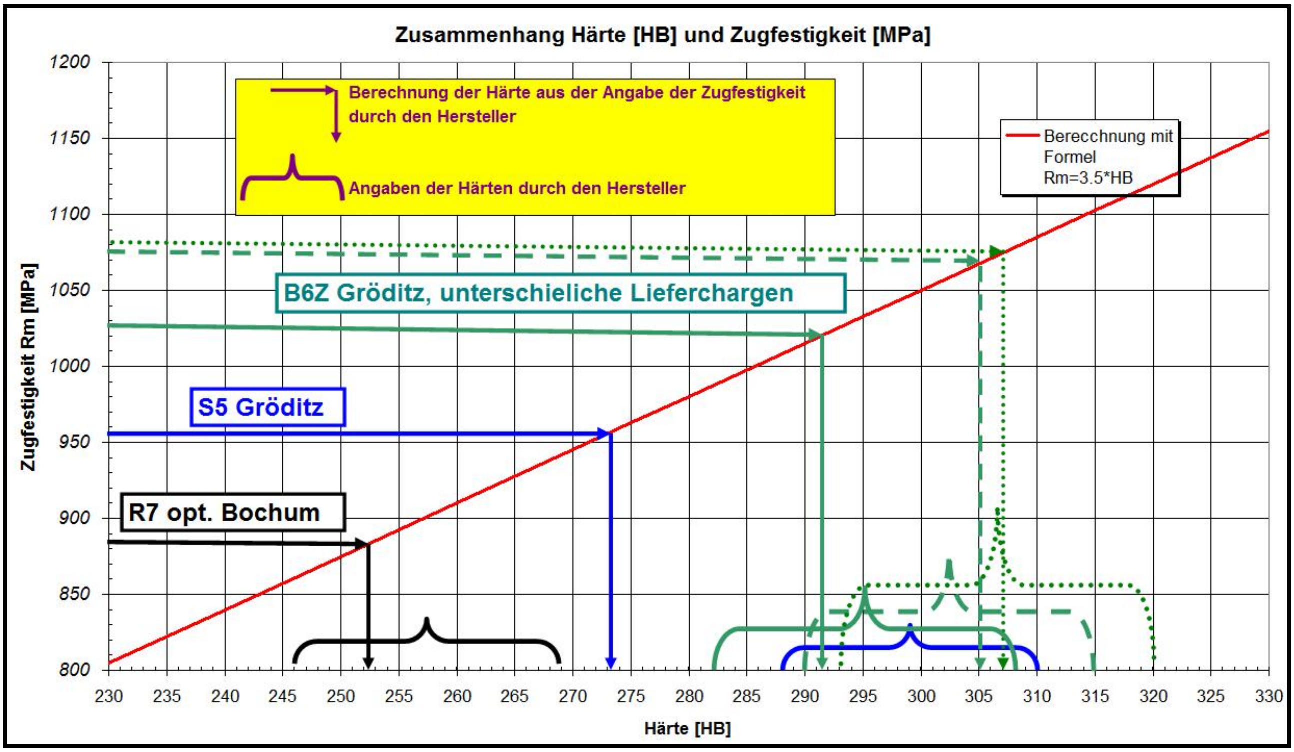
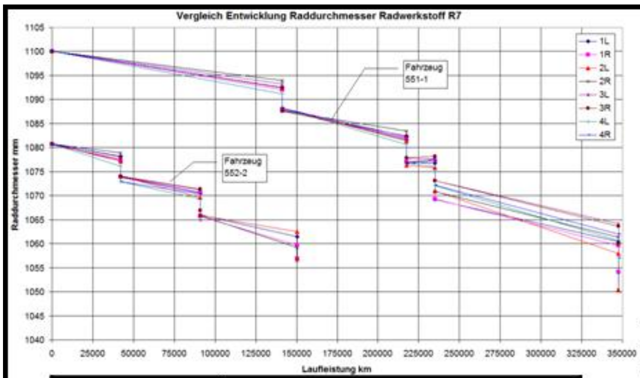
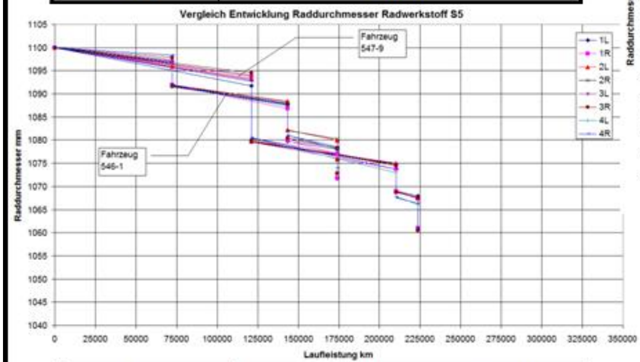


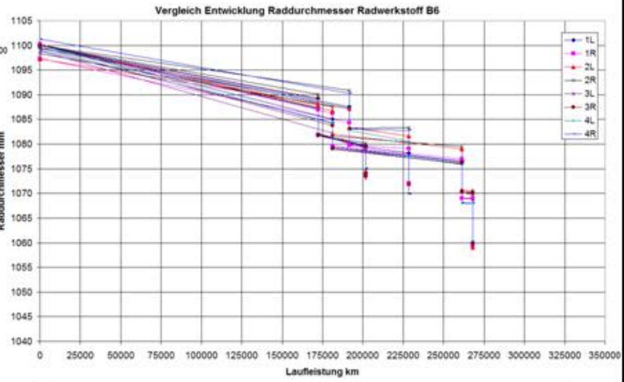
Figure 3.9: Steel grades in test on locomotives of Sihltalbahn



Fahrzeugnummer	Durchmesserreduktion in mm je 100'00 km
551-1	13.2 mm
552-2	14.6 mm



Fahrzeugnummer	Durchmesserreduktion in mm je 100'00 km
547-9	15.45 mm
546-1	14.8 mm



Fahrzeugnummer	Durchmesserreduktion in mm je 100'00 km
545-3	7.1 mm[1)]
544-6	12.27 mm
543-8	10.86 mm
542-0	10.1 mm

[1)] Ohne Reprofilierung

Figure 3.10: Durability diagrams for locomotives of Sihltalbahn

3.6 Conclusion

The wheels of most vehicles in the European railways are still monitored by simple measuring equipment and visual inspection. Reporting is in use for locomotives by drivers and for passenger cars by conductors or by passengers. Especially for high speed applications (France, Germany, Spain, Switzerland, etc.) monitoring systems are applied. For the detection of OOR track based monitoring systems are applied (DafuR in Germany, GOTCHA in Netherlands, accelerometer sensors on high speed lines in France, wheel flat detectors at Trafikverket, WLC at SBB). Workshop based monitoring systems (ARGUS) are for example installed for ICE in Germany and for high speed passenger trains in Switzerland.

4. MITIGATION OPTIONS

The primary mitigation option for out of round wheels within maintenance is an optimized maintenance plan including optimised reprofiling but also the analysis of causes and effects in Annex C should be consulted.

4.1 Optimised reprofiling

Description of optimised reprofiling:

An important factor for wheel life is due to the controlling of wheel machining cycles within the current limits and the amount of metal that is removed during each cycle, which represents the "reprofiling philosophy". For example, if the reprofiling interval is increased, more material has to be removed by turning, due to sub-surface propagation of tread damage related to longer period. When optimising wheel life it is important to work on ways to reduce RCF damage in a continuous improvement process. The in service feedback results in diagrams of wheel diameter reduction (amount of material removed by turning) by mileage covered. This very important tool, which aids the collection of feedback results and the validation of tests related to a long period, is called a wheel Durability Diagram (see Figure 4.1).

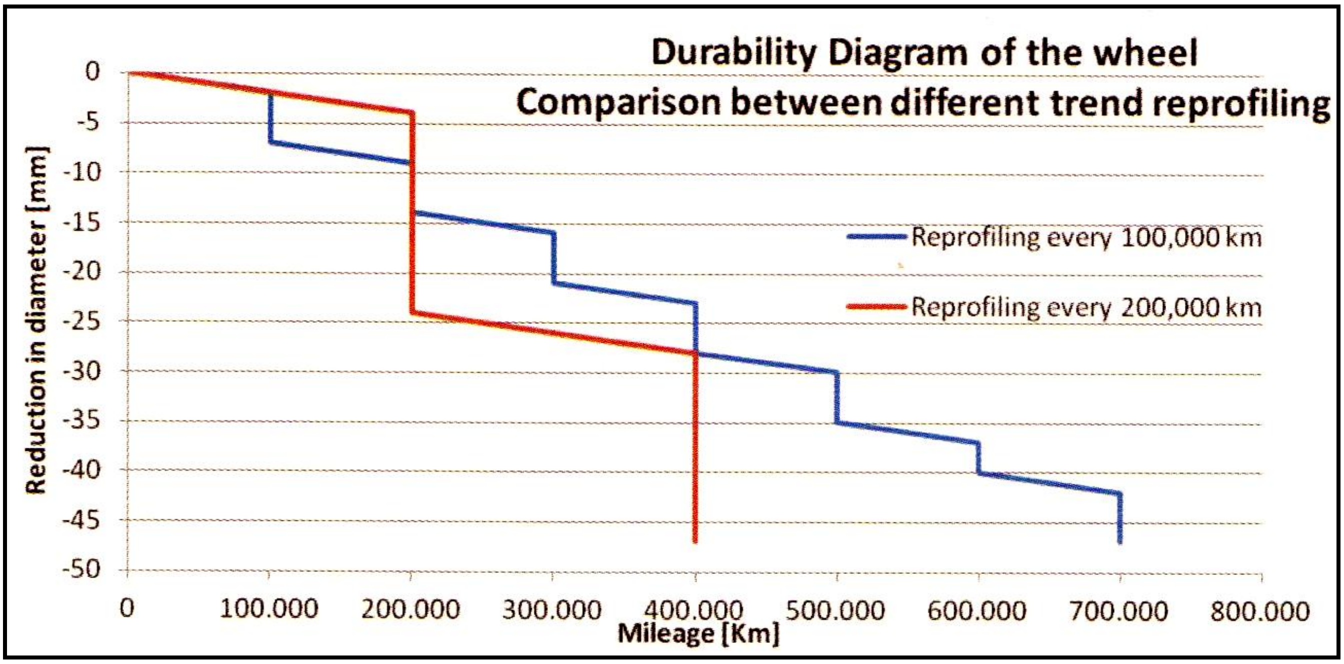


Figure 4.1: Typical diagram of reduction of thickness versus mileage

An analysis of the Durability Diagram shows that the performance of wheels is influenced mainly by the reprofiling philosophy and also by the few poorly performing wheels, due to strong machining clusters, wheel flats, OOR and so on. The overall system costs are preliminary influenced by

- the time of out of service of vehicles including logistical time
  - ➢ for wheel inspections (can be reduced by efficient automatically conditions monitoring,
  - ➢ for turning the wheels,

  - for replacement of wheels,
- the costs for turning the wheels (dependent from specification),
- the costs for replacement the wheels including the procurement price for new wheels.

4.2 TECHNOLOGY ASSESSMENT

4.2.1 Studies on the creation of a Technology Assessment

The Technology Assessment is based on a failure mode effect analysis (FMEA). Mitigation can be set only when the causes of errors and their effects are known. Effects of errors can be found in the following areas:

- Safety of the wheel (broken wheel, displacement of wheel on the axle, loss of track guidance relevant parts of the wheel as for example scattered wheels or vertical split);
- Safety of the track (rail brake, damage of switches and crossings, displacement of the track, etc.);
- Safety of the vehicle (derailment safety, stability, etc.);
- Ride comfort (noise immission and vibrations inside the vehicle);
- Environnemental impact (noise emission, ground vibration);
- Damage on vehicle components (axlebox, axle, etc.)
- Etc.

