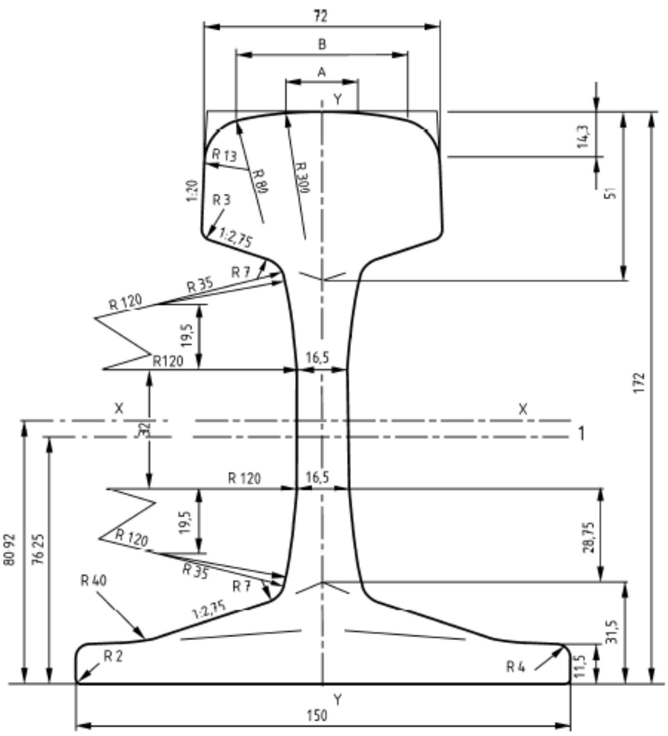
Integrated Project (IP)
Project No. TIP5-CT-2006-031415

Thematic Priority 6:
Sustainable Development,
Global Change and Ecosystems

Definitive guidelines on the use of different rail grades



INNOTRACK GUIDELINE

Deliverable report D4.1.5GL

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This guideline has been reviewed by eight different European railway experts.

Also for the interim guideline an extensive review process took place.

1. Executive Summary

The development of a Guideline for the selection of Rail Grades for different duty conditions is one of the important results of the INNOTRACK subproject SP4, which deals with questions concerning rails and welds.

In order to achieve the aim of the INNOTRACK project (reduction of total life cycle cost by 30%), the use of best performing performing rail steels with an improved durability and reduced needs for maintenance is regarded as being one of the key actions to be set. Based on results of a large number of different track tests and based on results of laboratory tests a recommendation was developed which defines the appropriate regions of application for different rail steels. Beside the traditional radii based rail grade selection recommendation also an innovative approach was elaborated, where the actual track degradation behavior defines the appropriate rail grade to be installed in future (Deterioration Based Rail Grade Selection).

Data from a wide range track trial sites evaluating a range of rail grades coupled with comparative laboratory simulation, testing, and assessment of microstructural deformation has clearly demonstrated that the use of heat treated rail grades (R350HT, R370CrHT and R400HT) is beneficial for curves with radii up to 3000m to counteract both main degradation mechanisms of wear and RCF. The life cycle cost benefits to be realized could be further extended to curves with radii up to 5000m for specific locations depending on local track and traffic characteristics.

2. Introduction

In order to be able to introduce innovations into a very complex system, such as a railway a courageous act is required to change things significantly while realizing that technical solutions may not be universally applicable and hence expectations will not be met for all possible situations. It is often forgotten that not changing the system could be more expensive if the beneficial innovations outweigh the mistakes that may be made along the way.

One of the reasons for the railway community's reluctance to change is the long pay back period for investments, which may only be profitable after many years. In addition, due to traditionally long lasting railway components, the advantages of new railway products (innovations) become visible only after a certain period of time in many cases. One area where high initial costs mean that possible life cycle savings are neglected is through the use of innovations that increase the use of planned maintenance as opposed to unplanned maintenance. Over the lifecycle of products, planned maintenance shows substantial benefits in terms of reducing compensation to operators along with better scheduling of resources, combined with the beneficial effect on passengers by increasing availability and safety, which would be lost by acting conservatively.

The current recommendations for the use of rail grades have developed historically. In recent years railways have been running new trains with heavier axle loads, at higher speed with different vehicle characteristics. New grades of harder (pearlitic) rail steels have also become available that have shown that their use on a wider basis reduces LCC of the track system.

This report is a guide to the selection of current rail grades in order to improve the system in a sustainable manner.

3. Rail Grades

The European standard EN13674-1:2008-01 is the comprehensive specification generally accepted by all major Infrastructure Managers for the supply of rail sections and rail steels. In the current version 7 pearlitic rail steels are covered which comprise all options: standard grade rail steels (naturally cooled), alloyed rail steels (naturally cooled) and heat treated rail steels.

In the recent past a preliminary standard (the prEN 13674-1:2009) has been worked out by the respective Technical Committee, which also includes two additional heat treated rail steels with increased levels of hardness: the R370CrHT and the R400HT. The inclusion of these two steel grades is in response to the need to increase resistance to both wear and rolling contact fatigue which have been demonstrated through track tests and laboratory evaluations. Like all others, these new rail steels are characterized by a defined chemical composition and material parameters such as tensile strength, elongation and hardness on the centre-line running surface.

Steel grade [a]		Hardness range (HBW)	Description	Branding lines
Steel name	Steel number			
R200	1.0521	200 to 240	Non-alloy (C-Mn) Non heat treated	No branding lines
R220	1.0524	220 to 260	Non-alloy (C-Mn) Non heat treated	————
R260	1.0623	260 to 300	Non-alloy (C-Mn) Non heat treated	—— ————
R260Mn	1.0624	260 to 300	Non-alloy (C-Mn) Non heat treated	———— ————
R320Cr	1.0915	320 to 360	Alloy (1 %Cr) Non heat treated	———— ———— ————
R350HT	1.0631	350 to 390 [b]	Non-alloy (C-Mn) Heat treated	—— ———— ————
R350LHT	1.0632	350 to 390 [b]	Non-alloy (C-Mn) Heat treated	—— ———— ———— ——
R370CrHT	t.b.a.	370 to 410	alloy (C-Mn) Heat treated	—— ———— ———— ————
R400HT	t.b.a.	400 to 440	Non-alloy (C-Mn) Heat treated	———— ———— ————

Figure 1: steel grades and branding lines acc. to prEN 13674-1:2009

In this guideline, all grades included in the prEN13674: 2009, are considered.

4. Rail Grade Selection

4.1. Behavior of different rail grades

Railways and rail manufacturers have collected large amounts of data on the in-service degradation of rail over the years together with the comparative assessment of key properties in selected laboratory scale tests. This has given invaluable information on the performance of different rail grades in service. The data has been collated in a database and reported in deliverable D4.1.1. Detailed analysis of this data has also been undertaken to derive algorithms to describe the degradation behaviour of rails as a function of track geometry, rail grade and loading conditions. An interim report on this analysis was given in deliverable D4.1.2 while a more comprehensive analysis is given in the final deliverable D4.1.4. It was shown that the influence of every track and traffic characteristic is extremely complex because of the wide range of variables that can affect rail degradation and not all variables were always recorded during the monitoring of the trial site.

Nevertheless general trends showing the relationship between curvature and rail degradation were apparent. Wear is dominant in curves with radii of less than 1000m while rolling contact fatigue[1] (RCF) occurs over a radius range of 500 to 5000m.

In general, pearlitic rail steels with higher hardness show a higher resistance to both wear and RCF. The improvement for the head hardened grade R350HT compared to standard grade R260 is about 3 times for wear and at least 2 times regarding RCF.

At locations where RCF occurs, the localised contact stresses within the rail head can be high compared to the ultimate tensile strength of the rail steels currently used. Thus it has to be considered that increasing the axle load and/or speed (a strategic aim for many European railways to increase their capacity) could not only result in more rapid initiation and growth of RCF in track segments already affected by RCF but also extend it to those segments that are currently RCF free, if the rail hardness and respectively strength remains unaltered.

[1] Rolling Contact Fatigue (RCF) covers all rail phenomena that appear on and in rails due to overstressing the rail material [8] and has become an increasingly widespread damage phenomenon on European tracks. Important exponents of the RCF-family are - beside others - head checking, spalling or squats (e.g.). As head checks represent the best investigated exponents of the RCF family, this document mostly deals with head checks, which then are generally called “RCF”.

4.1.1. Track behavior (INNOTRACK database)

The deliverable D4.1.1 ("Database for actual and new innovative rail/joints") describes the database which was compiled out of track tests performed by voestalpine and Corus together with European railways. Track tests are performed in order to evaluate the performance of different rail grades regarding RCF and wear. For rail suppliers, such a database will continue to provide extremely useful data to support further development of existing rail steels and the development of new rail grades. In addition, the database will assist the Infrastructure Managers by establishing rail grade selection criteria and the associated maintenance strategies. As also written in D4.1.1, Corus and voestalpine Schienen want to express their gratitude for an excellent cooperation over many years to the involved railways.

There are more than 200 different track sites covered by the INNOTRACK database, also the INNOTRACK track test in Wörgl (Austria) and those recently established in Network Rail (UK) are included. The analyses of the performance data can be summarized as follows:

- **Heat treated rails show an outstanding resistance against wear**
- **Heat treated rails show an excellent resistance against RCF at the same time**

The following two figures (examples out of the Innotrack track behavior database) demonstrate these coherencies, which as a matter of course do not represent new knowledge – see chapter 4.1.2. (Further details of the track test results are also available in Innotrack Deliverable D4.1.4)