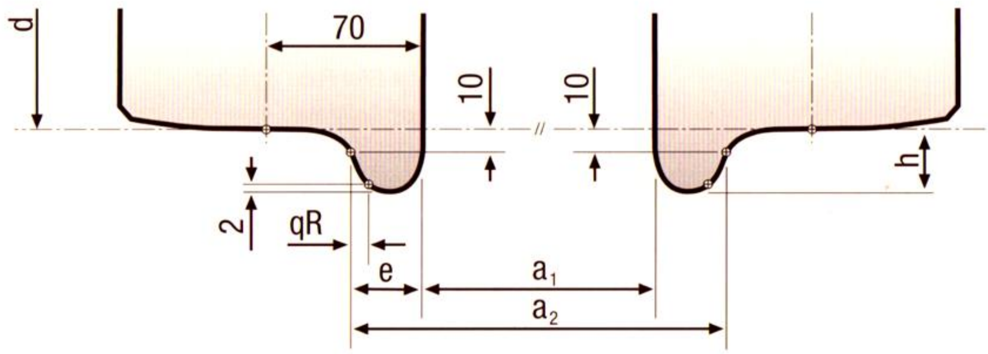
4.2.2 Failure modes

As a failure an error at the wheel or wheelset is considered which leads to an intervention by the maintenance. Failures are

- deviations from prescribed geometric limit dimensions of wheel or wheelset,
- inadmissible damages to the wheel tread.

Figure 4.2 shows the geometric wheel/wheelset parameters. In Table 4.1 the classic abbreviations are utilised. Table 4.1 lists the different failure types on wheels/wheelsets and on wheel treads which can cause a reprofiling procedure.

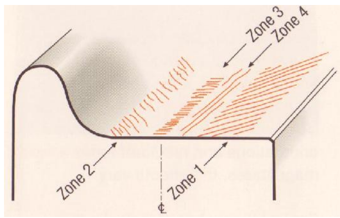
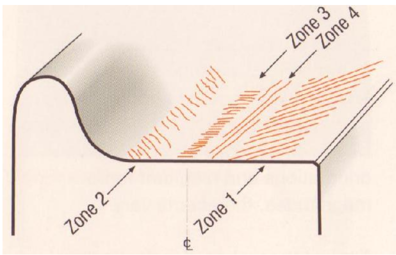
Geometric Wheelset Parameters

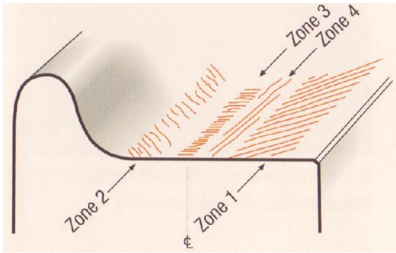


EuroNorm	Classic	Nomenclature
d	d	*Diameter*
a1	AR	*Back-to-back*
a2	SR	*Front-to-front*
e	S_d	*Flange thickness*
h	S_h	*Flange height*
qR	qR	*Flange angle dimension*

Figure 4.2: Geometric wheel/wheelset parameters

Abbreviation	Denomination	Description	Picture
AR	Back-to-back	Distance between the flange backs of the two wheels of the same wheelset	See Figure 4.2
SR	Front-to-front	Distance between the flange faces of the two wheels of the same wheelset	See Figure 4.2
S_d	Flange thickness	Normally due to wear the flange in service will be reduced. Due to unbalanced wear of flange and tread, the flange thickness in service can augment.	See Figure 4.2 The figure below shows reduction of flange thickness due to wear  Severe Flange Face Wear. A Toe Radius Build Up has also started to develop on this flange.
S_h	Flange height	Flange height is always augmented due to tread wear	See Figure 4.2 **Table 4.1 continued next page**

Abbreviation	Denomination	Description	Picture
qR	Flange angle dimension	Normally due to wear the flange angle in service will be reduced. Due to unbalanced wear of flange and tread, the flange angle in service can augment. It exists no limit value for minimum flange angle in service. Reduced flange angle can reduce the admitted derailment coefficient	See Figure 4.2 The figure below shows reduction of flange angle due to wear  Severe Flange Face Wear. A Toe Radius Build Up has also started to develop on this flange.
RCF1	Rolling Contact Fatigue in zone 1 of the tread	Cracks in the field side of the tread due to the contact of wheel on inner rails in curves. These cracks are due to high level of tangential creepage forces.	  Deeper shelling of RCF1 cracks.
RCF2	Rolling Contact Fatigue in zone 2 of the tread	Cracks on the flange side of the tread due to the contact of wheel on outer rail in curves. These cracks are due to high level of tangential creepage forces.	  Band of Zone 2 RCF cracks adjacent to the flange **Table 4.1 continued next page**

Abbreviation	Denomination	Description	Picture
RCF3	Rolling Contact fatigue in zone 3 of the tread	Crack between the flange side and the field side of the tread due to the contact of wheel/rail in straight lines or in curves with large curve radius. These cracks are due high levels of longitudinal creepage.	  Band of Zone 3 RCF cracks resulting from high levels of longitudinal creepage
RCF Clusters	Localised Rolling Contact Fatigue on the tread	RCF clusters are appearing in localised plastic deformations from locally increased lateral creep forces. They also appear when the amplitudes of polygons are elevated.	 An RCF Cluster with shelling  Cavity formed from a shelled RCF Cluster **Table 4.1 continued next page**

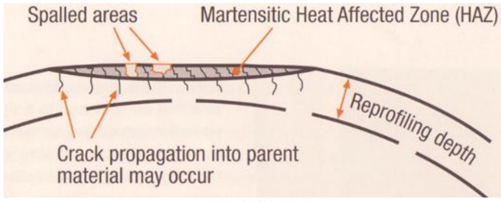
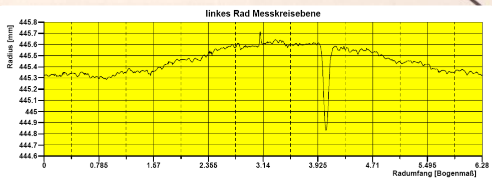
Abbreviation	Denomination	Description	Picture
Wheel flats	Singular out of roundness with lower amplitudes	Wheel flats are caused following the blockage or partial blocking of a wheelset whilst the vehicle is still travelling at speed. As the wheel slides along the rail, the resulting friction then heats the wheel contact patch locally.	  
Localised spreading	Singular out of roundness with higher amplitudes	Localised spreading is originated by not removed wheel flats or material hardness deviations along the circumference of the wheel tread.	 

Table 4.1 continued next page

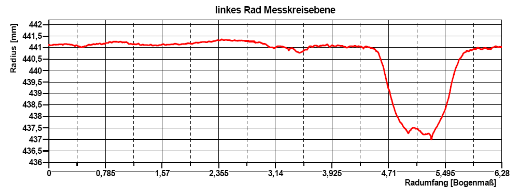
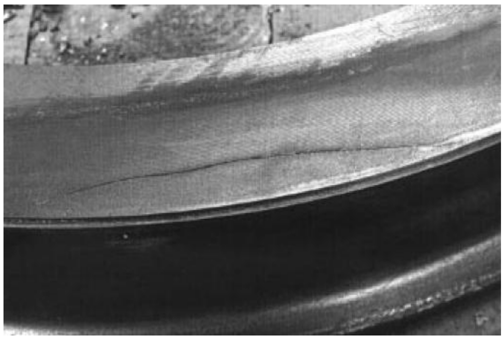
Abbreviation	Denomination	Description	Picture
			
Scattered wheel	Singular out of roundness due to subsurface RCF-damage	Subsurface fatigue cracks are usually, but not exclusively, initiated from the presence of a foreign body, slag or a metallurgical inhomogeneity within the wheel rim. Their amplitudes and extensions in the final stage (before collapsing) are comparable with those of localised spreading.	 
Periodic OOR	Poly-gonalisation	Pure periodic circularity defects with long wavelength (140mm to about 300 mm) and with high amplitudes (greater than 0.5 mm) are predominantly due to tangential creepage forces wheel/ rail in very small curves. However, they also have been observed at wheelsets with significant wheel diameter differences on the two wheels of the same wheelset. Periodic out of roundness with such characteristics are called polygons.	 

Table 4.1: Different failure types on wheels/wheelsets and on wheel treads

4.2.3 Failure mode effect analysis

The failure analysis and the methods of reliability analysis are using two different approaches (see Figure 4.3). The first follows the path of the cause to the effect. This procedure is known in the jargon as an inductive method. A second is based on the impact and search for the related causes. This is called the deductive method. If the causes are known, we will proceed to the inductive method. If the effects are known, we will apply the deductive method. It can be seen that depending on the knowledge of the cause or the effect, one or the other method is employed.

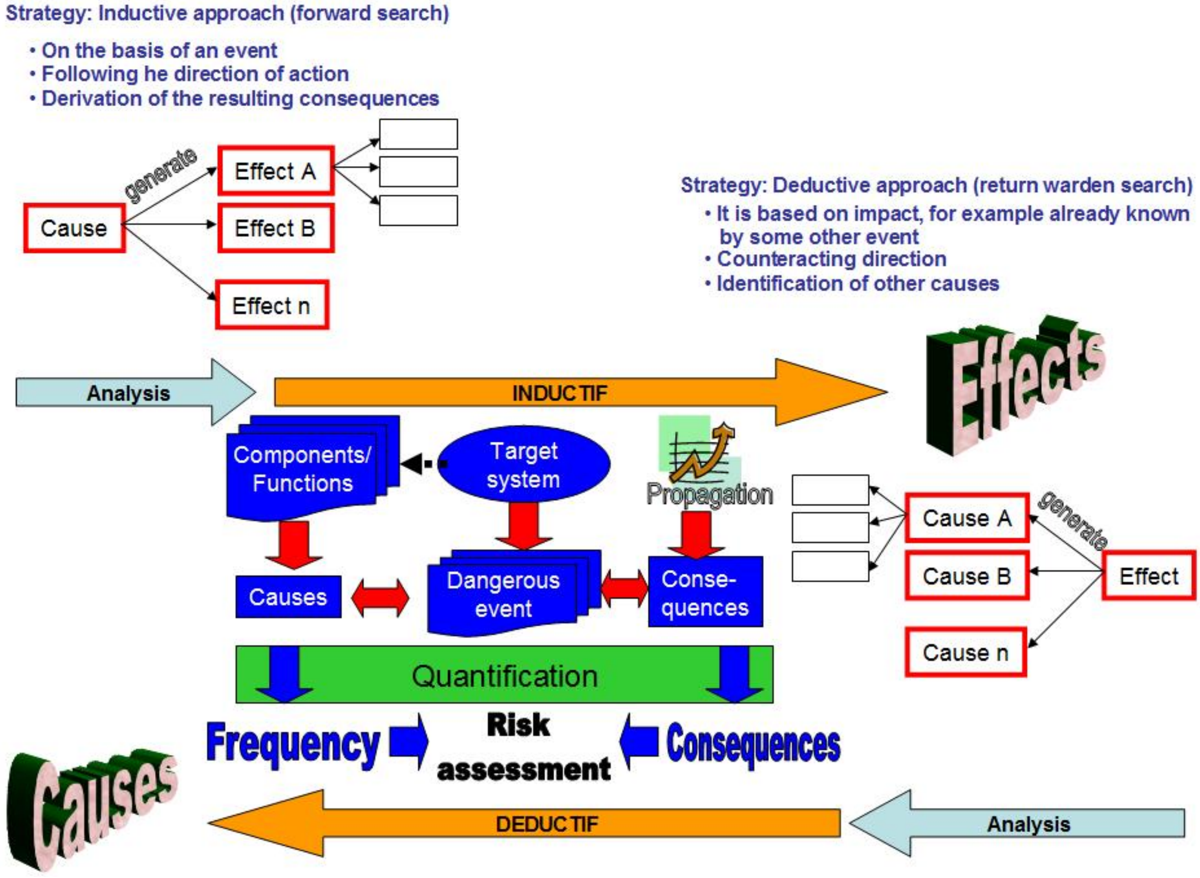


Figure 4.3: Different approaches for analysis of causes and effects

Damages in interaction wheel / rail show mostly the form of noticeable effects (for example: wheel breaking, derailment, out of roundness, corrugation). In these cases, the deductive method is used. If at passing trains vibrations in the ground or increased noise emissions are detected, you will be looking for the causes of this. If the causes are known (types, frequency of occurrences, importance, severity etc.) measures will be required depending on the results of the evaluation. The aim has to be the reduction of the impact at reasonable cost.