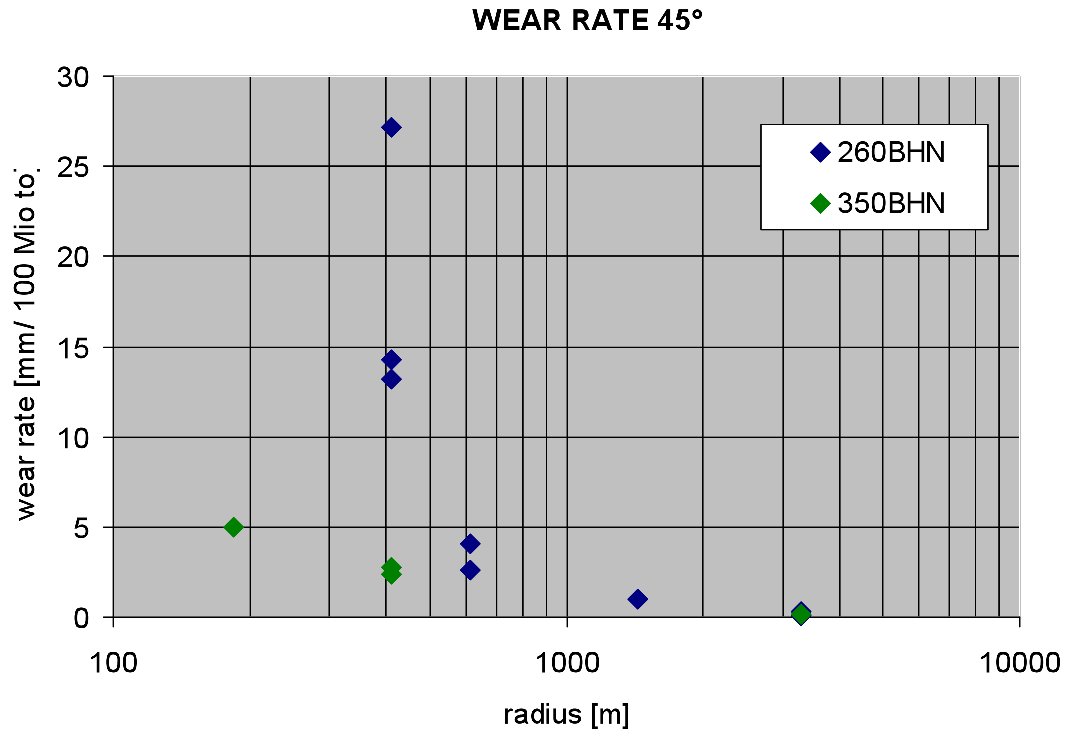


Figure 2: results of wear (45°) analyses – R260 vs. R350HT

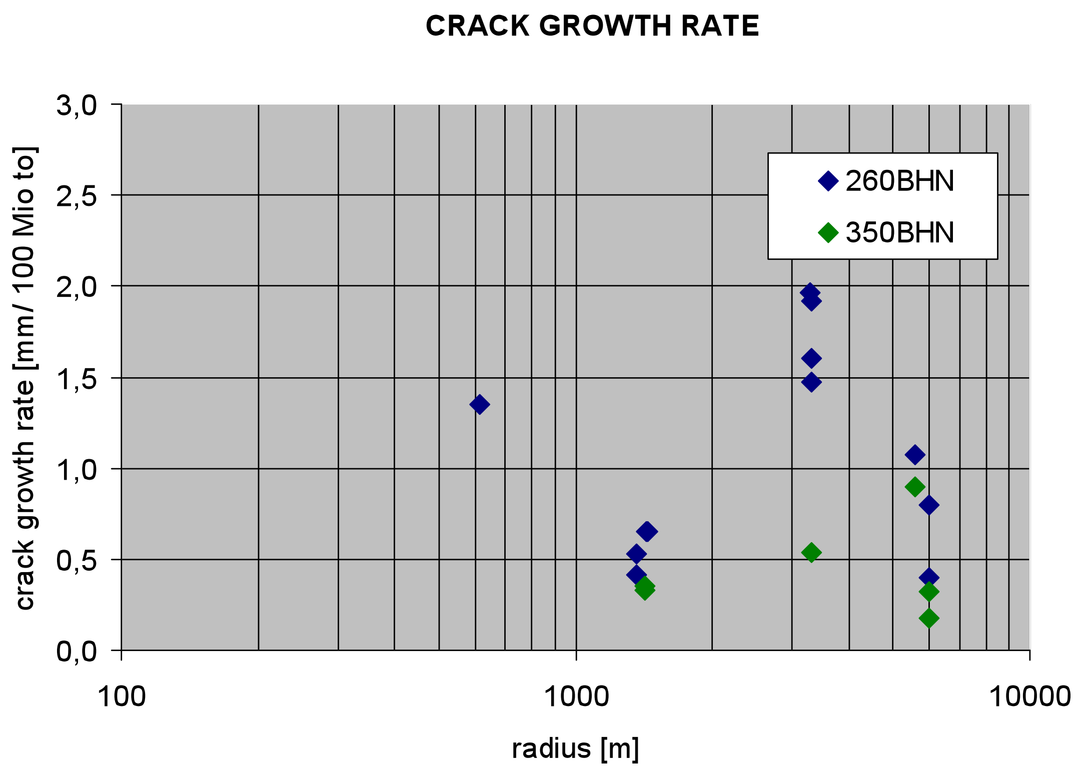


Figure 3: results of RCF analyses – R260 vs. R350HT (focused on wide curves)

The analyses of the INNOTRACK database show once again that the degradation mechanism "wear" is dominating in tight curves (radii up to about 700 to 1000m) and the mechanism "RCF" is generally prevalent in wide curves with radii between 500 and 5000m. (see figure 4)

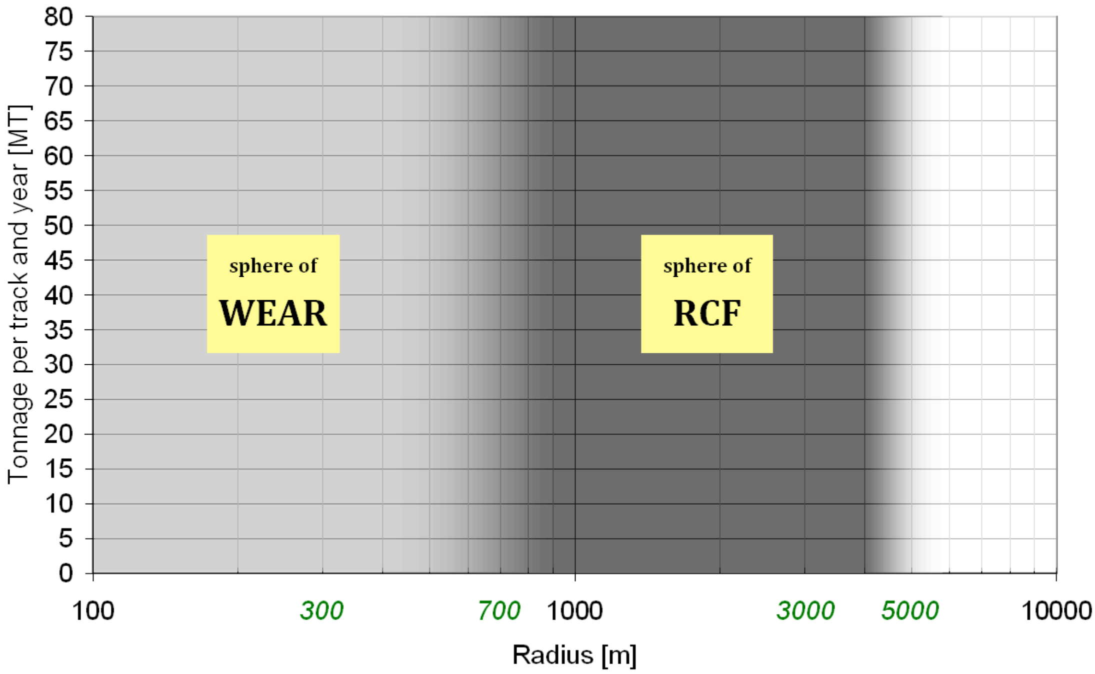


Figure 4: rail degradation mechanisms – radii

4.1.2. Track behaviour (general/literature)

The benefits of the use of harder rails in terms of their degradation behaviour is widely acknowledged and have been covered in many publications and consequently only a brief overview of the literature is given in this section.

A comprehensive study of the test results from an early FAST test (a test track at TTCI, Pueblo, Colorado, USA) is reported by Steele in 1982 [1]. Degradation due to wear and metal flow were improved by a factor of 3 by using alloyed and heat treated standard carbon rails and by a factor of 4 for heat treated alloyed rails compared to the standard carbon air cooled grades. Head check was not a topic of the study but in a second experiment it was stated that due to the reduction in wear by the use of lubrication rail fatigue became a major problem. The results also showed that the tonnage to failure decreased significantly when the nominal wheel load was increased.

Marich and Mutton [2] have shown decreasing wear rate by increasing rail hardness under conditions of moderate lubrication and more extensively lubricated rails. For example the standard carbon rail shows 2.5 times the wear rate of a head hardened rail with moderate lubrication and nearly 2 times the rate under more extensive lubrication. Understandably, the effect of lubrication in reducing wear is higher for the standard rail grade.

Similar results were reported by Muster [3] with slightly reduced benefit of a head hardened grade of hardness 370HB when compared with a standard R260 grade rail with 2 times the wear resistance without lubrication and 1.5 times with lubrication. In general, the hardened steel grade also showed a 30% reduction in the depth of RCF cracks. At one lubricated location the standard rail grade had to be removed due to severe spalling while the 370HB rail remained in track with Head Checks of a short length.

More recently Heyder and Girsch [4] reported on tests performed on high-speed tracks of DB where the main degradation mechanism is head checking. On grade UIC800 rails the depth of rail damage, due to head checks, was twice as much as for grade R260 and six times greater than for grade R350HT. The rails made of grade R350HT showed the lowest wear rate, which was about half of that for grade UIC900A (R260) and one-third compared to grade UIC800. It was also found that the wavelength and depth of corrugations could be reduced by the use of the harder rail grades. Similar results have been found on French mixed traffic lines where the harder heat treated rails were more resistant to both wear and RCF [5].

In general, the results of track tests and site monitoring of wear and rolling contact fatigue (head checks) that have been reported in the literature show broadly similar trends when the relative degradation behaviour of one rail steel grade is compared with a different one at specific test sites. However, in view of the complexities of rail-wheel interaction and differences in track and traffic characteristics, the absolute rate of degradation can vary from site to site. But there are different opinions regarding the influence of rail grades on discrete faults such as squats.

For example Deroche [6] observed that squat occurrence could be solved by changing the rail from grade UIC700 to UIC900 (R260), due to kinematic hardening to a level corresponding to the maximum applied shear stress by the driven wheels. On the other hand the replacement of present standard rails by head hardened ones has led to significant problems with squats at one site at SNCF recently.

As a general conclusion the results from historic track tests reported in the literature demonstrate that the use of high strength pearlitic rail steel grades reduces degradation due to wear and RCF crack growth compared to standard grades such as the R220, the R260 and the R320Cr. Regarding wear Coenraad Esveld summarizes in his book Modern Railway Track [7]: "*The head hardened steels exhibit a wear resistance of at least tree times larger than grade R260 and are superior to grade R320Cr by a factor about two."* Regarding RCF Magel et al. [8] summarize in their paper "Control of rolling contact fatigue of rails" as follows*: "Install harder (…) rail steels since they are more resistant to both initiation and propagation of crack that contribute to RCF (…)."*

The consequence for the railways is that less maintenance would be required and the total lifetime of the rails would increase.

4.1.3. Laboratory tests (INNOTRACK – WP 4.3)

Within the INNOTRACK project laboratory tests were performed at the facilities of DB, voestalpine and University of Newcastle.

For the tests at DB and voestalpine (Figure 5), full scale rail-wheel test rigs were employed while those at the University of Newcastle used a well established smaller scale (1:20) twin-disk test facility. Full scale testing is executed in order to approximate reality also in terms of boundary conditions while small scale testing is performed concentrating on the damage mechanism alone.