In Table 4.2 (which is shown completely in annex C) the possible failures on wheels and wheelsets which may have implications in various fields are listed.

The analysis of the failures listed in Table 4.1 is shown in Annex C whereas in Table 4.2 the form and the headline of the table is shown.

Failure Mode	Cause of failure	Effect on the interaction vehicle/track	Effect on the track	Effect on the vehicle	Effect on the environment	GS	GA	F	Detection of failure	Mitigation
1*)	2*)	3*)	4*)	5*)	6*)	7*)	8*)	9*)	10*)	11*)

Table 4.2: Table presenting the columns for the analysis (see Annex C)

Explanation of each column of Table 4.2:

1*) Description of the failure mode (for more details see Table 4.1)

2*) Identifying the causes of failure

3*) Measuring the impact of a failure on the vehicle track interaction (geometric interaction, interaction in contact geometry, dynamic vehicle behaviour, etc.)

4*) Measuring the impact of a failure on track components (rails, sleepers, ballast, etc.)

5*) Measuring the impact of a failure on the vehicle (equipment of bogies, especially in the not suspended part)

6*) Measuring the impact of a failure on the environment (Noise emission, ground vibrations)

7*) Gravity in terms of safety corresponding to the EN50126 standard (IV - Catastrophic, III – Critical, II - Minor)

8*) Gravity in terms of availability (3 = Critical, 2 = Significant, 3 = Minor)

9*) Trading frequency of occurrence of the cause of the failure mode (EI = Extremely Improbable, R = Rare, O = Occasional)

10*) Describe the methods by which the failure can be detected and localized

11*) Measures to be taken into account to reduce the risks inherent in the system and the system cost so as to augment the availability of the system.

4.2.4 Mitigation measures

Mitigation measures can be defined based on the FMEA. These measures can be located in different areas:

- In the field of design (e.g., use of radially adjustable wheelsets, changing brake-type, adjusting motor regulation of acceleration and braking)
- In the field of system maintenance (adaptation reprofiling strategy, application, or adaptation of flange lubrication devices, control of the wheels and axles, application of automation technology in the field of wheelset diagnostics (workshop based monitoring))
- In the area of products (e.g. improve the material properties of the wheels)
- Track based monitoring of wheel tread defects
- Etc.

Constructive mitigation measures (see. RIVAS WP5, Deliverable D5.4) could be more cost effective than improved maintenance plans.

4.3 Analysis of Life Cycle Costs

When doing analysis on life cycle costs it is for example possible to analyse and decide if in a specific case it is cheaper to invest in better wheel material than in wheel maintenance.

4.3.1 Theoretical approach for cost estimation

Integrated Logistics Support (ILS) is the main system to ensure its operational availability. Studies on Logistic Support Analysis (ASL) are conducted to determine the support system that will be most effective for the lowest total cost of ownership (TCO = Total Cost of Ownership or Life Cycle Cost LCC). This comes in two parts

- Cost system
- Cost operating system

Some railways have methods of calculation to determine the Global Cost of Maintenance and Support (GCMS), sub-systems and system equipment "axles mounted."

This study assesses firstly the costs of corrective and preventive maintenance of equipment and the cost of repairs and support tools. The overall cost of maintenance-support (GCMS) will be calculated in a second step, taking into account the various costs mentioned above.

Evaluation of GCMS is based on a number of assumptions related to the items specified below:

- maintenance concept (including parity rules, etc.)
- reliability of the considered element (MTBF = Mean Time between Failure especially for electrical elements) and its life,
- the time to repair (MTTR = Mean Time to Repair),
- amount n of similar type (wheelsets, etc.),
- duration and type of the maintenance task,
- number of involved persons and the hourly cost applied,
- nature and type of support tools,
- parameters related to the PMST (PMST = Packing, Manipulation, Storage, Transport)

The entire wheel set, depending on the technical solution, consists of different components. There is a difference if the wheelset is used in a freight car, with a coach or in a driven vehicle. If for the reduction of wear of wheel and rail also additional elements are used (equipment for steering the wheelsets, lubrication, etc.), these must be taken into account in wheelset maintenance. In addition it is known that faults on the driving surfaces of the treads can lead to stress on components in the unsprung part of the bogie (springs, connection rods, earthing brush, speed sensors, etc.). They can also cause damage to track components (rails, sleepers, ballast). They also affect the environment (noise, vibration, etc.). To avoid damage to “overstressed” elements, additional expenses have to be taken into account in the wheelset maintenance. The resulting savings are difficult to quantify. They can be estimated based on the back of experience, test results, theoretical investigations, etc..

The method for calculation of GCMS is divided into several steps as shown in Figure 4.4:

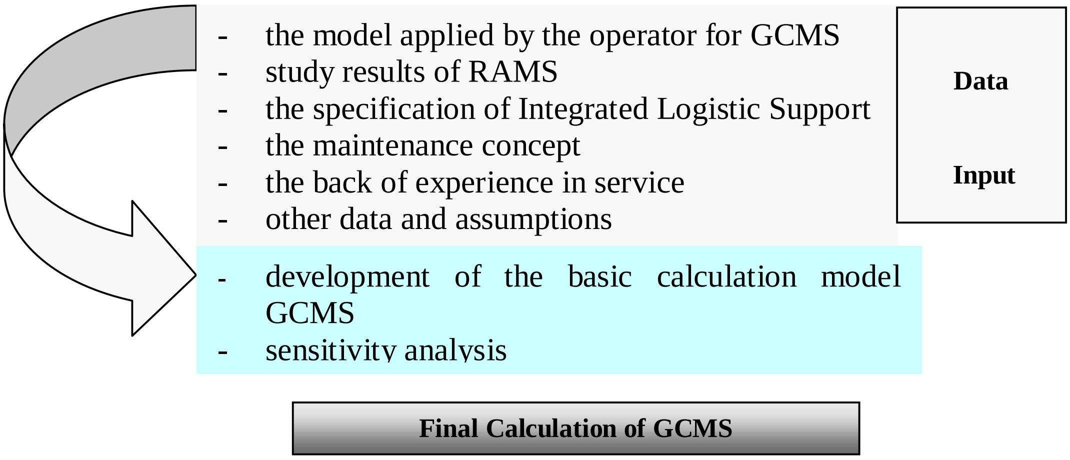


Figure 4.4: Process of calculating the GCMS

In accordance with Figure 4.4 four steps are needed to calculate the GCMS:

- identification of input data and assumptions,
- development of the model and preliminary calculation of the GCMS
- sensitivity analysis of costs,
- final Calculation GCMS.

4.3.2 Pragmatic approach

As can be seen in Figures 2.15 and 4.1, the costs for wheelset maintenance, apart from costs of vehicle operating loss, depend predominantly from the wheel replacement costs (including the procurement costs for new wheels). On long term this costs can be influenced in a limited range by optimised reprofiling (see Figure 2.16).

Figure 4.5 shows the vehicle miles travelled to limit of flange height wear in dependence of natural wear characteristics. It is assumed in the diagram, that the criterion for determinant wear is flange height, expressed in diameter reduction. Based on European experience the specific wear rate for diameter reduction depends of line characteristic, steering principles of bogies, axle load and traction. It can be seen, that still for heavy freight cars the specific diameter loss is about 2 mm/100’000km. When composite brake blocks are applied, the tread wear will be doubled compared with vehicles equipped with cast iron brake blocks. Due to the applied traction forces the specific wear rates for driven wheelsets are significantly higher than those for trailer wheelsets.

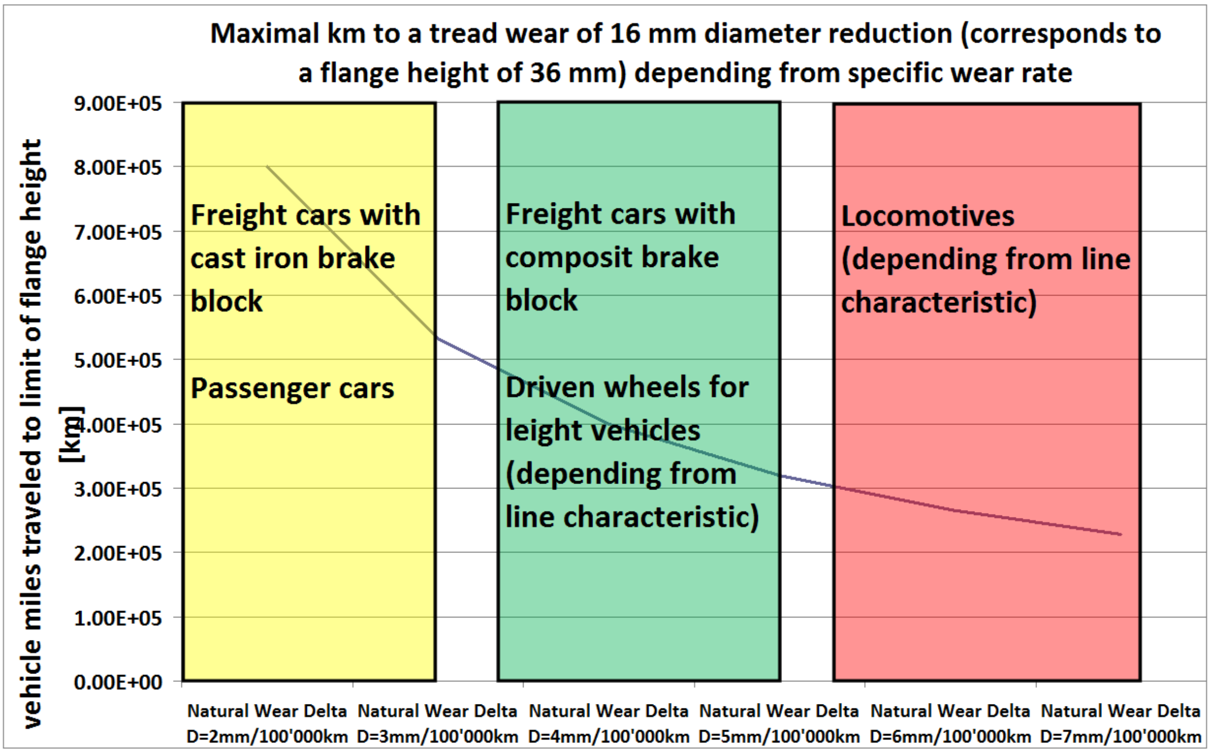


Figure 4.5: Vehicle miles travelled to limit of flange height wear in dependence of natural wear characteristics

Based on durability diagrams (see Figure 4.1) the wheelset maintenance costs can be estimated as follows [1]:

$$\text{Total costs for Time T } (C_{\text{Time T}}) =$$

$$N_1 * (C_{\text{Reprofiling}} + C_{\text{Operation loss reprofiling}} + C_{\text{Transfer vehicles to Wheel lathe}}) + N_2 * (C_{\text{Wheel Replacement}} + C_{\text{Operation loss wheel replacement}} + C_{\text{Transfer vehicles to overhaul workshop}})$$

where N_1 : Quantity of reprofiling, N_2: Quantity of wheel replacements, C: Costs

The costs for periodic controls of the wheel treads and the wheelsets as well as the costs for the spare parts storing are not included in the above formula.

If in time T the vehicle travels X kilometres, the specific costs are

$$T_{specific\,per\,kilometer} = \frac{C_{Time\,T}}{X} \left[\frac{Euro}{Kilometer}\right]$$

4.4 Conclusion and Recommendations to Improve Maintenance Plans

Important factors of wheel life duration are the control of numbers of wheel machining cycles within the current limits and the amount of metal that is removed during each cycle, which represents the “reprofiling philosophy”. Reprofiling is required when geometric failures on the wheels and wheelsets occur or when setting inadmissible damage to the wheel treads. Table 4.1 lists the different failure types on wheels/wheelsets and on wheel treads which can cause a reprofiling procedure. Technology Assessment is based on a failure mode effect analysis (FMEA) where the different failures in Table 4.1 are treated in a systematic way. Based on this analysis mitigation measures are defined. These measures can be located for example in the field of design, of system maintenance, of workshop based monitoring, of track based monitoring and in the area of improved wheel material properties.

The entire wheel set, depending on the technical solution, consists of different components. There is a difference if the wheelset is used in a freight car, with a coach or in a driven vehicle. If for the reduction of wear of wheel and rail also additional elements are used (equipment for steering the wheelsets, lubrication, etc.), these must be taken into account in wheelset maintenance. In addition it is known that faults on the driving surfaces of the treads can lead to stress on components in the unsprung part of the bogie (springs, connection rods, earthing brush, speed sensors, etc.). They can also cause damage to track components (rails, sleepers, ballast). They also affect the environment (noise, vibration, etc.). To avoid damage to “overstressed” elements, additional expenses have to be taken into account in the wheelset maintenance. The resulting savings are difficult to quantify. They can be estimated based on experience, test results, theoretical investigations, etc.. As long as these different costs of the overall system are not known, LCC has to be established in a pragmatic way taking into consideration durability diagrams as a basis for the calculation. Based on these durability diagrams it can be verified if the reprofiling philosophy is correct or if it should be modified. The LCC is the sum of costs for reprofiling, for wheel replacement including required material, for immobilisation of vehicles, and for transfer of the vehicles to the different workshops (wheel lathe, overhaul).

The best approach to improve wheel maintenance plans is to investigate the causes for failures and their effects and to have in mind LCC over a reasonable lifetime (e.g. wheelset lifetime). A preventive reprofiling according to the train and track specifications can then be a mitigation solution to reduce vibrations considerably, but it has to be checked if other solutions could be more cost-effective.

5. CONCLUSIONS AND NEXT STEPS

Chapter 2 is showing: The EN 15313 applies as a maintenance base for secure interoperability of the wheelsets. The standard handles primarily the organizational aspects and the management of the wheelset maintenance, contains the geometrical limits for safe interaction of wheel / rail or wheelset / track, shows pictures of damage to wheels and axles, and contains mandatory requirements for wheel/wheelset geometry and wheel damages. Overall, the impression appears that the EN15313 is imprecise regarding the permissible errors at the wheel treads. Railway Group Standard GM/RT2466 specifies limits on wheel wear and general crack conditions that may be found on the tread of a wheel. By the application of GM/RT2466 it is common practice for train operators to turn the wheels at short enough intervals to avoid either crack length or cavity length limits being reached.

Different condition monitoring systems are used to detect out of round wheels. Most of the condition monitoring systems for railway vehicles are focused on the wheels and bogies since these parts of the vehicle have the largest impact on the performance and are also the mayor cost drivers in maintenance. There are track based detection systems and workshop based detection systems. The difference is that track based detection systems are installed in lines and are working without speed restriction. By using wheel impact detectors structural health monitoring trends can be observed based on the wheel impact data which indicate the actual condition of the wheels. Those trends can indicate the critical wheels that actually need to be removed, while at the same time allowing wheels that aren’t critical to remain in service. Track based detection systems in long-time commercial use are for example DafuR in Germany and GOTCHA in Netherlands.

Workshop based detection systems allow the detection of different wheel/wheelset data (cracks, wheel profiles, out-of-roundness, wheel diameter, wheel tread defects), but they are situated in the vicinity of a workshop. The monitoring requires reduced train speed or stand still. A sophisticated workshop based monitoring system is for example ARGUS. It is important to share data from measuring devices directly with the rolling stock owner. The direct data transfer allows the vehicle owner to take immediate remedial actions. On the other side, if different alarming-levels are implemented in such devices, it allows the vehicle owner to pass from corrective maintenance to conditional maintenance.

In practice, e.g. wheelsets of high-speed trains require regular attention on a wheel lathe to remove tread defects before the depth is more than 0.5 mm. Research of real situations showed that OOR of up to 2.5 mm are removed by the ground wheel lathes.

A methodology for establishing reprofiling strategies uses a two-stage process. The first step involves tread defect frequencies and wear rate statistics from the raw data gathered as part of normal wheelset maintenance activities. The tread defect and wear data are then used as the input to a probabilistic computer simulation specifically designed to explore the impact of different wheel lathe operating strategies on wheelset maintenance costs. This simulation has to investigate the effect of a number of different aspects of a wheelset maintenance strategy (Re-profiling policy, Parity rules, Planned turns). Another approach is based on systematic preventive maintenance. Instead of applying condition based maintenance with the scope to maximise the reprofiling intervals with the consequence of cutting depth of 6 to 7 mm the wheels are reprofiled in short terms (e.g. about all 70’000km) with a cutting depth of around 1 mm. As a consequence wheelset overhaul (lifetime) can be extended significantly due to this “reprofiling philosophy”.

Chapter 3 summarizes some of the European experiences in maintenance: The wheels of most vehicles in the European railways are still monitored by standard measurement equipment and visual inspection. Reporting is in use for locomotives by drivers and for passenger cars by conductors or by passengers. Especially for high speed applications (France, Germany, Spain, Switzerland, etc.) monitoring systems are applied.

In Chapter 4 the Table 4.1 lists the different failure types on wheels/wheelsets and on wheel treads which can cause a reprofiling procedure. Technology Assessment is based on a failure mode effect analysis (FMEA) where the different failures in Table 4.1 are treated in a systematic way. Based on this analysis mitigation measures are defined. These measures can be located for example in the field of design, of system maintenance, of workshop based monitoring, of track based monitoring and in the area of improved wheel material properties.

The entire wheel set, depending on the technical solution, consists of different components. There is a difference whether the wheelset is used in a freight car, with a coach or in a driven vehicle. If for the reduction of wear of wheel and rail also additional elements are used (equipment for steering the wheelsets, lubrication, etc.), these must be taken into account in wheelset maintenance. In addition it is known that faults on the driving surfaces of the treads can lead to stress on components in the unsprung part of the bogie (springs, connection rods, earthing brush, speed sensors, etc.). They can also cause damage to track components (rails, sleepers, ballast). They also affect the environment (noise, vibration, etc.). To avoid damage to “overstressed” elements, additional expenses have to be taken into account in the wheelset maintenance. The resulting savings are difficult to quantify. They can be estimated based on experience, test results, theoretical investigations, etc.. As long as these different costs of the overall system are not known, LCC has to be established in a pragmatic way taking into consideration durability diagrams as a basis for the calculation. Based on these durability diagrams it can be verified if the reprofiling philosophy is correct or if it should be modified. The LCC is the sum of costs for reprofiling, for wheel replacement including required material, for immobilisation of vehicles, and for transfer of the vehicles to the different workshops (wheel lathe, overhaul).

The best approach to improve wheel maintenance plans is to investigate the causes for failures and their effects and to have in mind LCC over a reasonable lifetime (e.g. wheelset lifetime). A preventive reprofiling according to the train and track specifications can then be a mitigation solution to reduce vibrations considerably but it has to be checked if other solutions could be more cost-effective.

Next steps:

Maintenance tests will run at SBB in Switzerland for preventive maintenance in the next months.

The technology assessment in Table 4.2, resp. Annex C shall be filled by experience of the RIVAS partners and others and will be included in the RIVAS WP5 guideline (Deliverable D5.5).

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ANNEX A REPROFILING AND ITS CAUSES

A.1 ACCIDENTAL FAULTS

These faults are either due to the wheel concerned (e.g. metallurgical defects), a time anomaly interface with the track (raised bad welding on the rail, obstacle on the rail, ...), or an occasional system failure of traction or braking (wheel slide protection, mechanical blocking, ...). Treatment of accidental defects demands specific practices for each default.

A.2 NATURAL WEAR

Natural wear is related to interactions between the wheels and rails as well as the braking on the wheels (brake shoes). Of the many types of wear described in the literature on contact mechanics, only two appear to be dominant in wheel/rail contact: adhesive and delamination.

A.2.1 Adhesive wear

Adhesive wear is relatively mild. Thin flakes are produced on the surface over a large number of cycles. It is possible that the thin flakes break away from the surface when they adhere to asperities in the rail surface. Bolton [22] found the mild wear debris to be a mixture of iron oxide (Fe_2O_3 and Fe_3O_4) and metallic iron. He found the flakes are typically 100µm long and less than 10µm thick from scanning electron micrographs. Their thinness implies that they come from the transformed white phase at the wheel’s surface. Wheel and rail surfaces remain shiny under adhesive wear.

A.2.2 Delamination wear

Delaminating wear is more severe than adhesive wear. It is characterised by light grey wear debris that is entirely metallic. Delaminating wear begins when a crack is initiated at the surface. The crack propagates under the surface until it turns up and breaks through the surface, allowing a flake of material to become detached. Delaminating wear produces a rougher surface than adhesive wear. The surface contains ripples with smooth peaks and troughs with a pitted appearance.

Wear is difficult to predict because of the number and nature of cumulative causes. One can easily anticipate that the wear of the flanges will be more important in the case of circulation of a train on a conventional line than a TGV operating exclusively on high speed lines. But it is more difficult to quantify the wear, even if we know they will happen. Natural wear can also be very low but it is required much of reprofiling for reasons of vibration behavior (roundness of wheels), or limiting the risk of accidental defects such as peeling by hardening of the tread and thermal defects caused by braking on the wheel treads. The natural wear of the wheels may not be constant and evolve over time according to changes in the track, of line velocity, suspension characteristics of the vehicle, traffic etc. It is therefore necessary to consider that strategies for reprofiling require constantly the questioning and monitoring of natural wear throughout the life of the equipment.

The "normal" wear can be divided mainly into two categories:

- wear on the tread,
- wear on the flange, knowing that in this case the connection area between the tread and the flange is also affected.

Reprofiling must be adapted according to the type of wear. The damage that can be encountered in the profile is not considered “normal” wear.

Also the changed profile between the new form and the form at the agreed time for reprofiling can be considered for reprofiling. The profile can temporarily adopt progressive forms. But it should ensure that in its evolution the profile does not reach critical feature for traffic safety (equivalent conicity for example). In this regard particular attention has to be taken when synthetic brake blocks are applied.

A.3 ROLLING CONTACT FATIGUE (RCF)

A3.1 Definition of RCF

Rolling contact fatigue (RCF) is a family of damage phenomena that appear on and in wheel treads due to overstress of the wheel material. This damage may appear first on the surface (e.g. tread checks, shelling) or the subsurface (deep seated shell). In either case, these phenomena are the result of repeated overstressing of the surface or subsurface material by the hundreds or thousands or millions of intense wheel-rail contact cycles.

RCF is the damage to the wheel and close to its surface from cracks that propagate by changes in mechanically induced stress that occur when the wheel rotates. Thermally induced RCF produced from a wheel slide that initiates from martensite is a special case and will not be discussed here. The type of RCF discussed here is initiated by mechanical changes to the microstructure resulting from normal and tangential forces in the contact patch.