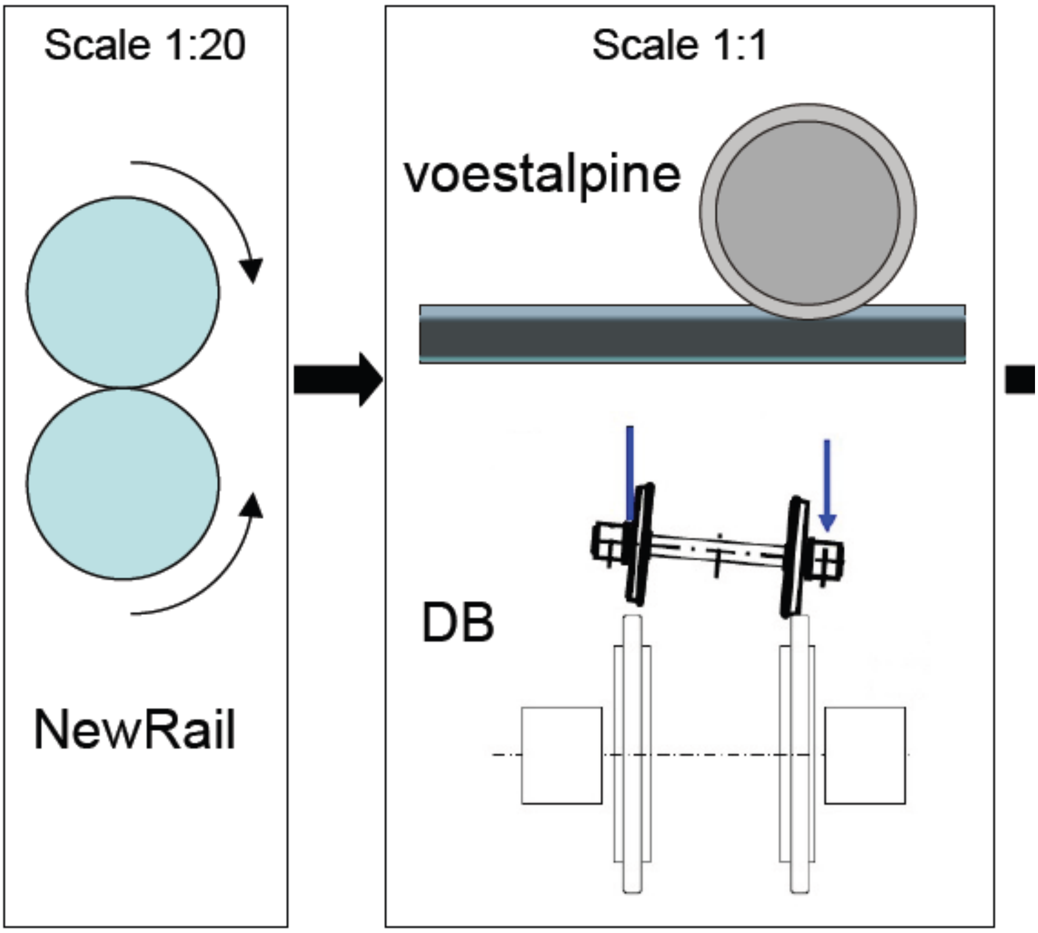


Figure 5: different types of laboratory tests (small scale and full scale)

Details concerning the results of the lab tests are presented within all deliverables of WP4.3. Although laboratory tests are not able to mirror the reality in complete detail as there is a great variety of different parameters which cannot be reproduced in laboratories, in many cases the lab tests are able to give an indication on the rail-performance in track with good accordance to track test results. As an example the test rig of voestalpine clearly shows the same trends as seen in track: heat treated rail grades (R350HT, 400BHN grade) show an increased wear resistance and also RCF resistance compared to the standard rail grade R260.

4.1.4. Laboratory tests (general/literature)

This chapter gives a short review of the literature on laboratory tests performed in order to investigate the wear and RCF behaviour of rail steels. Although laboratory tests are not able to simulate precisely the conditions in track, the vast majority support the observations made in track.

Garnham and Beynon [9] performed rolling sliding twin disc tests on bainitic and pearlitic steels and emphasized the superior wear resistance of pearlitic steel grades compared with bainitic steels of similar hardness but lower carbon content. They recommended the development of a pearlitic rail steel with fine lamellar microstructure which should have a high wear resistance.

Clayton [10,11] showed by the use of Amsler twin disc testing that there was a decrease in the wear rate by a factor of approximately 3.5 for an increase in hardness of 50 HB for pearlitic steel grades, while bainitic grades show less dependence of wear rate on their hardness (the earlier work was restricted to bainitic steels with a lower range of hardness and the results could be interpreted as an inverse dependence of wear with hardness). The applied slide/roll ratio was 35% and the maximum Hertzian contact pressures were varied from 500 to 1220 MPa. Experiments were also carried out on rolling contact fatigue (RCF) as well with a slide/roll ratio of 10% and contact pressures from 750 to 1450 MPa. The RCF resistance is approximately doubled for an increase in hardness of 50 HB. Clayton also found that microstructures consisting of carbide-free bainite mixed with lath martensite could have improved wear resistance over fully pearlitic rail steel, while other bainitic microstructures often show an inferior wear resistance.

In contrast to these results are those by Herbst *et al*. [12] who performed twin disc tests with 3% slip and 1250 MPa contact pressure. Three pearlitic rail steels have been tested in combination with two pearlitic and one bainitic wheel steels. Only in combination with the softest wheel grade was the expected lower wear rate realized for a head hardened grade, with 390HB, compared to a standard grade R260 (with 290 HB). In contact with harder wheel steels and a bainitic grade the wear increases. This is contradictory to field tests and the authors stated this could only be explained by the conditions chosen in the test. This experience fits to Garnham and Beynon's work [9] who state that the material ranking with respect to wear resistance depends on the test conditions. Considerable difference between the wear of bainitic steels at different slip ratios were observed with a change in the wear mechanism at high slip ratios being the likely cause.

Cyclic non proportional and proportional testing of grade R260, hardened rail grade R350HT and additional non commercial steel grades have been performed by Stadlbauer [13] and Tapp [14]. The results show that the high strength steels bear load levels over several hundreds of cycles while the standard grade fails after the initial cycles. Further on it was observed that on lower applied loads the number of cycles to failure for the hardened grade is almost one order of magnitude higher than for the standard grade. The other tested grades behaved similarly regarding their ranking of hardness versus load resistance. The resulting microstructure in the severe sheared area showed similar characteristics to the deformed surface layers of used rails. A bainitic grade and an annealed steel sustained still higher load levels but showed a tendency for cyclic softening. The cyclic softening of such high strength steels is assumed to be uncritical for rail application since plastic deformation would only occur in a layer of 0.1 mm resulting in wear by initiation and spalling of shot fatigue cracks at the surface.

The results of wear and RCF initiation tests undertaken by Corus and closely controlled twin disk tests involving a range of pearlitic rail steels is shown in the Figures below. They clearly show an increased resistance to both wear and RCF initiation with increasing hardness of the rail.

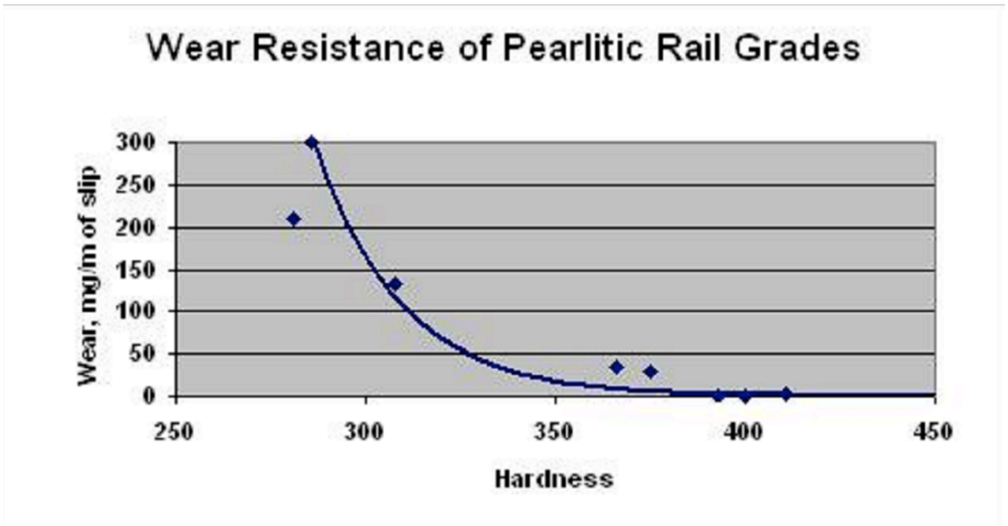


Figure 6: wear resistance of different rail grades

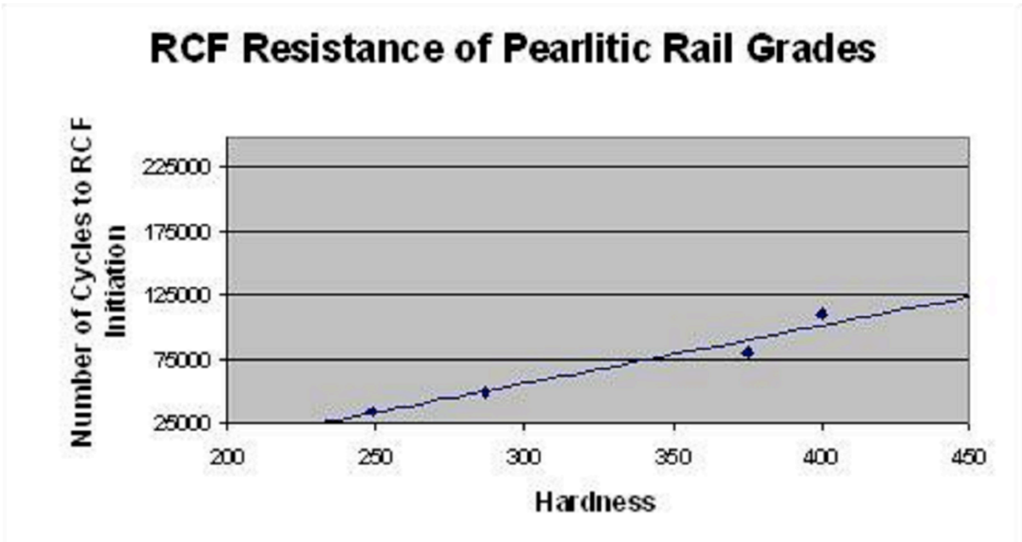


Figure 7: RCF resistance of different rail grades

These results strongly support the superior resistance of hardened pearlitic rail grades against RCF crack growth compared to the standard pearlitic grades.

4.2. Track parameters

The performance of rails depends to a great extent on the parameters, which characterise the actual conditions in the respective track. Since several parameters are together influencing rail-wheel contact conditions, the precise influence of every single parameter on the deterioration behaviour cannot be assessed separately.

The UIC leaflet 721 lists the following parameters, which (may) influence the development of wear and rolling contact fatigue significantly. Basically these parameters can normally be split into three different groups: *track* related, *traffic* related and *maintenance* related parameters. As an example of a “free” parameter, the “cant deficiency” represents a parameter, which cannot be assigned clearly to any of these three groups. Therefore the “cant deficiency” is not listed below, but the radius, the cant and the speed, which finally lead to the “cant deficiency”.

- Curve Radius

  The curve radius is one of the most important parameters. This characteristic value of the track therefore mainly provides the basis for every evaluation concerning track degradation.

- Cant

  The cant in combination with the curve radius and the speed of the vehicles leads to another important parameter, the “Cant deficiency”.

- Gradients

  The gradient of the line has an influence on the wheel-slip processes at the contact patch as well as on lateral forces in tight curves.

- Accumulated tonnage

  The total gross tons of a track primarily give an indication concerning the durability of rails (in terms of life time in years), which has a strong input on the economic evaluation of the track.

- Driving dynamics

  Traction and braking efforts of trains (stations, signals etc.)

- Axle loads

  The axle loads, respectively the distribution of axle loads, is directly associated with the damage behaviour of rails.

- Speed

  As written before the speed is important input information when used for the calculation of the cant deficiency.

- Type of rolling stock

  The characteristics of the rolling stock strongly influence the forces between vehicle and track and therefore also the degradation of the entire track including rails. Beside the type of rolling stock also its maintenance respectively its condition plays an important role.

- Lubrication

  Lubrication has been identified as being an appropriate action in order to reduce the wear of the rail. It is pointed out that lubrication alone does not provide a solution and does not represent an alternative to the installation of higher grade rails.

- Friction Management

  Friction modifiers are materials that increase or decrease friction between two surfaces so as to attain a specific friction level. Thus they are able to set up a fixed friction coefficient, which leads to a homogenisation of the transversal forces. Friction Management is a specific application of lubrication (rail gauge corner) and friction modifiers (top of rail) in a track network in order to reduce wear (rail and wheel) and rail damage (RCF), but it does not represent an alternative to the installation of higher grade rails.

- Grinding

  Rail grinding is executed in order to increase the quality of the running surface as well as in order to remove small defects which may develop and cause severe problems in the future. A well defined grinding strategy is a key action concerning an elongation of the service-life of rails for both standard grade rails and heat treated rail grades. As above, also grinding does not represent an alternative to the installation of higher strength rail grades.

4.3. Actual use of different rail grades

4.3.1. UIC leaflet 721

The UIC leaflet 721 provides the basis for the rail grade selection as do the national guidelines of different European railway administrations. The UIC recommendation is based mainly on the degradation mechanism "wear" and covers therefore radii up to 700m, beyond which the use of standard grade rail is recommended.

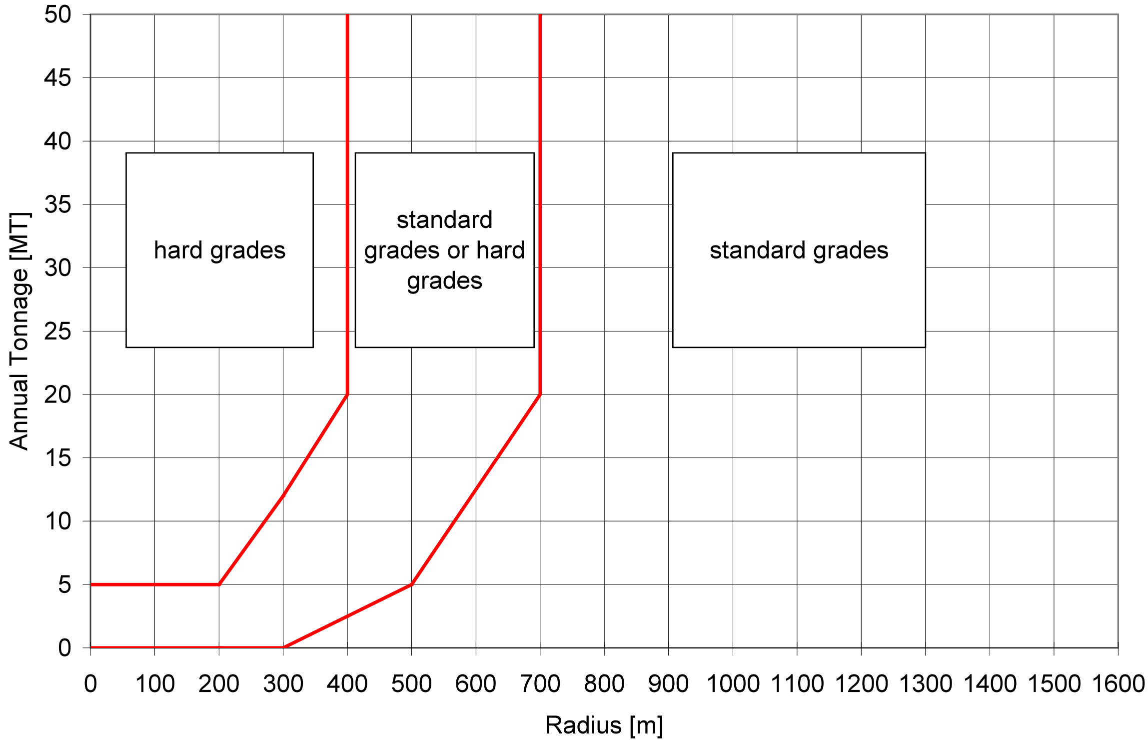


Figure 8: Recommendation for the use of standard and hard steel grades according to UIC Leaflet 721

The steel grades mentioned in the leaflet are the grades R260 and R260Mn ("standard grades") and the grades R320Cr, R350HT and R350LHT ("hard grades" – listed in ascending wear resistance).

4.3.2. National guidelines

The areas of application of different rail grades are defined in national and/or internal guidelines, which have to be observed by the different European railway administrations. These guidelines provide the basis ("reference case") for the evaluation of the benefits which can be achieved by introducing heat treated rail grades. The economical benefits were calculated within SP6 (LCC) of Innotrack, details of which are included in the deliverables of SP6.

Table 1 presents an overview over these guidelines.

Radius [m]	≤ 300	≤ 400	≤ 500	≤ 600	≤ 700	≤ 800	≤ 1500	≤ 3000	> 3000
UIC	R350HT		R350HT/R260			R260			
DB	R350HT (≥ 30.000 t/d)					R260			
DB new	R350HT (≥ 50.000 t/d)							R260	
CH	R350LHT		R350LHT/R320Cr			R320Cr R350LHT	R260		
CH (proposal)	R370CrHT		R350LHT		Bainite up to 1200 m			R260	
AT	R350HT	R260							
SWE	R350HT	R260							
SWE (HH)	R350HT								R260
NOR	R350HT					R260			
UK	R260								
IT	R260								
BE LUX	R350HT					R260			
NL	R350HT R370CrHT	R370CrHT					R370CrHT		R260
DK	R350HT					R260			
PL	R350HT					R260			
H	R350HT					R260			
RO	R350HT					R260			

Table 1: Summary of present national guidelines for rail grade selection on mixed traffic lines with up to 22.5t axle load and at least 20 MGT annual load

Based on the known duty conditions and the operating degradation mechanisms, there is a wide variety of locations where the use of premium grade rails offers significant LCC advantages – tight and medium curves where wear is predominating as well as medium and wide curves where RCF represents the primary degradation mechanism. Nevertheless most Railways install (*in several cases:* used to install) these higher grade rails (only) in curves up to 700 m radius to utilize the superior wear resistance of heat treated rails. Based on track tests all over Europe, which have also demonstrated the greater RCF resistance offered by heat treated rails, several railway administrations are currently changing their rail grade strategy such as DB does. At the end of the day this gives even more economic benefits to the Infrastructure Managers as was demonstrated within the Innotrack SP6 subproject also for curves up to 5000m. This report presents the Guidelines for the selection of rail grades based on this economic analysis and the rail degradation algorithms reported in deliverable D4.1.4.

4.4. Recommended rail grade selection

4.4.1. Preface

The future high performance railway track will have to show an enhanced long-term performance as it will have to meet increased operational demands both in terms of imposed stresses and traffic density. Consequently, a better durability and reduced non-availability are strong future needs for performing a high quality railway operation.

Advances in the understanding of vehicle-track interaction and contact mechanics has and will continue to contribute to improved vehicle design and the management of rail and wheel profiles to minimise contact stresses. However, the role of rail metallurgy in increasing the tolerance of the track to the increasing demands is becoming increasingly apparent and acknowledged. Therefore the use of an appropriate rail grade is a key action for the purpose of matching the future demands.

As described before, premium heat treated rail grades are able to extraordinarily counteract the two main rail degradation mechanisms such as wear on the one hand and rolling contact fatigue on the other hand, which definitely influence the service life of standard steel grade rails to a great extent. In order to tap the full potential of heat treated rail grades, some collateral activities have to be taken into consideration: a sophisticated lubrication (or friction) management and an appropriate grinding strategy.

Furthermore, a distinctive feature of European Railways is the mixed traffic operation in which the proportion of freight traffic is expected to increase. This will rapidly lead to a very significant increase in the loads imposed on the low rail of highly canted curves. Under such conditions, gross plastic deformation becomes the dominant mode of degradation, as shown in Figure 9 below.

Figure 9: gross plastic deformation of a low rail in highly canted curve

Rail degradation to put it simply, it can be looked on as a function of track radius. However, the reality is far more complex and a huge number of parameters have an influence on the total track behavior. Beside the axle loads also the cant deficiency (as a combination of speed, radius and superelevation) as well as the type of vehicle (construction of bogie, springs, dampers, unsprung masses etc.) have an appreciable influence on the degradation functions of railway rails. Therefore beside the *traditional rail grade selection,* which can be characterized as a choice based on the average yearly tonnage and the track radius, also a *deterioration based recommendation for the rail grade selection* will be presented within this deliverable. This condition based suggestion allows infrastructure managers to better match the attributes of the various steel grades available with the conditions in the specific track, which cannot be covered by the traditional radii based rail grade selection.

Nevertheless, since track radius is the main factor contributing to the rate of degradation, the traditional approach of rail grade selection based on track radii could be used to provide a broad guideline. However to facilitate transition to a degradation mechanism based choice, the correlation between track radius, tonnage carried, and vehicle traffic type has also been considered.

4.4.2. Radii based rail grade selection recommendation

The newly developed radii based rail grade selection follows experience based on track tests performed by the two premium rail suppliers voestalpine and Corus rail as well as on feedback forwarded by different European railway administrations.

The acknowledged lower rate of degradation of heat treated pearlitic rail grades has lead to the general recommendation for the use of heat treated rail grades in regions with radii below 5000m for heavily loaded tracks. For moderately loaded tracks and for those heavily loaded tracks that are not susceptible to RCF (indicated by the shaded area in the figure), heat treated rail grades are recommended for track radii up to 3000m. In the case of lightly loaded track, the use of standard grade rails is recommended for track radii >1000m with use extended to radii down to 700m if susceptibility to RCF or accelerated wear has not been observed (shaded area). These recommendations are summarised in the Figure 10 below.