RCF failure of a wheel can be separated into four phases:

1. crack initiation,
2. early crack growth,
3. extended crack growth and
4. separation of a piece of material from the surface and the formation of a cavity.

In the final two stages, the crack grows below the surface at a shallow angle to the surface until it joins with another crack and allows the piece of material above the crack to become detached. The following discussion concerns the first two stages. After stage two, a wheel should show a band of surface cracks around its circumference which are visible to the naked eye.

Initiation can occur at the surface, just below the surface (say up to 10mm below the surface) or deep below the surface [23]. Deep initiation requires a large material defect, such as a void or inclusion, to be present to produce a stress concentration. It is assumed that these defects are not a significant problem in wheels manufactured to modern standards [24]. Surface initiation of RCF is from the same mechanism that causes delaminating wear. Repeated plastic deformation of the surface layer eventually leads to the plastic strain limit of the material and a crack being initiated. If the contact conditions are severe then wear by delaminating will take place. If the contact conditions are less severe, but are still above a certain threshold, then the cracks may propagate to form RCF, and the effect of fluid on crack propagation becomes important.

Fatigue of the wheel surface is an extremely common problem that affects virtually every railroad. There is a regular progression in the development of these defects: from light checking to regular cracking to light shelling and to heavy shelling. The combinations of normal contact stress (Po), surface tractions (T/N) and shear strength of the steel (K) required to generate an increment of fatigue are summarized in Johnson’s Shakedown Diagram [25]. It must be emphasized that RCF cannot be evaluated based on normal contact stress alone since the interdependence with tractions and material strength is too intimate. Assessing wheel/rail performance with respect to contact fatigue requires consideration of all three parameters.

A3.2 Wheel/rail tractions (T/N)

Rail/wheel traction develops due to a small relative slip between the rail and wheel (this is in the interfacial layer of the contact zone). The level of slip (also known as creep) depends on the curving and traction demands. These creep forces or tractions, cannot exceed the available adhesion – the vertical force on the wheel times the friction coefficient. Controlling tractions is therefore a process of controlling the properties of the interfacial layer and minimizing creepage.

A.3.2.1 Operating parameters influencing traction (T)

Traction (T) has lateral (T_{lat}) and longitudinal (T_{long}) force components which at the limit approaches the wheel/rail friction coefficient [28]. The actual traction ratio T/N for any given wheel/rail combination depends on several operating parameters including:

- ***curving requirements:*** When a bogie negotiates a curve the wheelsets are restricted by the suspension from aligning radially to the curve. The leading wheelset typically flanges against the outside rail with a significant yaw angle, with the trailing wheelset (in a mild curve) being more or less central in the track with a small yaw angle. The exact positions will vary depending upon the specific conditions but in most cases, angle of attack and creepages (both lateral and longitudinal) increase with curvature and bogie wheelbase. Accordingly, the rate and severity of RCF formation in curves increases with curvature and bogie wheelbase.
- ***bogie suspension:*** A stiff bogie resists displacement of the wheelset with respect to the bogie frame. The more flexible the suspension, the greater the potential for favourable steering moments to reduce the yaw angle in curves and thereby reduce RCF. However, a more flexible bogie has a greater ability to respond to unfavourable steering moments and increase the yaw angle, especially in the case of bogies that have been poorly maintained and are running with a number of worn-out components.
- ***friction coefficient:*** Minimizing friction coefficient reduces the peak tractive force but simultaneously reduces the steering moments that develop. The result is a measurable impact on the yaw angles.

  Reference [26] recommends that the difference in top-of-rail (TOR) friction coefficients should not be less than 0.3 and the difference in TOR value between the two rails should not exceed 0.1. TOR friction control should be considered for track where high friction problems, such as weak track, high TOR wear rates and wheel climb concerns exist.
- ***cant deficiency:*** The additional sideways load on the bogie from cant deficiency changes the orientation of axles. Typically, in the case of high speed trains running on mild curves with large cant deficiency, both the leading and trailing wheelsets offset heavily to the outside rail, sometimes to the extent of flanging (depending on the profiles). This lateral shift is much greater than when running at balance speed in the same mild curve. The result is increasing (longitudinal) tractions with cant deficiency and high potential for RCF of the mid-gauge position on the rail.

A3.2.2 Traction and braking forces

Typical braking and acceleration rates for passenger vehicles are $0.8 m/s^2$ (corresponding to 9% g). Assuming a four axle vehicle has a mass of 45,000kg gives a wheel/rail longitudinal force of 4.5kN during braking and acceleration. As can be shown, this is significantly less than the tangential forces that are typically generated when a vehicle travels through a curve.

Modern vehicles have wheel spin and slide control systems that optimise traction and braking performance. With these systems the wheels in a train do not necessarily carry the same traction and braking effort. Levels of creepage on some wheels can be very high (up to 20%). This is thought to be a possible cause of raised amounts of RCF on the leading wheels of some trains or on the wheels of locomotives.

The most severe contact conditions on the wheel arise when a train is curving at the same time as braking with high creepage.

A.4 WHEEL MATERIAL INFLUENCE

The performance of wheels in service with modified steel grades can be validated on behalf of the so-called durability diagram. Increases in wheel life are believed to be possible, particularly by controlling the wheel machining cycle within the current limits, and the removed amount of metal during each cycle, which represents the “reprofiling philosophy”. For example, if the reprofiling interval is increased more material has to be removed by turning due to subsurface propagation of tread damage related to longer period. Figure 4.1 presents feedback results in a diagram of wheel diameter reduction (amount of metal removed on service and by turning) by mileage covered. An analysis of the durability diagram shows that the performance of a wheel material is influenced mainly by the above-mentioned “reprofiling philosophy” and also by a few poorly performing wheels due to strong machining of RCF clusters, wheel flats, OOR and so on. The wheel life can be highly dependent on damage phenomena such as RCF clusters, OOR, wheel flat, etc., which can cause loss in diameter during machining operations and compromise the LCC of the wheel. For example, in the case of a material with a reference wear of 4-5mm/100’000km, effects due to RCF and other damages on a few badly performing wheel increase the wear rate up to 20mm/100’000km, due to strong turning operations to remove a thick layer of material which is required to clear the tread of RCF/geometrical damage. The true performance of an innovative material, selected theoretically according to the above procedure, can give different results in different environmental conditions or with the application of different “reprofiling philosophies”.

From RIVAS WP5 deliverable D5.4 [14]: Materials with a higher resistance to wear are already used in service, for example on the Shinkansen trains in Japan. This material has been compared to R7, both in laboratory and in service and has been demonstrated to be more resistant. For an equivalent wheel roughness degradation, the Shinkansen material performed 31 500 km while the standard R7 performed 10 000 km, see Figure A1. In service, the Shinkansen material required much less reprofiling than the R7 steel for the same period. Other grades of steel that were more resistant than R7 in laboratory are also discussed, but these materials could not be tested in service due to difficulties in manufacturing.

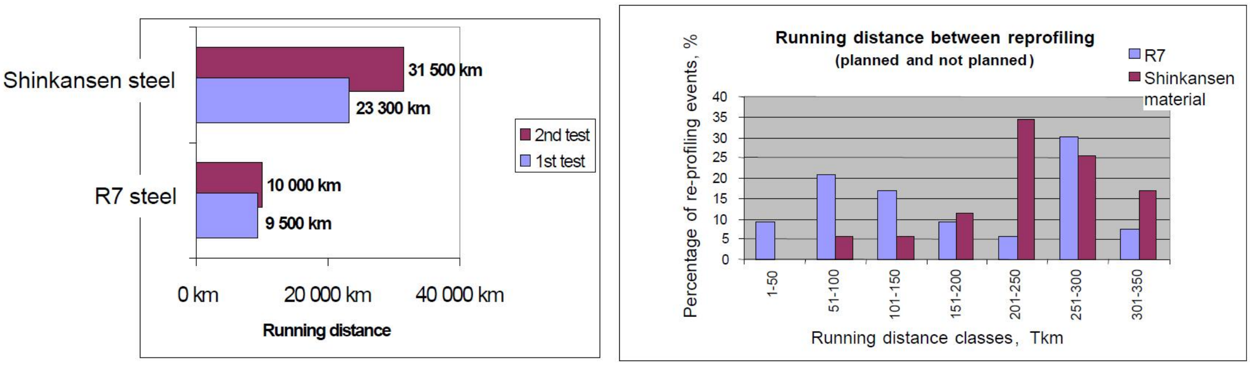

Figure A1: Comparison of material quality in terms of tread defects. left: laboratory (test rig) running distance for a given roughness degradation, right: in service running distance between reprofilings

Lucchini experience

Steel grades used for the wheel manufacturing and the wheel-rail loads have a role in the RCF generating cracks, spalling and shelling; examples of RCF are illustrated in Figure A2. Normally in presence of RCF, the rim material toughness should be increased together with the hardness; this works for the European steel grades (EN13262) passing from ER7 to ER8 and ER9, but sometimes the increase of hardness reduces much more the wear than the RCF so that small cracks have longer time to propagate at more critical sizes before the wear actually manages to wear them off. In the last years it has been shown that a further improvement can be obtained through the use of special steel grades which can be applied to reduce RCF. Lucchini RS has introduced the so-called Superlos steel grade that will be introduced also in the future revision of EN13262 under the name ERS8. Superlos is a pearlitic silicon and manganese carbon steel derived from the standard ER8. The chemical composition of ER8 and Superlos are compared in Table A1. The use of Superlos leads to increases in impact toughness and fracture toughness, see Figure A3 and Figure A4.

Grade Of Steel	**Elements**	**C Max**	**Si Max**	**Mn Max**	**P Max**	**S Max**	**Cr Max**	**Cu Max**	**Mo Max**	**Ni Max**	**V Max**	**Cr + Mo + Ni Max**
R8T	-	0.56	0.40	0.80	0.040	0.040	0.30	0.30	0.08	0.30	0.05	0.60
SUPERLOS	Min (%)	0.49	0.60	0.60	-	-	-	-	-	-	-	-
	Max (%)	0.56	**1.10**	**1.10**	0.020	0.015	0.30	0.30	0.08	0.30	0.08	≤0.50

Table A1: Comparison of chemical composition in R8T and Superlos wheel steel grades

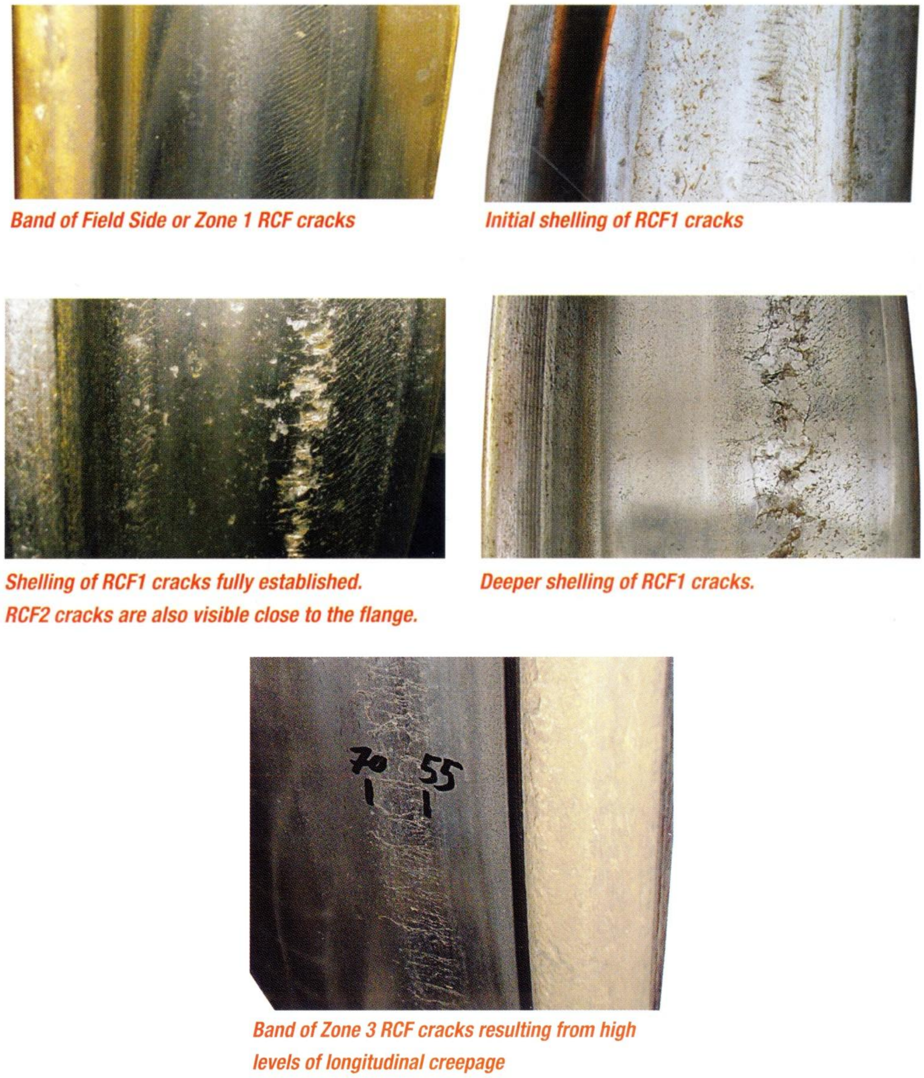

Figure A2: Examples of wheel tread damage due to RCF

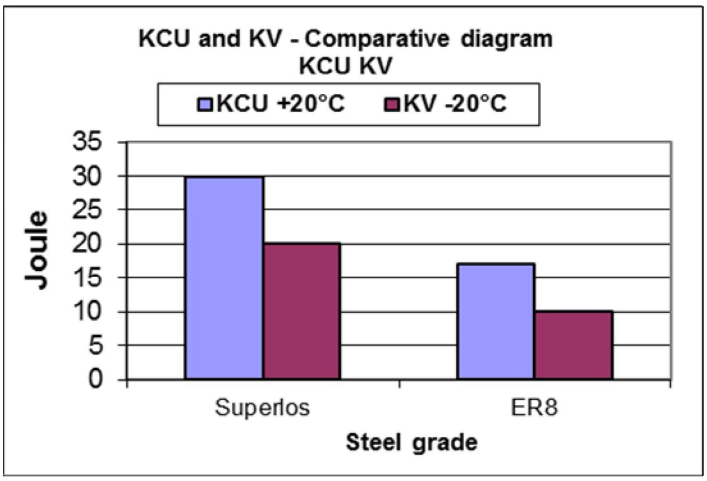

Figure A3: Diagrams of impact toughness tests KCU (U notch) and KV (V notch) at 20 and -20 °C for Superlos and ER8 steelgrades

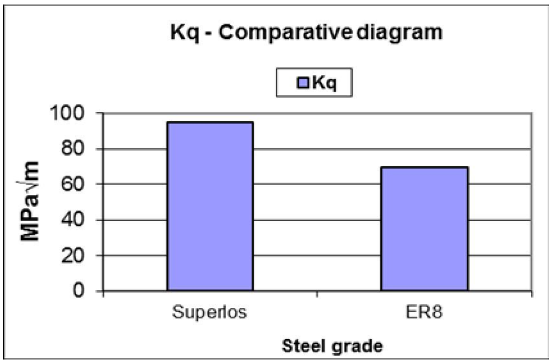

Figure A4: Diagram of impact toughness tests KCU (U notch) and KV (V notch) at 20 and -20 °C for Superlos and ER8 steelgrades

Below is a list of references in which the Superlos wheels were applied with an appreciable improvement of the RCF phenomena:

- Italian-Switzerland Pendolino Cisalpino Alstom
- CRH5 EMU Alstom
- Czech Republic Pendolino EMU Alstom
- Finland Pendolino EMU Alstom
- Slovenia Pendolino EMU Alstom
- UK Intercity EMU Coradia Alstom
- Denmark Intercity EMU Bombardier
- UK Siemens Desiro
- Slovenia Siemens Desiro
- Switzerland regional train NPZ

As an example on the Coradia passenger vehicles running in the UK, ER8 wheels were used with the following maintenance regime:

- remove 5mm radius per reprofiling
- an interval of 75.000 miles (typically due to RCF problems)
- wheel life time = 6 times reprofiling => 7 x 75.000 = 525.000 miles

When the Superlos wheels were introduced, it was possible to increase the reprofiling interval to 200.000 miles and the following wheel life time to about 1.000.000 miles.

	
Vehicle 175003 Car 50 Wheel-1 152.000 Miles (SUPERLOS)	Vehicle 175005 Car 50 Wheel-1 88.000 Miles (R8T)

Figure A5: Example of the conditions of the two type of wheels running under the same trainset.

A.5 HARDNESS INFLUENCE

Localised spreading is like a flat containing local radius reduction in the circumference of the wheel tread. The difference to a flat is that the localised radius reduction of a localised spreading is some times bigger. There exist different origins for localized spreading:

- wheel flat not removed from service,
- material hardness deviation along the circumference on the wheel tread (for example inappropriate tempering process at wheel heat treatment),
- material hardness deviation along the circumference due to inhomogeneous material characteristics.

Localised spreading has been observed in the past on different types of railway vehicles (passenger coaches, locomotives, freight cars). The vehicles with localised spreading often have been taken out of service due to consequential damages in the non suspended part of the running gears (broken springs, broken lineages, damaged suspensions, etc.) or due to noise emissions.

Figure A6 shows the development of localised spreading on one wheel of a locomotive type Re460. 106’000 km after reprofiling there was measured a localised spreading with amplitude of around 0.5 mm. Due to the form of spreading in the circumferential direction, a flat can be excluded as a cause. After another 50’000 km, the damage has developed to an amplitude of about 2 mm. Localised spreading in an advanced state can be detected by visual control. Due to the defect, high vertical forces in the contact patch will be produced. Therefore

- the material in the damaged area of the tread is flowing and is producing a localised roll over,
- local high cyclic contact pressure is producing RCF (rolling contact fatigue).

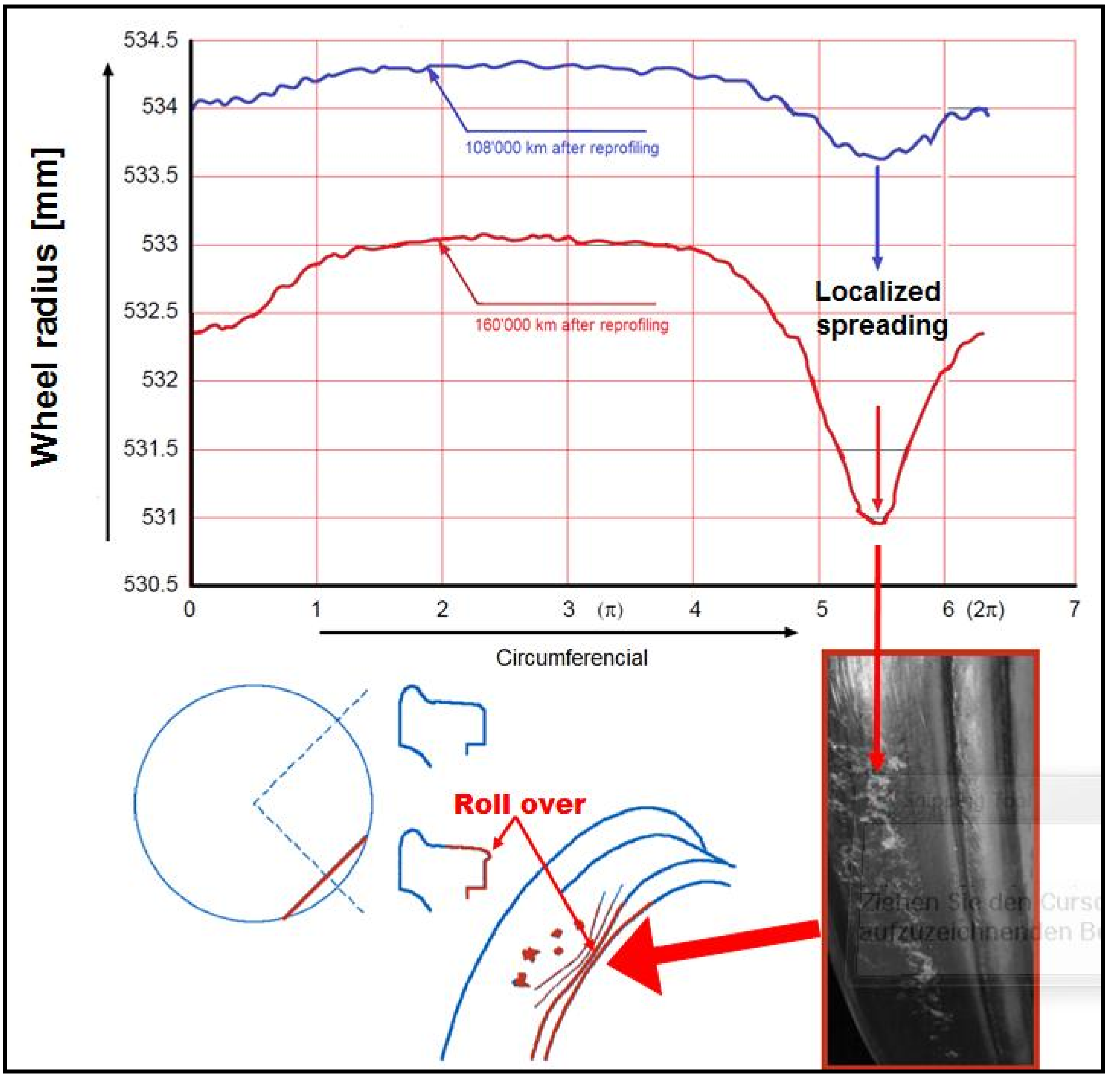

Figure A6: Development of localized spreading at SBB locomotive Re460

In the beginning of 1990-ies, several locomotives of type Re460 showed localized spreading. Further investigations showed that after reprofiling this type of damage appeared still in the same place. Figure A7 shows the reason for this behaviour. In the area of the localized spreading a reduced material hardness was present. This hardness reduction was due to inappropriate heat treatment at the manufacturer of the wheels. After modification of the manufacturing process this kind of damage disappeared on locomotive type Re460.