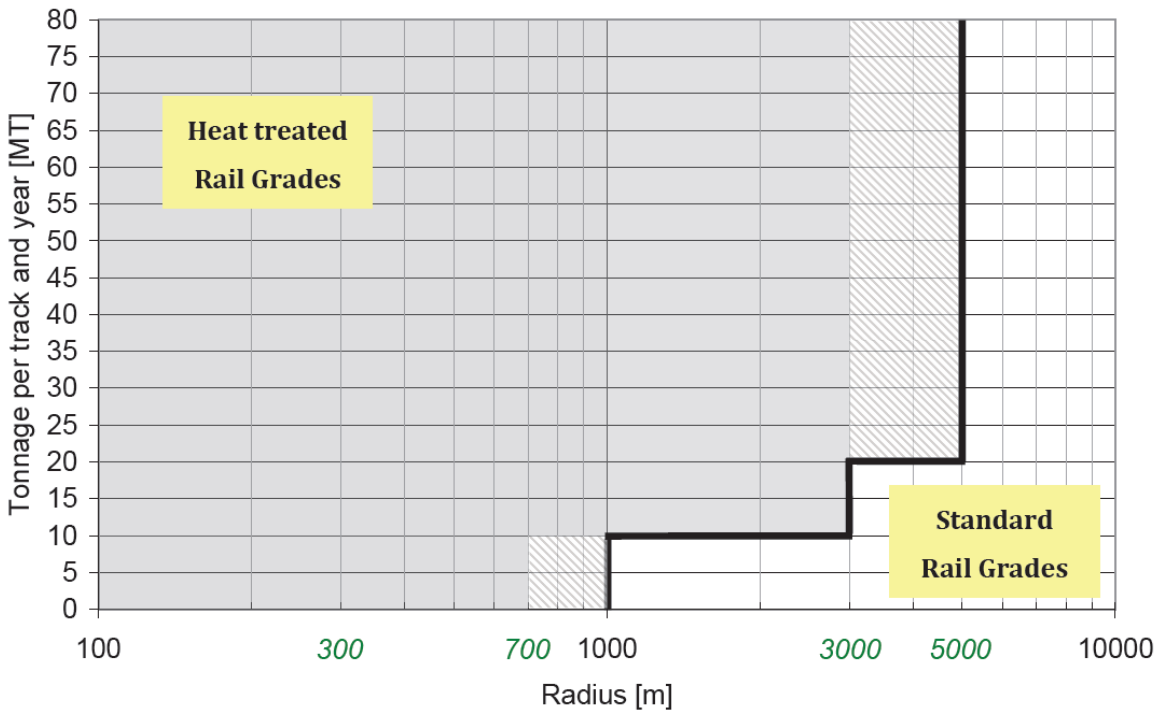


Figure 10: rail grade selection (overview)

In addition to the overview recommendation, a more detailed rail grade selection criteria is shown below that takes into account a wider range of rail steel grades included prEN 13674: 2007 (shaded areas again indicate overlaps). It should be noted that grades such as R370CrHT and R400HT have been on the market for several years (under different brand names but with very similar property specifications) and have proven their higher resistance to the key degradation mechanisms in several track tests.

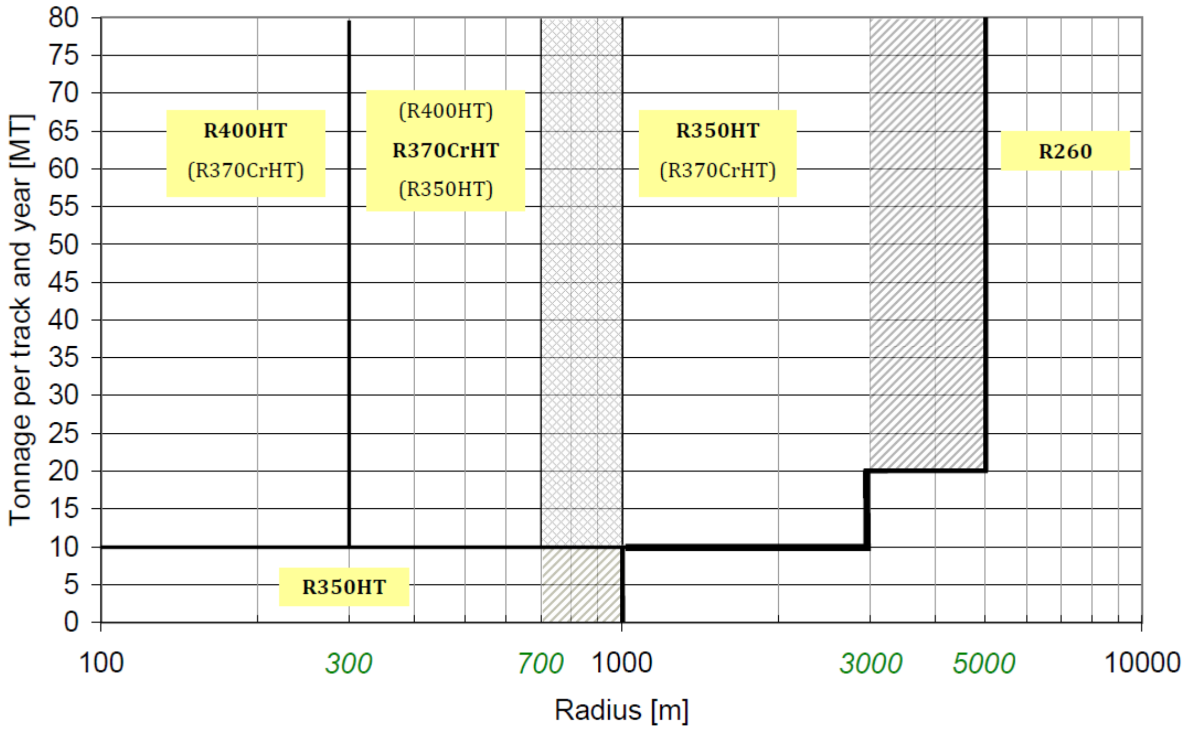


Figure 11: rail grade selection (detail)

The basic recommendation which is expected to maximise rail life at lower LCC is given in bold text. It should also be emphasized that the above recommendations are based on observed past performance of the available rail grades in the selected radii categories. However, in the future, the introduction of different vehicle types (or increased axle loads or speeds etc.) could alter the degradation mechanisms and hence the optimum choice of rail steel.

In summary, for heavily and moderately loaded tracks the suggested steel grades are:

- **For tight curves (R<300m) the R400HT grade**
- **For medium curves (300m<R<700m) the 370CrHT (for heavily loaded tracks also the grade R400HT) grade, followed by the R350HT steel grade with increasing radii (R>700m).**
- **In case of heavily loaded tracks the R350HT steel grade is also proposed in wide curves with radii between 3000m and 5000m. (Standard rail grades may represent the appropriate solution if RCF is negligible.)**

For lightly loaded tracks the proposal is as follows:

- **Use of the R350HT steel grade in curves with radii up to 700m to 1000m depending on the local boundary conditions.**

The key recommendations are also summarised in the Table below in which the current actual usage is used as a reference while the optimised selection is based on the work within Innotrack:

System			"reference"	"optimized"	*Remarks*
Description of the track elements, boundary conditions and track condition					
Track elements - Alignment					
curve	radius [m]	<300	R350HT	**R400HT** (R370CrHT)	Each individual rail grade (possible alternatives in brackets) and radius class of the optimised system can be interpreted as a separate alternative for LCC calculations.
		300 - 700	R260	(R400HT) **R370CrHT** (350HT)	
		700 - 1500	R260	**R350HT**	
		1500 - 5000	R260	**R350HT** (R260)	
		>5000 m	R260	R260	

Table 2: input table for LCC calculations

4.4.3. Deterioration based rail grade selection

The actual degradation behaviour of track and rails depends as mentioned on various different parameters, some of which are either not available or not recorded by the IMs. In other cases, although the parameters are identified, their interaction with other parameters and the resulting influence on the deterioration mechanisms is not fully understood or quantified.
In cases where operational experience is available, the behaviour of the respective rail steel under the specific boundary conditions is well known

even without knowing the actual contribution of each parameter. The traditional radii based rail grade selection recommendation however provides only a limited opportunity to implement this high quality information into the decision making process for the selection of the steel grade. For this reason a deterioration based criterion for optimised rail grade selection is also presented within this deliverable.

The rail degradation mechanisms generally comprise wear and rolling contact fatigue. The magnitude of the effect of the degradation mechanism wear generally reduces with increasing track radius but susceptibility to RCF cracks can be present in track radii up to 5000m. In mixed traffic railways, gross plastic deformation can also become a dominant cause of premature replacement of low rails in highly canted curves. Furthermore, corrugation can be a rail life determining parameter in many tracks including those with very wide radii. The degradation mechanisms always act together, nevertheless there is always or at least in most cases one degradation mechanism that is dominant and represents the limiting factor concerning the durability of the rail. The deterioration based rail grade selection proposed here takes into consideration both main mechanisms (wear and RCF) within one recommendation chart.

Harder steel grades also offer resistance to corrugation growth and gross plastic deformation. Hence their use is recommended in track segments where these degradation mechanisms are deemed to be the predominant mode.

As mentioned before the starting point for the rail grade selection is the rail degradation behavior of the currently installed steel grade. Depending on the actual severity of wear and/or RCF a rail grade selection recommendation is given. The guideline always gives the appropriate steel grade which is the steel grade referring to the dominating rail degradation mechanism. It is pointed to the fact that the deterioration based rail grade selection does not depend on a respective radius nor on a certain traffic situation as it is only based on the actual rail degradation behavior of an installed rail.
By choosing a rail steel with an improved hardness, the rate of damage can be significantly reduced. Thus replacement of R260 grade rail steel with a R350HT grade can lead to very significant improvements – wear can be reduced by a factor of between 3 and 5 while the RCF resistance is increased by a factor of between 2 and 5.

actual installed rail steel **R260**	**DETERIORATION BASED RAIL GRADE SELECTION**			
WEAR (45° wear rates on high rail - calculated out of the absolute wear measured in track)				
SEVERE >15 mm / 100MT	R400HT	R400HT	R400HT	R400HT
HEAVY ≤15 mm / 100MT	R370CrHT	R370CrHT	R400HT	R400HT
MODERATE ≤5.0 mm / 100MT	R350HT	R350HT	R370CrHT	R400HT
LIGHT ≤2.0 mm / 100MT	R260	R350HT	R370CrHT	R370CrHT
	LIGHT ≤0.5 mm / 100MT	**MODERATE** ≤1.0 mm / 100MT	**HEAVY** ≤3.0 mm / 100MT	**SEVERE** >3.0 mm / 100MT
	ROLLING CONTACT FATIGUE (Head Check crack depth rate - calculated out of measured crack depths detected in track)			

The rail deterioration behavior of the actual installed rail steel defines the appropriate choice of a rail grade to be inserted within the next track relaying action in order to achieve an optimum rail degradation behavior. In case of dominating wear (curves) the use of the recommended rail grade is suggested for both high rail and low rail (plastic deformation).

figure 12: deterioration based rail grade selection (currently installed grade: R260)