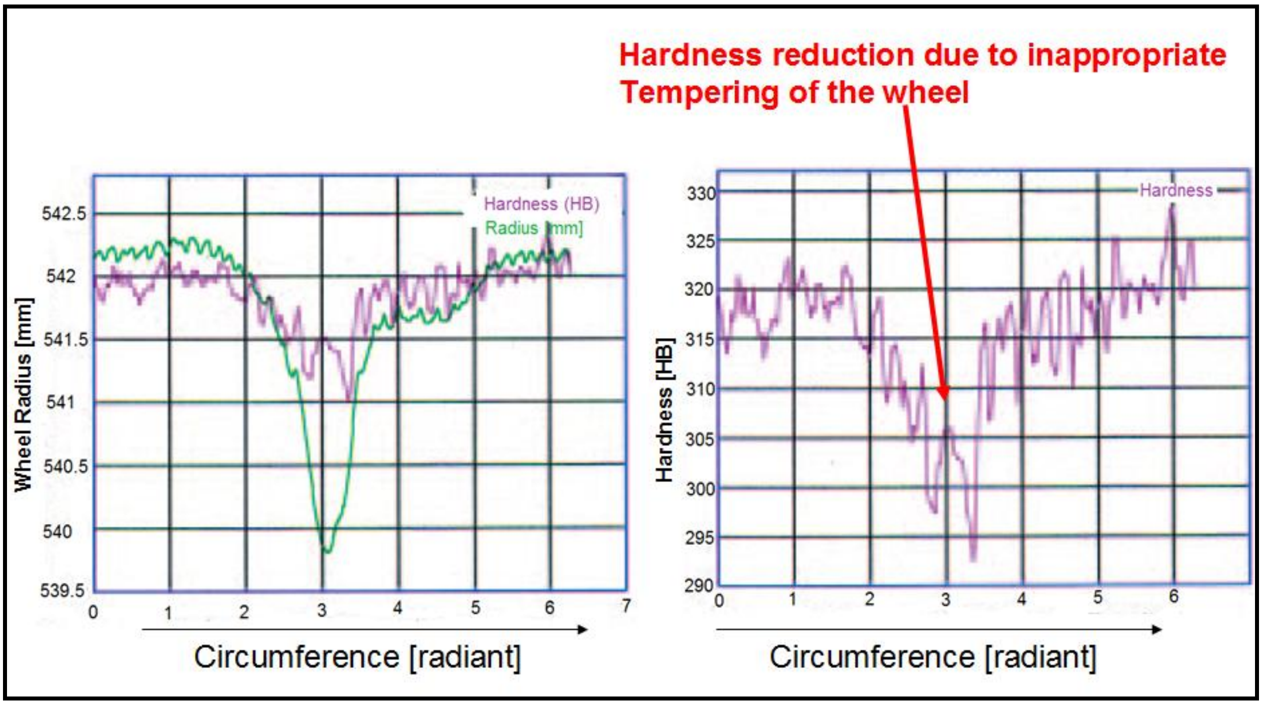

Figure A7: Correlation between out of roundness and material hardness

ANNEX B: RECOMMENDATIONS HOW TO TEST MAINTENANCE STRATEGIES

If it is mentioned in the following “wheel profiles”, the following is included

- the shape of the flange,
- the cross section from the perspective of the contact geometry,
- the transverse dimensions of the wheelset,
- out of roundness (OOR),
- damage to the wheel treads.

Between the commissioning of a new wheel profile or a new wheel material and reaching the limits of profile wear, the profile undergoes changes depending on many factors and parameters. Some areas of the profile will wear faster than others (adaptation of wheel profile to rail). Generally, a phase of stabilized wear succeeds the adaptation of the wheel profiles. However, it is impossible to predict whether this will happen or not. It is therefore necessary to establish regular measurement cycles. The spacing depends on the observed profile wear.

In order that the profile analysis for determining reprofiling strategies is complete, you must select the significant wheels (test), and therefore the associated vehicle, which will be subject to analysis. Analyses of wheel profile- and OOR-development in service are long-time investigations. It is therefore considered that the trains and vehicles as objects of analysis can face unexpected events that can possibly provoke unusable measurement data and possibly the vehicle has to be removed from the analysis.

B.1 FREQUENCY OF RECORDINGS WHEEL PROFILE [18]

The wear of profile is considered normal, acceptable to sense when the frequencies of reprofiling are over 50 000 km. Below that value the consumption of wheels, occupation of lathes and downtime for processing profiles become excessively burdensome.

Therefore, at least initially, measuring cycles of profiles must allow understanding the trends of wear and in this regard should be made at about 25 000 km. This frequency can be increased if the changing of profiles is weak. Ideally, you should get four profile measurements between reprofiling. To determine whether the frequency of measurement is correct it should be estimated an RWS (Rate of Wear in Service) based on the CDW (Criteria for Determinant Wear) and then calculate the potential of reprofiling.

B.2 SELECTION OF SIGNIFICANT WHEELS

B.2.1 Statistical test planning

A) Reliability requirements

The probability of failure is the sum of losses as a function of time t. For many problems, however, one is mainly interested in the sum of intact components. The sum of the loss and the sum of the still intact parts arising at any time is always 100%.The survival probability R(t) is the complement to the failure probability F(t)

$$R(t) = 1 - F(t) \qquad \{1\}$$

The survival probability R (t) is referred to in the reliability theory as reliability R (t). Reliability is the probability that a product during a defined period of time does not fail under the given function and environmental conditions.

For the statistical test planning especially the test lot size must be specified. The test lot size is closely related to the confidence level and the dispersion of the measurement results. The less parts are tested, the greater the confidence interval and therefore more uncertain is the result of the statistical analysis. For an accurate result, an appropriate number of vehicles or axles shall be checked for this reason. When a statistical test is planned it is to be determined how the determination of the objects to be tested has to take place (sampling). The sample should be a real random sample. This means that the vehicles to be inspected or axles shall be determined purely by chance.

In addition, it is important to determine an appropriate testing strategy in the statistical test planning. A distinction is made between

- complete tests,
- incomplete tests (censored) and
- strategies of test time reduction.

The statistically best option offers a complete test in which all the elements of the sample are subjected to a life endurance test. The test is made here to the failure of the last element. In this case, there are down times for all elements available for the evaluation.

To limit the amount of testing, it may be useful to perform an incomplete test. This is sometimes referred to as censored test. Here tests are performed only up to a pre-determined life or up to a certain number of failed elements. Such tests are not as meaningful as full tests, but often associated with a significantly lower testing cost. Other ways to provide a strong test time reduction can be achieved by the application of Sudden-Death-Test and trials with increased stress.

The main task of test planning is to determine from given requirements for reliability

- the number of test objects (n=?) and
- the required test time (T_{test} =?)

to demonstrate the required reliability.

Usual requirements in practice for railway equipment are, for example, a minimum reliability R at a specified lifetime T (T, for example, in time or km) of 90%. In the case of mechanical wearing parts this corresponds to a required B_{10} life of T in time or km. In addition, a confidence level P_A is set by which the reliability requirement must be demonstrated (for example P_A=95%).

It is common that no failure is expected at test run. Therefore, in this case one speaks of Success-Run.

B) Generalization of failures during the test

To establish the confidence level generally the binomial theorem can be applied

$$P_A = 1 - \sum_{i=0}^{x} \binom{n}{i} \bullet (1 - R(t))^i \bullet R(t)^{n-i} \qquad \{2\}$$

Here x denotes the number of failures in time t and n is the sample size. Occurred during the test up to the time t, a failure, it is

$$P_A = 1 - R(t)^n - n \bullet (1 - R(t)) \bullet R(t) \qquad \{3\}$$

For the evaluation of this formula charts are available (see Larson nomogram for example in [27]). For example, if a confidence PA = 90% is required and for the test a sample of n = 20 are used, they will reach a reliability of 75% for the failure of x = 2 elements. If this reliability in the example above is not sufficient, the sample size n must be increased.

C) Test planning based on the binomial distribution

Here the general case is considered that the operator in his specification requires a certain mileage. The specification can include on the one hand the reprofiling interval and / or otherwise the service life of the wheels. In general, the proof must be provided during the warranty period. The question now is how many samples are required for this verification.

The starting point here is the observation of n specimens. If the specimens are identical, they will all have the reliability R(t). Then applies at time t for each of the samples $R_1(t)$, $R_2(t)$, $R_3(t)$, ..., $R_n(t)$ with $R_i(t) = R(t)$. According to the product law of probability the probability, that all n samples survive up to time t, is $R(t)^n$. So when examining the sample of size n up to time t, which represents the required service life, no failure observed and R(t) is the survival probability of the test object, then the probability up to time t that all n sampled parts survive, is $R(t)^n$. In other words, one can say that the probability, that at time t to observe at least one failure, is

$$P_A = 1 - R(t)^n \qquad \{4\}$$

From the reversal of this consideration, we can say that if that happened in a test sample of size n is not a failure until time t, the minimal reliability of a sample is equal to R(t) with a confidence level of P_A. Therefore applies:

$$P_A = 1 - R(t)^n \quad or \quad R(t) = (1 - P_A)^{\frac{1}{n}} \qquad \{5\}$$

Example:

The following reliability specifications is given: R (200'000km) = 90%. The proof has to be given by a confidential level P_A = 95%. With the help of the equation {5} the required sample size n results after conversion:

$$R(t) = (1 - P_A)^{\frac{1}{n}} \quad <=> \quad n = \frac{\ln(1 - P_A)}{\ln(R(t))} \quad => \quad n = \frac{\ln(0.05)}{\ln(0.9)} = 28{,}4 \qquad \{6\}$$

B.2.2 Test planning according to [18]

Analyses of wheel profiles are long investigations. It is therefore considered that the train and vehicle objects of analysis will face unexpected events that can possibly stop monitoring. The number of trains involved must be greater than 2, and it is recommended to set to 3. It is best to select the most stressed trains in commercial service, that is to say, those who accumulate the greatest number of miles faster.

For the same reasons, three vehicles will be selected in each train to be involved in monitoring profiles. Both an end vehicle and an intermediate vehicle would be a wise choice, but it is possible that the specific rolling stock leads to more appropriate choices.

For each selected vehicle each bogie and every axle will be monitored.

Finally, on each axle both wheels should be followed. It is important to analyse the wear for both wheels to quickly detect abnormalities related to the characteristics of the operation of trains and tracks.

The typical profile analysis therefore includes 3 trains x 3 vehicles x 2 bogies x 2 axles x 2 sides = 72 wheel samples.

Based on Equation {6} it is obtained in this experiment for both the number of selected wheels and wheelsets a high reliability and a high level of confidence. Provided, however, that the wheelsets belong to the same statistical population.

B.3 ULTRASONIC MEASUREMENTS IN SERVICE OR TEST INSPECTION OF THE RIM

During the wheel service life some type of damages (typically called RCF cracks) can take place on the rim that can then become responsible for the generation of high vibration and in some extreme situation become critical for the safety of the vehicle.

Such damages can be prevented by performing a periodic inspection of the wheel. The inspection can be visual or supported by Ultrasonic NDT (UT) equipment, see Figure B1. With the simple visual inspection it is possible to detect advanced damages due to RCF cracks starting from internal defects or surface wheel flats due to a braking fault or to local inhomogeneous rim material. The UT inspection can detect internal defects before they become critical. This helps also for tests so that defects are earlier visible.

Figure B1: Ultrasonic detection station in Swiss workshop

Existing internal defects in the rim can grow (under sufficiently high loads, RCF) generating a local collapse of the rim radial section similar to a wheel-flat or a breakage of a slice of the rolling surface material called shelling or deep shelling. Similar, but normally smaller, defects called spalling can origin from surface cracks growing a few millimeter in depth and having the effect of breaking off a piece of material. An increased toughness of the rim material may reduce the occurrence of RCF cracks.

The UT solutions to detect internal defects are mainly two: the so called “Tandem” probe that is able to detect defects that have a radial plane orientation and the “Double focalized probe” that is able to detect defects that have a circumferential plane orientation.

The Tandem probe is made of 2 angular probes placed at a fixed distance one from the other on the rim internal side; one probe works in transmitting mode and the second in receiving mode; a radial defect in the rim will make the ultrasonic wave reflect against the rim external side and then back to the receiving probe; the transmitting probe may work also as receiving mode as in Figure B2.

This inspection method can be used when the train is in a workshop and there is the possibility to stay under the train, normally the rim internal side will be free for applying the probes.