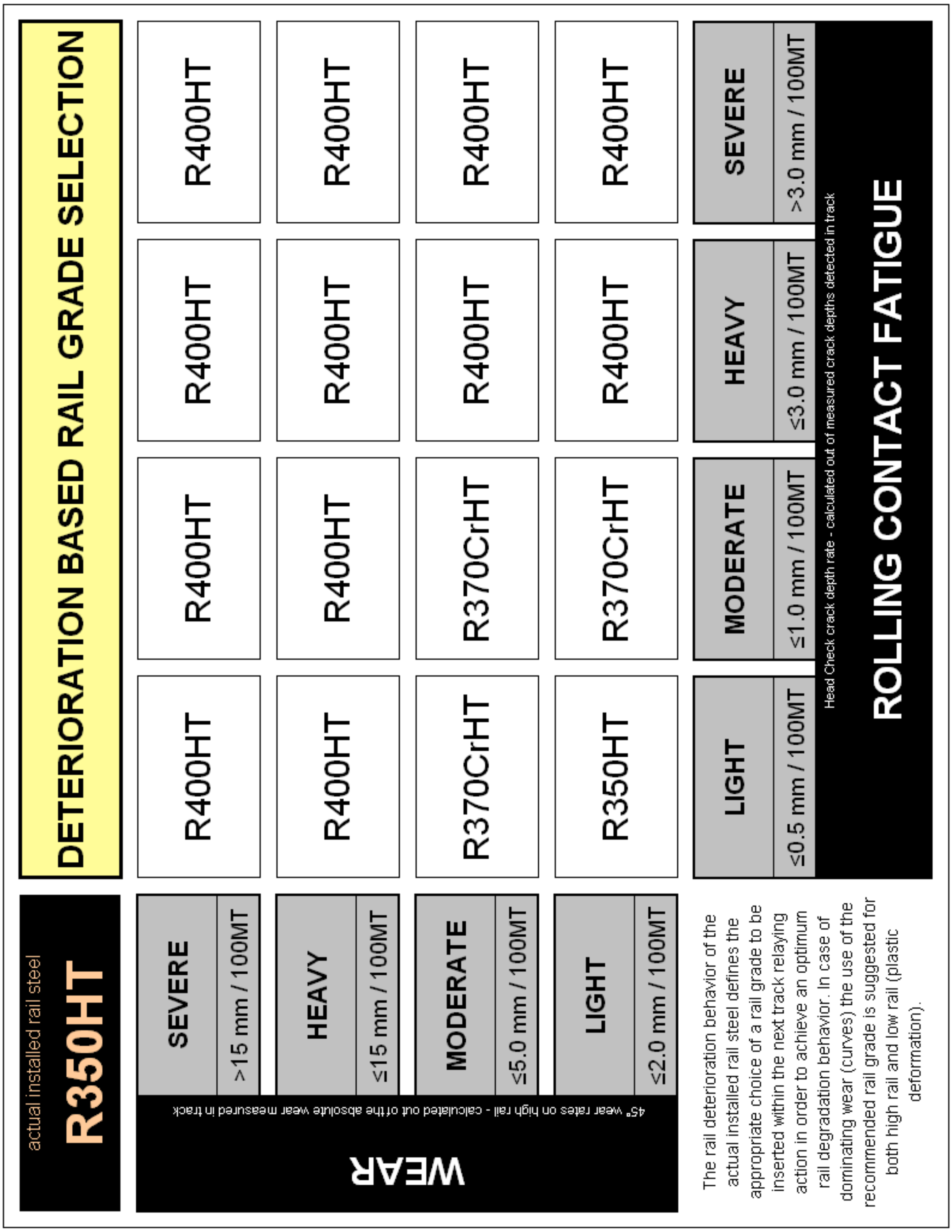


figure 13: deterioration based rail grade selection (currently installed grade: R350HT)

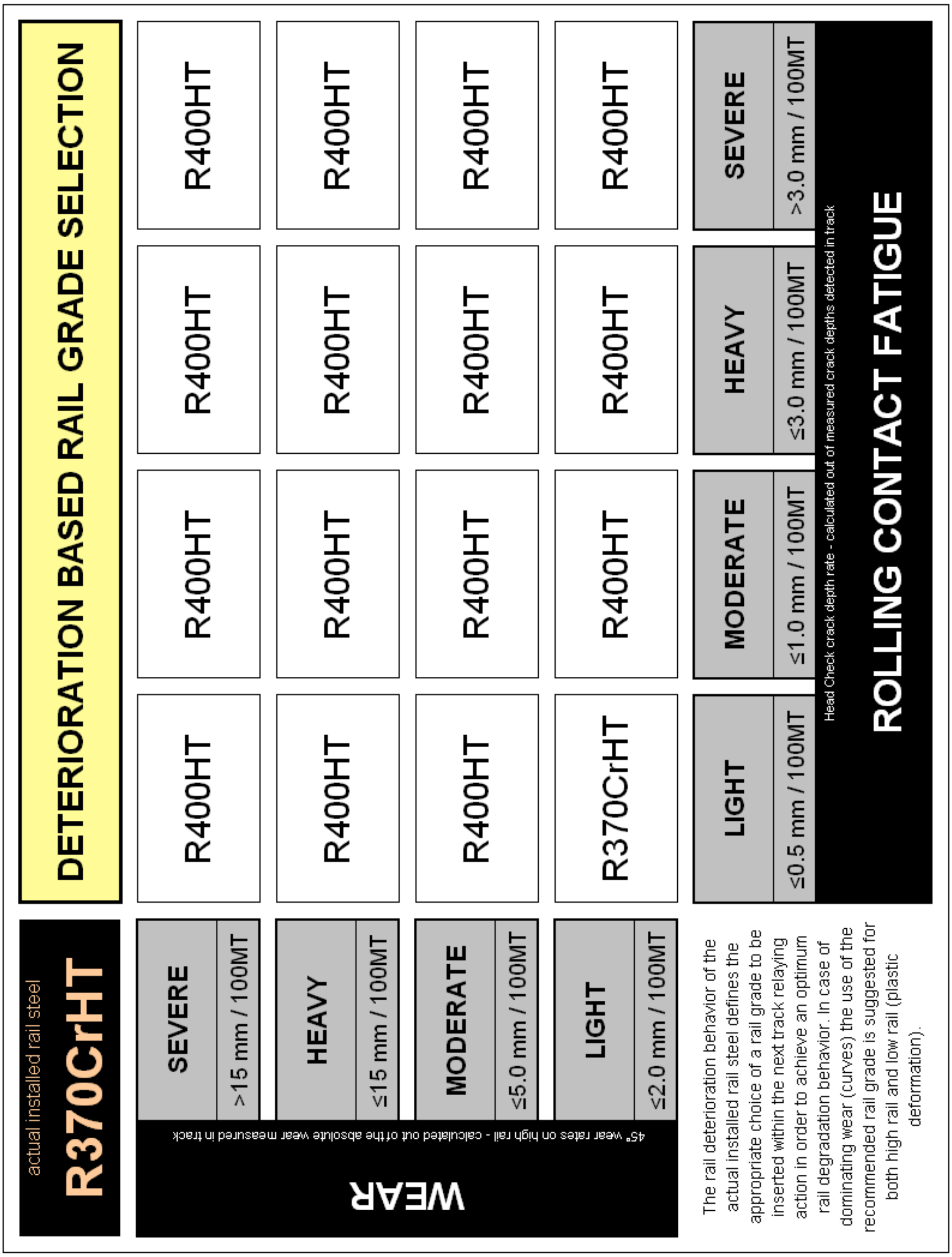


figure 14: deterioration based rail grade selection (currently installed grade: R370CrHT)

Below an example is given:

For a defined section of a track a relaying action is planned. The section also comprises a curve, where a R260 grade rail is installed. This curve shows both rail degradation mechanisms such as wear and RCF. Measurements have shown that this curve can be characterized by a 45°wear rate of roughly 8mm every 100 million gross tons and a crack growth rate of approximately 0,8 mm every 100 million gross tons.
Based on this information the appropriate steel grade for this curve (to be installed within the track relaying action) has to be determined as follows:

❶ Choice of the appropriate recommendation chart

➔ **R260**

❷ Classification of the measured wear-rate

➔ **“heavy”**

❸ Classification of the measured crack growth rate

➔ **“moderate”**

❹ Determination of the appropriate steel grade for this section

➔ **R370CrHT**

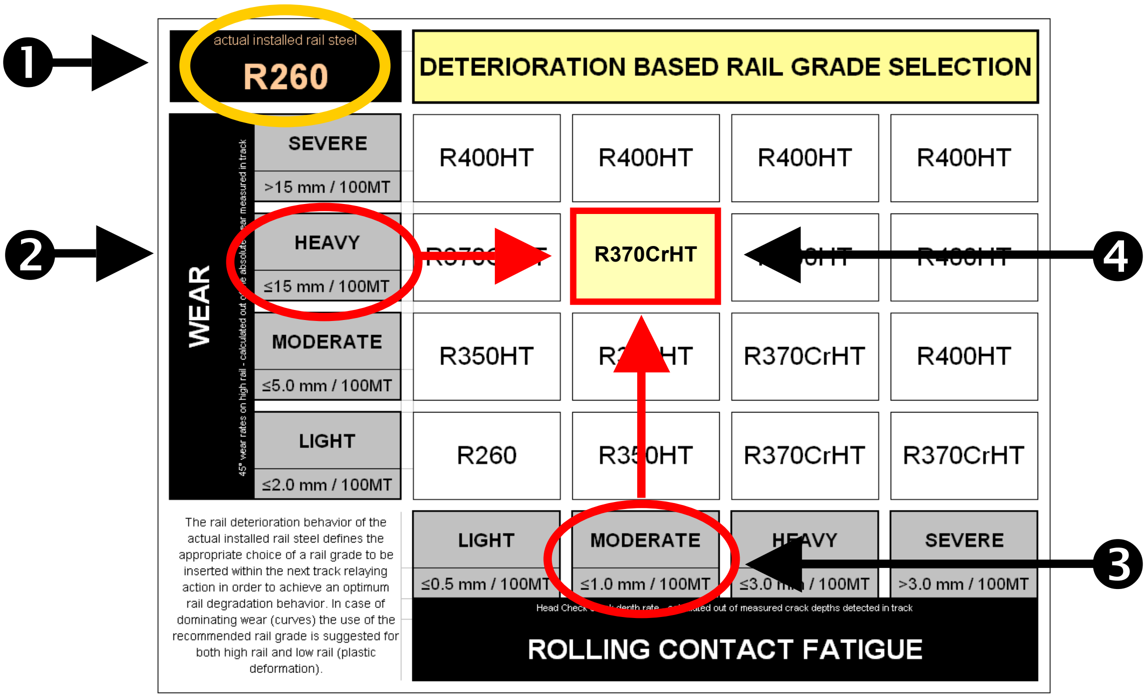


figure 15: deterioration based rail grade selection (actual grade: R260)

The classification of deterioration severities is based on the findings of the rail degradation investigations executed within the Innotrack SP4 subproject (WP4.1) and was defined as follows:

WEAR (45° wear)

"light"	**< 2.0 mm** per 100 million gross tons
"medium"	**≤ 5.0 mm** per 100 million gross tons
"heavy"	**≤ 15 mm** per 100 million gross tons
"severe"	**> 15 mm** per 100 million gross tons

The 45° wear rate represents a very important factor concerning the limitation of the lifespan of rails and was therefore chosen for the degradation based rail grade selection.

As an example a wear rate of 10mm/100MT (classified as "medium") in combination with a 45° wear limit of 10 mm and 50 million cumulated gross tons per year lead to a lifespan of 2 years while a rail grade with an increased wear resistance and a resulting wear rate of 1.9 mm/100 million gross tons leads to a durability of 10.5 years under the same operational and boundary conditions.

RCF (based on measured crack depths)

"light"	**< 0.5 mm** per 100 million gross tons
"medium"	**≤ 1.0 mm** per 100 million gross tons
"heavy"	**≤ 3.0 mm** per 100 million gross tons
"severe"	**> 3.0 mm** per 100 million gross tons

Also the head check crack depth (see figure 16) rates influence the service life of rails to a great extent. These crack depth rates are based on in-track measurements and therefore represent the theoretical growth of the fissures reduced by natural wear due to train operation.

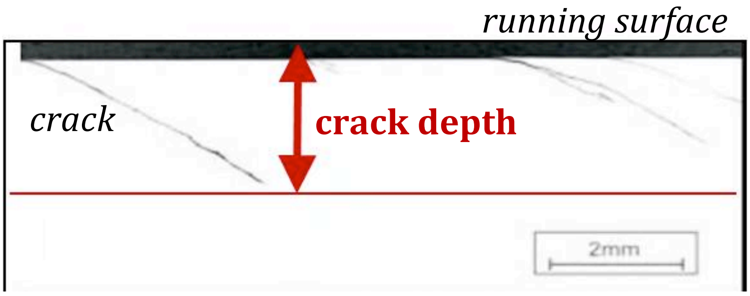


figure 16: crack depth of head checks

As an example a crack growth rate of 2.0 mm / 100MT (classified as "heavy" - removed by grinding) in combination with a natural wear of 0.15 mm/100MT leads to a material loss of 2.15mm/100MT. Taking into consideration 10mm being the maximum vertical wear and a yearly traffic of cumulated 50 million gross tons, this leads to a total lifespan of the rail of approximately 9 years while a higher grade rail with a crack growth rate of 0.4mm/100MT will show a service life of approximately 36 years.