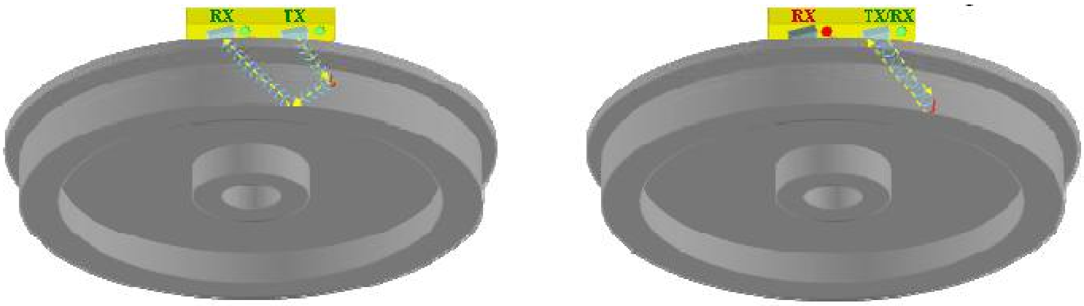

Figure B2: Correlation between out of roundness and material hardness

The double focalized probe inspects the rim from the rolling surface down to a depth of about 30 mm. Figure B3 shows how it works. In this case to inspect the whole rim it is necessary to be able to turn the wheel what may be difficult to perform if the wheelset is mounted under the train. This type of probe is more effective in detecting shelling defects before they become visible by an external crack or a detachment of material.

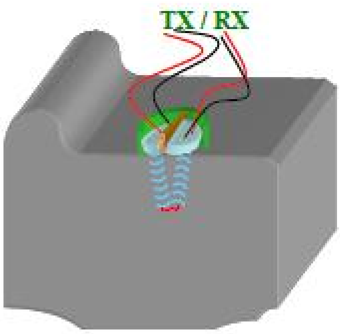

Figure B3: Double focalized probe, ultrasonic wave path scheme

ANNEX C: TECHNOLOGY ASSESSMENT

System Element	Failure Mode	Failure description	Effect on the interaction vehicle_track	Effect on the track	Effect on the vehicle	Effect on the environnement	GS	GA	F	Detection of failure	Mitigation
Wheelset lateral dimension	AR too big or tendency for augmenting AR in service	wheel displacement on the axle	-Derailment -Instability -Impact on ride comfort	-Damage of switches &crossings (S&C) -RCF on rails	-Instability -Forces elevated on axles and wheels	- Noise when instable vehicle run - Noise and vibrations in S&C	IV	3	R	Measurement in workshop	Improve wheelset maintenance in accordance to EN13260 and UIC 813
		Axial deformation of wheel plate	-Derailment in S&C -Instability -Impact on ride comfort	-Damage of S&C -RCF on rails	-Instability -Forces elevated on axles and wheels	Noise and vibrations in S&C	III	2	R	Measurement in workshop	-Improve wheel plate geometry in accordance to EN13979-1 -Avoid elevated thermal load
		Elevated conicity	-Instability	-RCF on rails	-Instability	Noise	III	2	R	Measurement in workshop	-Improve wheel plate geometry in accordance to EN13979-1 -Avoid elevated thermal load
	AR too small or tendency for reduction of AR in service	wheel displacement on the axle	-Derailment -Impact on ride comfort	-Damage of S&C	Forces elevated on axles and wheels	Noise and vibrations in S&C	IV	3	R	Measurement in workshop	Improve wheelset maintenance in accordance to EN13260 and UIC 813
		Axial deformation of wheel plate	-Derailment in S&C -Impact on ride comfort	-Damage of S&C	Forces elevated on axles and wheels	Noise and vibrations in S&C	III	2	R	Measurement in workshop	-Improve wheel plate geometry in accordance to EN13979-1 -Avoid elevated thermal load
	SR too big or tendency for augmenting SR in service	AR too big due to axial deformation of wheel plate	-Derailment in S&C -Instability -Impact on ride comfort	-Damage of S&C -RCF on rails	-Instability -Forces elevated on axles and wheels	Noise and vibrations in S&C	III	2	R	Measurement in workshop	-Improve wheel plate geometry in accordance to EN13979-1 -Avoid elevated thermal load
		Sd too thick	-Derailment in S&C -Instability -Impact on ride comfort	-Damage of S&C -RCF on rails	-Instability -Forces elevated on axles and wheels	Noise and vibrations in S&C	III	2	R	Measurement in workshop	Improve wheelset maintenance in accordance to EN15313 or utilize reduced wheel flange thickness according to EN 13715
		Elevated conicity	-Instability	-RCF on rails	-Instability	Noise	III	2	R	Measurement in workshop	-Improve wheel plate geometry in accordance to EN13979-1 -Avoid elevated thermal load
	SR too small or tendency for reduction of SR in service	Sd too small	-Derailment in small curves -Derailment in S&C	-Damage of S&C	Forces elevated on axles and wheels	Noise and vibrations in S&C	III	2	R	Measurement in workshop	-Improve wheelset maintenance in accordance (reprofiling philosophy) -Apply steering bogies -Improve fricion management

Wheel flange dimension	Wheel flange thickness Sd too big or tendency for augmenting Sd in service	Wear not equilibrated between flange and tread	-Derailment in S&C -Instability -Impact on ride comfort	-Damage of S&C -RCF on rails	-Instability -Forces elevated on axles and wheels	Noise and vibrations in S&C	III	2	R	Measurement in workshop	Improve wheelset maintenance in accordance to EN15313 or utilize reduced wheel flange thickness according to EN 13715
	Wheel flange thickness Sd too small or tendency for reducing Sd in service	Elevated wear on flange in curves	-Derailment in small curves -Derailment in S&C	-Damage of S&C	-Forces elevated on axles and wheels -Elevated costs for wheel maintenance	Noise and vibrations in S&C	III	2	R	Measurement in workshop	-Improve wheelset maintenance in accordance (reprofiling philosophy) -Apply steering bogies -Improve fricion management
	Wheel flange hight Sh too high or tendency for elevated Sh in service	Elevated wear on the tread due to wheel C25slippage	-Derailment in S&C	-Damage of S&C -Elevated rail wear	-Forces elevated on axles and pressfits -Elevated tread wear and as a consecquence elevated costs for wheeel maintenance	Noise and vibrations in S&C	III	2	R	Measurement in workshop	-Improve slippage protection on driving wheelsets -Improve fricion management
		Elevated wear on the tread due to creapage in curves	-Derailment in S&C	-Damage of S&C -Elevated rail wear	-Forces elevated on axles and pressfits -Elevated tread wear and as a consecquence elevated costs for wheeel maintenance	Noise and vibrations in S&C	III	2	R	Measurement in workshop	-Improve rail material -Improve wheel material -Improve fricion management -Apply steering wheelsets
		Elevated wear on the tread due brake shoe material	-Derailment in S&C	-Damage of S&C	-Forces elevated on axles and pressfits -Elevated tread wear	Noise and vibrations in S&C	III	3	R	Measurement in workshop	-Improve brake shoe material -
	Wheel flange angle elevatted qR to low	Elevated wear on flange in curves	-Derailment in switch blades	-Damage of switch blade	Derailment	_	III	3	R	Measurement in workshop	-Improve wheelset maintenance in accordance (reprofiling philosophy) -Apply steering bogies -Improve fricion management
		Elevated wear on flange due to elevated torque friction of the bogie	-Derailment in switch blades	-Damage of switch blade	Derailment	_	III	3	R	Measurement in workshop	Improve bogie maintenance
		Elevated wear on flange due to misalignment of the bogie	-Derailment in switch blades	-Damage of switch blade	Derailment	_	III	3	R	Measurement in workshop	Improve bogie maintenance

Wheel tread RCF	RCF in zone 1	Cracks in the field side of the tread due to the contact of wheel on inner rails in curves. These cracks are due to high level of tangential creepage forces.	If cracks are developped to spalling ==> vibrations and noise	Elevated vibrations and forces	Elevated vibrations and noise	Elevated vibrations and noise	III	3	R	-visual control in workshop -if cracks are elevated measurement on track in workshop	-Improve wheelset maintenance in accordance (reprofiling philosophy) -Apply steering bogies -Improve fricion management -Improve steel qaulity
	RCF in zone 2	Cracks on the flange side of the tread due to the contact of wheel on outer rail in curves. These cracks are due to high level of tangential creepage forces.	If cracks are developped to spalling ==> vibrations and noise	Elevated vibrations and forces	Elevated vibrations and noise	Elevated vibrations and noise	III	3	R	-visual control in workshop -if cracks are elevated measurement on track in workshop	-Improve wheelset maintenance in accordance (reprofiling philosophy) -Apply steering bogies -Improve fricion management -Improve steel qaulity
	RCF in zone 3	Crack between the flange side and the field side of the tread due to the contact of wheel/rail in straight lines or in curves with large curve radius. These cracks are due high levels of longitudinal creepage	If cracks are developped to spalling ==> vibrations and noise	Elevated vibrations and forces	Elevated vibrations and noise	Elevated vibrations and noise	III	3	R	-visual control in workshop -if cracks are elevated measurement on track in workshop	-Improve slippage protection on driving wheelsets -Improve steel quality
	RCF clusters	RCF clusters are appearing in localised plastic deformations from locally increased lateral creep forces. They also appear when the amplitudes of polygons are elevated.	vibrations and noise	-Elevated vibrations and forces -Damages on track to be investigated	-Elevated vibrations and noise -Damages on elements of non suspended part of the bogies	Elevated vibrations and noise	III	3	R	Measurement on track or in workshop	-Improve wheelset maintenance in accordance (reprofiling philosophy) -Apply steering bogies -Improve fricion management -Improve steel qaulity
Wheel tread OOR	Wheel flat	Wheel flats are caused following the blockage or partial blocking of a wheelset whilst the vehicle is still travelling at speed. As the wheel slides along the rail, the resulting friction then heats the wheel contact patch locally.	vibrations and noise	Vibrations	vibrations and noise	noise	II	1	EI	-Measurement on track or in workshop -visual control in workshop	-Improve sliding protection -Improve fricion management -Imrove detection methods
	Localised spreading	Localised spreading is originated by not removed wheel flats or material hardness deviations along the circumference of the wheel tread.	vibrations and noise	-Elevated vibrations and forces -Damages on track to be investigated	-Elevated vibrations and noise -Damages on elements of non suspended part of the bogies	Elevated vibrations and noise	III	3	R	-Measurement on track or in workshop -visual control in workshop	-Improve sliding protection -Improve steel qaulity -Improve detection methods
	Scattered wheels	Subsurface fatigue cracks are usually, but not exclusively, initiated form the presence of a foreign body, slag or a metallurgical inhomogenity within the wheel rim. Their amplitudes and extensions in the final stage (before collapsing) are comparable with those of localised spreading.	-Danger of derailment -vibrations and noise	-Danger of derailment -vibrations and noise -Damages on track to be investigated	-Danger of derailment -vibrations and noise -Damages on elements of non suspended part of the bogies	Elevated vibrations and noise	III	3	R	-Measurement on track or in workshop -visual control in workshop	-Improve steel qaulity -Improve detection methods
	Polygonisation	Pure periodic circularity defects with long wavelength (140mm to about 300 mm) and with high amplitudes (greater than 0.5 mm) are predominantly due to tangential creepage forces wheel/ rail in very small curves. However, they also have been observed at wheelsets with significant wheel diameter differences on the two wheels of the same wheelset. Periodic out of roundness with such characteristics are called polygons.	vibrations and noise	-Elevated vibrations and forces -Damages on track to be investigated	-Elevated vibrations and noise -Damages on elements of non suspended part of the bogies	Elevated vibrations and noise	III	3	EI	-Measurement on track or in workshop -visual control in workshop - Non destructive testing (Ultrasonic, etc.)	-Improve wheelset maintenance in accordance (reprofiling philosophy) -Apply steering bogies -Improve fricion management -Improve steel qaulity -Improve detection methods