On the next page an example is given of how the service life of rails (life time of the rails in track) is affected by these wear rates and crack growth rates. Based on a certain limit value concerning material loss provoked by both natural and artificial wear the service life of rails is calculated[2] and given in terms of cumulated total gross tons and years (then based on a certain annual load).

It can clearly be noticed, that the change-over from "medium" wear to "light" wear will possibly lead to a lifetime that is increased to 11 to 40 years. This will be achieved by choosing the appropriate steel grade following the condition based rail grade recommendation presented before. In some cases the lifetime of the rails is elongated to such an extent that the wear limit of the rails does not represent the limiting factor concerning the service life of the rails any longer and other limiting factors come into operation. In this context it has to be pointed to the fact that the lifetime of a 60kg rail can reach more than 2 billion cumulated gross tons (heavy haul experience) in case of good track quality over the whole lifetime only.

[2] Please note that the life time is calculated separately for both wear and RCF. Certainly these two mechanisms always act together and this has to be kept in mind when the results are assessed.

WEAR	classification		example	service life*			
				MGT	years in track		
	verbal	wear rates			10 MGT/year	20 MGT/year	30 MGT/year
	[-]	[mm/100MGT]	[mm/100MGT]	[MGT]	[years]	[years]	[years]
	"light"	0 - 2	1	800	80	40	27
	"medium"	2 - 5	3.5	225	23	11	8
	"heavy"	5 - 15	10	75	8	4	3
	"severe"	>15	15	50	5	3	2

*values based on wear (natural and artificial) being limited to 8mm

Table 2: service life of rails under different boundary conditions (wear)

RCF	classification		example	service life*			
				MGT	years in track		
	verbal	crack growth rates			10 MGT/year	20 MGT/year	30 MGT/year
	[-]	[mm/100MGT]	[mm/100MGT]	[MGT]	[years]	[years]	[years]
	"light"	0 - 0.5	0.25	>2.500	>100	>100	>100
	"medium"	0.5 - 1	0.75	1.075	>100	53	36
	"heavy"	1 - 3	2	400	40	20	13
	"severe"	>3	3	275	27	13	9

*values based on wear (natural and artificial) being limited to 8mm

Table 3: service life of rails under different boundary conditions (RCF)

There is a big scatter of wear and crack growth rates in track (see deliverable D4.1.4) which results in the fact, that an overall assessment of service lives of rails cannot be made. Nevertheless the two tables are deemed to be a good visualization of the benefits of reduced wear and crack growth rates in terms of elongated service life of the rails in track.

An additional example concerning the condition based rail grade selection is presented in figure 17. Based on the classified 45° wear rates the results of choosing a higher grade rails concerning rail degradation are presented. Following the arrows it can be clearly demonstrated that in case of an actual “moderate” wear of an installed R260 rail, its replacement by an R350HT rail would generate a big advantage concerning wear resistance and lead to a rail degradation that can be assessed as being “light”. As a consequence a big advantage regarding rail durability can be generated as well, which leads to significantly reduced life-cycle costs.

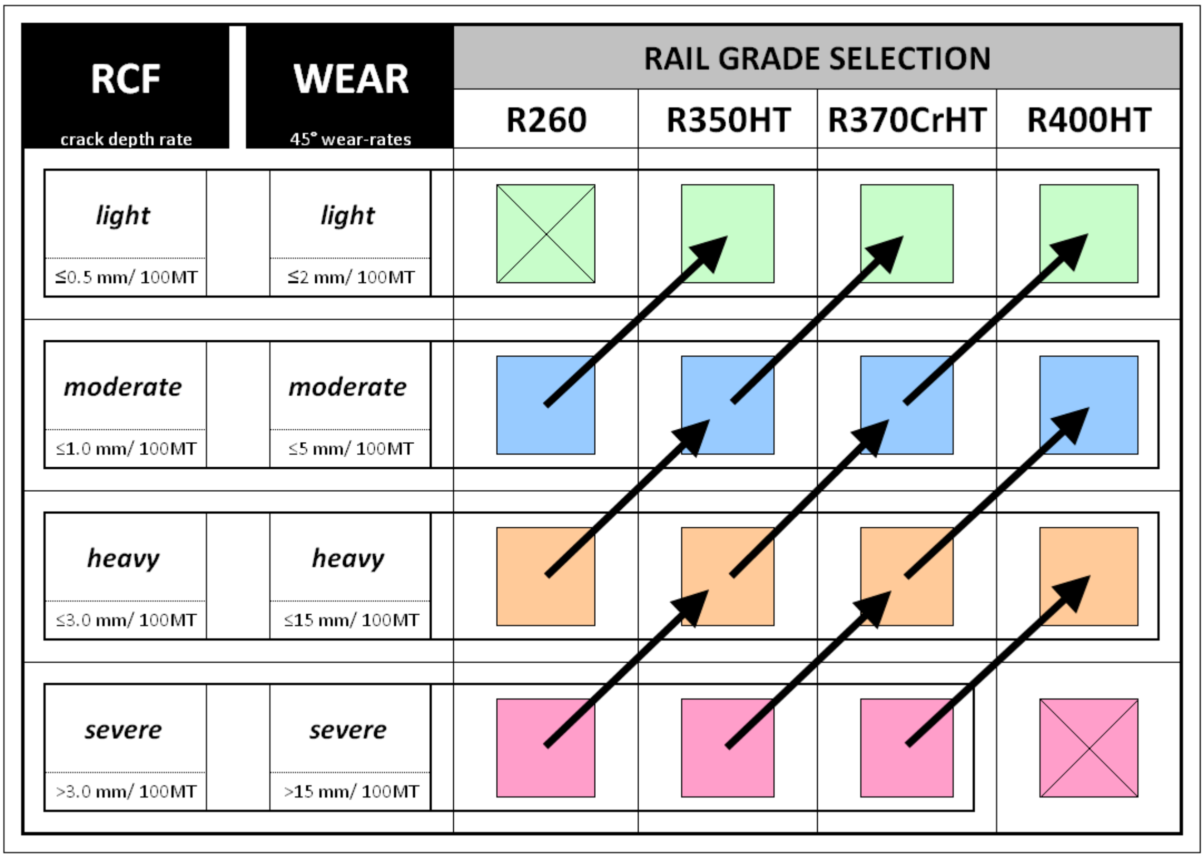


figure 17: rail degradation behavior of different steel grades

However, there is also additional information covered by figure 17. In the case of a “heavy” wear location site, the replacement of grade R260 with R350HT rails would offer a distinct advantage in terms of LCC. Following the arrows further on this improvement would be continuously extended through the use of R370CrHT or even R400HT rails. As a matter of course every change of rail steel material can be assessed in an analogous way (also for RCF being the dominating mechanism) in order to examine the benefits of using a heat treated rail grade.

4.5. Economic issues

The rail grade recommendations are based on LCC calculations which have been performed within SP6. Based on boundary conditions which can be found in the network of DB (track and traffic characteristics, maintenance strategy and cost) the effect of using heat treated rail grades in terms of economic benefits has been assessed.

The calculations clearly demonstrate the high influence of using an appropriate steel grade on the total LCC cost of an entire track. Especially by replacing standard grade rails (R260) huge benefits can be reached, as the durability of the rails can be increased significantly.

Below a LCC calculation performed within SP6 is presented:

The calculation is focused on the benefits provoked by the use of heat treated rails instead of standard grade rails in curves characterized by a medium radius class **(700 ≤ R < 1500)**.

The traffic type for the calculations was standard European "mixed traffic" with various cumulated annual tonnages.

The input data in detail is as follows:

Parameter	Reference case R260 (standard rail grade)	Innovation R350 HT (hard rail grade)
Service life (R 700-1500 m)	20 years for 30 MGT/a	40 years for 30 MGT/a
Wear rates	w_1: 0,3 mm/100 MGT, w_3: 0,7 mm/100 MGT	w_1: 0,2 mm/100 MGT, w_3: 0,4 mm(100 MGT
RCF rate / Head-Check	0,75 mm/100 MGT	0,30 mm/100 MGT
Grinding interval for 0,8 mm metal removal	~2 [a] 30 MGT/a	~6 [a] 30 MGT/a
Rail renewal	Load dependent, at least 1 during 40 years	Load dependent

- Discount rate: 8 %
- Inflation rate: 2 %
- Effective rate: 5.8 %

Figure 18: input data of LCC calculation of SP6

The results of the calculations are as follows: With increasing annual loads the benefit of a use of heat treated trail grades increases significantly also in curves of medium radii as this example shows. Beginning with 15 million annual gross tons savings have been confirmed and for highly loaded tracks - regarding rail only - **savings up to 50%** are possible. If the whole track system is taken into consideration the benefits remain at up to 7%, which is impressive anyway as the rail provides a very small asset concerning the cost of all individual track elements of an entire track.

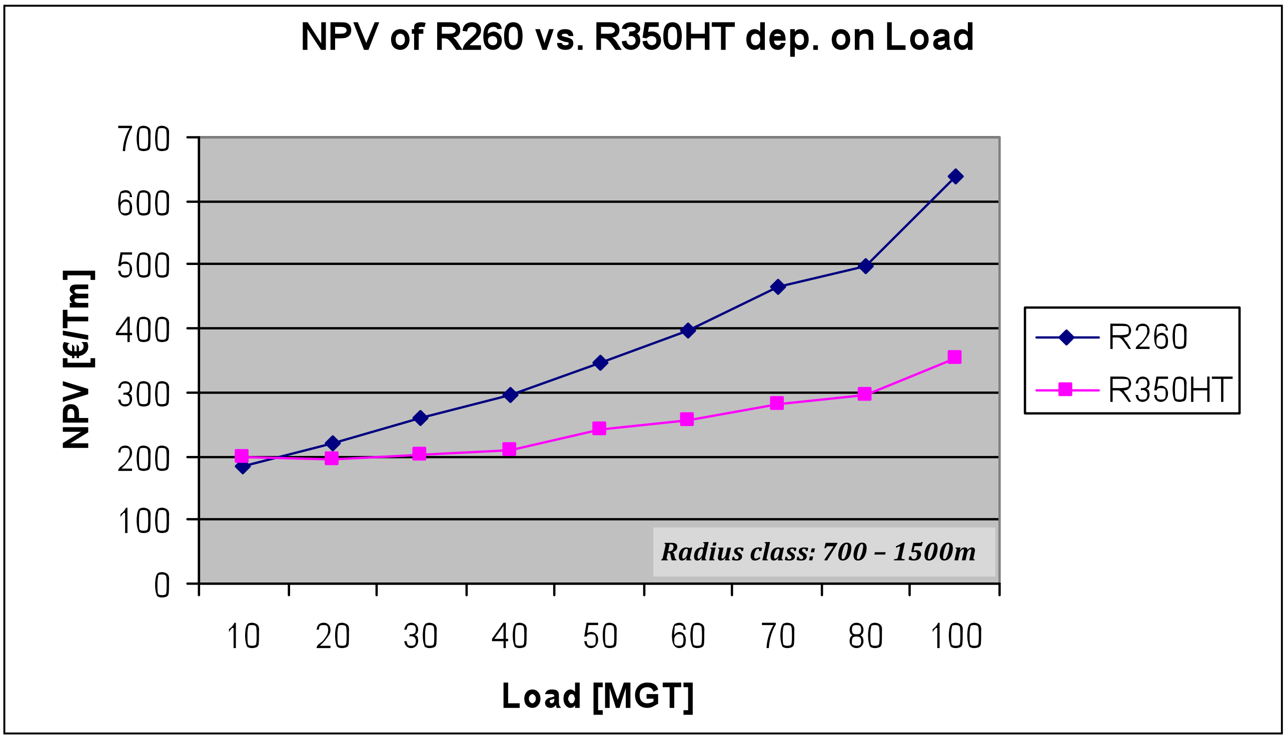


Figure 19: results of LCC calculation of SP6

More details concerning the calculations and especially the influence of several parameters (such as the discount rate or distribution functions of the rail degradation behavior) are given in the deliverables of SP6.

LCC calculations were performed in the past too. Below an example of a former LCC analysis of DB is given:

The LCC cost and the savings calculated for an example out of DB's network (based on actual track data – dominating mechanism: RCF – crack growth rate of R350HT three times lower compared to R260 – traffic: 30MT per year) are listed in figure 20. The results represent a wide curve with a radius of 3000m.

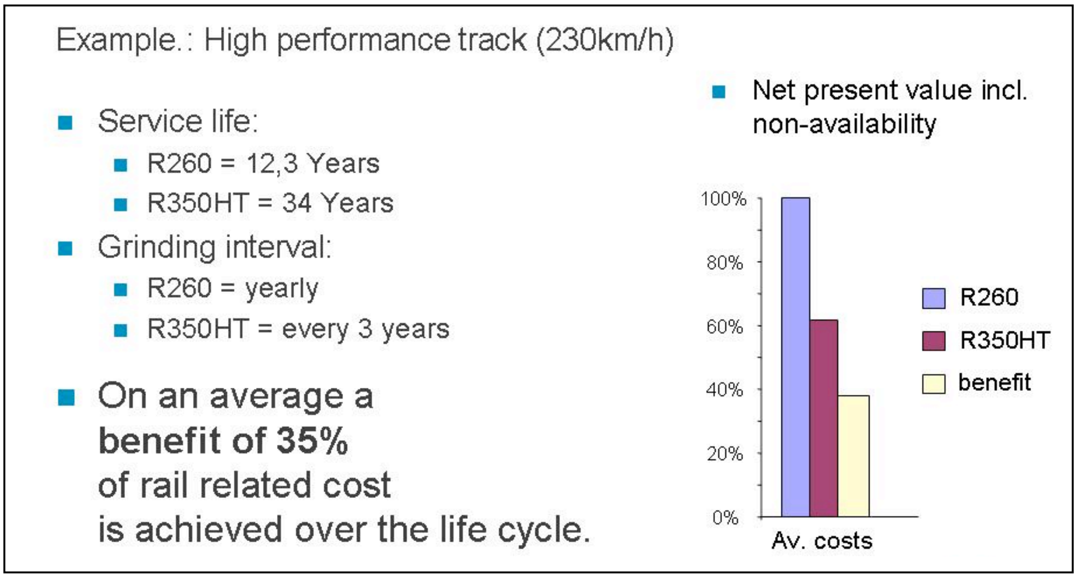


Figure 20: results of LCC calculation (example DB)

The results of the second example given in this report can be summarized as follows: By using an appropriate steel grade, savings of rail related cost of 35% and more are possible also in wide curves. Such savings can be achieved through a change of the rail steel only rather than the full track system.

The results of the LCC analyses performed within the Innotrack project impressively show the high potential regarding economic benefits that can be achieved, if heat treated rails are used appropriately in European tracks.

In addition to the overall benefit of a use of heat treated rail grades, the performed LCC calculations also show that the amortization of the slightly higher investment of heat treated rails takes place after a very short period after installation (down to 2 years).

4.6. RAMS issues

The use of high strength heat treated rail steels in areas defined in the rail grade recommendations leads to a substantially better rail degradation behavior, which as a consequence causes

- **Reduced maintenance efforts**

  as the necessity of grinding is reduced significantly, and in some cases also a replacement of rails within the expected track durability (entire track) is avoided

- **Further reduction of non-availabilities**

  as reduced maintenance actions also reduce non-availabilities caused by maintenance

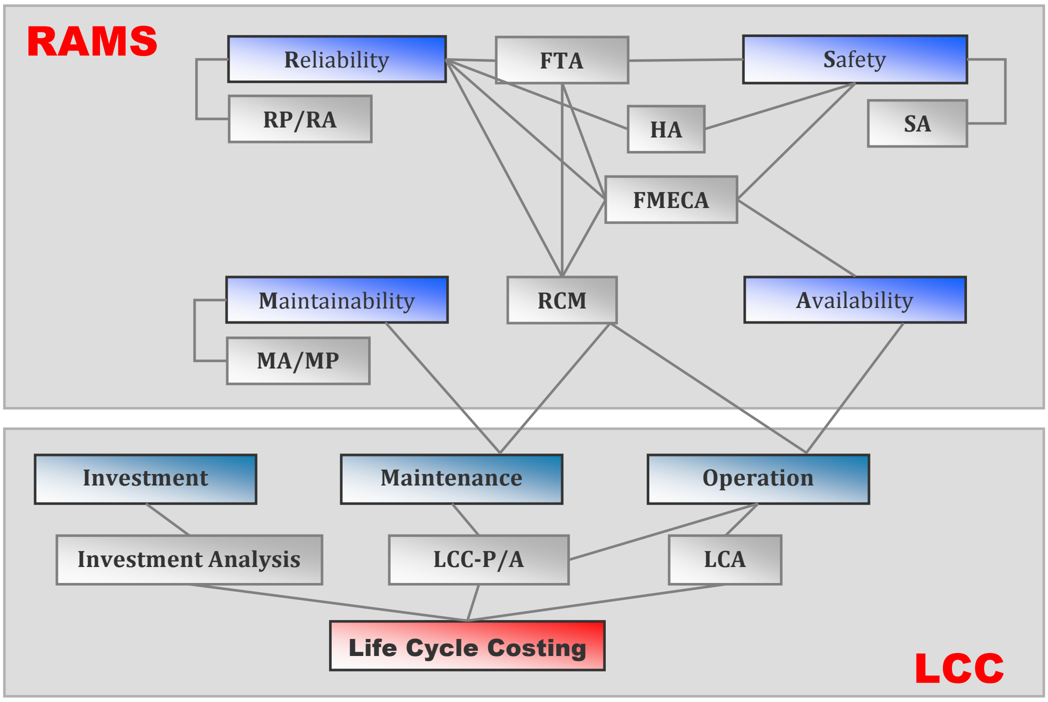
- **Increased safety against rail breakage**

  as cracks develop slowly and the fatigue resistance of material supersedes values as quantified in EN 13674

Therefore the use of heat treated rails will lead to an improvement in RAMS of the overall system too.

The three items above also clearly demonstrate that RAMS deals with cost-effectiveness. Although they are hard to quantify in some cases they should be taken into consideration when performing LCC analyses as this is the case within the INNOTRACK project.

The close connection between RAMS and LCC analyses is demonstrated on the following page



LCA	- Lifecycle Assessment
LCC	- Lifecycle Cost(ing)
PM	- Preventive Maintenance
CM	- Corrective Maintenance
RCM	- Reliability Centred Maintenance
RAMS	- Reliability, Availability, Maintainability, Safety
FME(C)A	- Failure Mode, Effects (and Criticality) Analysis
FTA	- Fault Tree Analysis
HA	- Hazard Analysis
SA	- Safety Analyse
MA/MP	- Maintenance Analyse/ Maintenance Philosophy
RP/RA	- Reliability Philosophy/ Reliability Analyse

Figure 21: Correlation between RAMS and LCC

4.7. Welding issues

Also welding aspects have to be taken into consideration when decisions concerning an installation of a certain rail grade have to be made. Usually rail producers develop welding procedures for new and further developed steel grades in conjunction with welding experts[3]. As a matter of course every welding method for a new steel grade has to run through a homologation process until it can be executed in a network without restrictions. In this context it has to be pointed to the fact that welding of heat treated rail grades of all different types (R350HT, R350LHT, R370CrHT and also the R400HT grade and their various joint possibilities) generally represents a standard procedure which is executed since many years all over the world (even if a homologation for a certain rail grade and a certain country is still missing).

To put it simple, it is only the chemical composition of the rail steel that defines the weldability of this material. Other mechanical properties, such as hardness do not influence the weldability. Therefore it is valid for rail steels that the higher alloyed the rail the more challenging is the welding process (in terms of pre- and post-heating).

A brief overview[4] on important welding procedures of *flash butt welding* and *aluminothermic welding* are given below (based on "welding recommendations for rail steels" compendium of TSTG [15]).It can be clearly demonstrated that especially the alloyed R320CrHT rail grade requires the execution of a special and complex methodology, which represents an advantages for heat treated rails.

<u>Flash butt welding</u>

R260

- No post-heating
- No compressed air
- Minimum cooling time of 800 to 500°C: *3½minutes*

[3] Also during the Innotrack project welding issues were dealt with. Several interesting deliverables concerning new processes and improvements of existing processes were produced. (See SP4 – welding)

[4] Rail producers can give more detailed recommendations for the different rail steels and their joint variations with other rail steels if required.

Flash butt welding *(continuation)*

R320Cr

- Post-heating
- No compressed air
- Minimum cooling time of 800 to 500°C: *18 minutes*

R350HT

- No post-heating
- Accelerated cooling of the rail head in order to achieve the required hardness in the rail head.

R370CrHT

- Post-heating
- No accelerated cooling

R400HT

- Post-heating
- No accelerated cooling

Aluminothermic welding

R260

- No heat treatment
- Use of appropriate welding portions

R320Cr

- Use of special welding portions
- Slow cooling of the rail after welding required

R350HT, R370CrHT, R400HT

- Use of specially alloyed welding portions required

5. Conclusion

In recent years the duty conditions of rails have become substantially more severe. This tendency is also expected to continue into the future. In the (recent) past rail manufacturers have reacted and developed heat treated rail grades. These innovations in railroading represent the appropriate answer to altered duty conditions developments and demonstrably improve RAMS figures as well as they demonstrably reduce the total LCC of the entire track in a substantial manner.

Based on site monitoring (D4.1.1), rail degradation mechanism analyses (D4.1.4) and results of laboratory tests, the following statements can be made:

- Tight curves show high wear-rates, which decrease significantly with increasing radii.
- Especially wide curves with radii above approximately 500m are affected by rolling contact fatigue (RCF).
- **Compared to standard rail grades heat treated rails show a superior wear resistance <u>and</u> a superior RCF resistance at the same time.**

The installation of heat treated rail grades is therefore generally recommended for curves with radii up to 3000m – 5000m. In detail the appropriate steel grade for specific boundary conditions can be found in two different rail grade recommendations of this guideline. Beside the traditional radii based recommendation also an innovative deterioration based rail grade recommendation was developed within WP4.1 and is presented within this deliverable.

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