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INNOTRACK

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D4.1.3 - Interim Guidelines on the selection of rail grades

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Glossary

Abbreviation/acronym	Description
CM	Corrective Maintenance
FME(C)A	Failure Mode, Effects (and Criticality) Analysis
FTA	Fault Tree Analysis
HA	Hazard Analysis
IM's	Infrastructure Managers – i.e. the railway partners involved in the project
LCA	Lifecycle Assessment
LCC	Lifecycle Cost(ing)
MA/MP	Maintenance Analyse/ Maintenance Philosophy
MGT/MGTPA	A measure of traffic in units of million gross tonnes per annum
PM	Preventive Maintenance
RAMS	Reliability, Availability, Maintainability and Safety
RCF	Rolling Contact Fatigue (in this case usually related to head checks)
RCM	Reliability Centred Maintenance
RP/RA	Reliability Philosophy/ Reliability Analysis
SA	Safety Analysis

1. Executive Summary

This interim document describes the work carried out within work package WP4.1 on rail grade selection. It should be emphasised that this is an interim report and is the basis for further work within Innotrack. Comments and supplementary information from other partners or expert groups are most welcome and will be considered for the final deliverable.

The development of the interim guidelines on rail grade selection is based on the analysis of data from the monitored sites (Deliverable D4.1.1 and D4.1.2). However, material properties determined under closely controlled tests on specialist equipment in WP4.3 will be used to assess the efficacy of available wear and RCF models and when combined with the observed in-service performance data will form the basis of establishing definitive guidelines for the selection of rail grades.

2. Introduction

To be able to introduce innovations into a very complex system, such as a railway, requires a courageous act to change things significantly while taking the risk that 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 the railway community is reluctant to change is the long pay back period for investments, which may only be profitable after many years. 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 been developed historically on a piecemeal basis railway by railway. 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 strong indications, that their use on a wider basis could reduce LCC of the track system. Therefore this report is an interim guide to the selection of current rail grades to improve the system in a sustainable manner. When the final guidelines are complete the recommendations should demonstrate a step change from present recommendations.

3. Rail Grade Selection

3.1 Basic Studies on Wear and RCF

As a basis for the recommendations on rail grade selection data on the degradation of rails in service is required. The results from work performed within Innotrack and previously are used to sketch an overview of rail grade performance.

3.1.1 Results from Site Tests

Railways and rail manufacturers have collected large amounts of data on the degradation of rail over the years. This has given invaluable information on the performance of different rail grades in service. This data is being collected together in a database with the results reported in D4.1.1. Deliverable D4.1.2, reports on an initial analysis of this data aimed at deriving algorithms for the degradation of rails as a function of track geometry, rail grade and loading conditions. The initial analysis has demonstrated that to do this for every track characteristic is a non-trivial task because of the wide range of variables that are present within the collected data. Further problems also include the lack of information on certain parameters that are important to the performance of rail in track.

Nevertheless general figures can be drawn for the relationship of curvature and rail degradation. Wear is dominant in curves with radii of less than 1000m. The results also indicate that RCF (the observed data limits this to so called “head checks”) is a problem that can occur over a radius range of 500 to 5000m.

Pearlitic rail steels with higher hardness show in general a higher resistance against wear and RCF. The improvement for the head hardened grade R350HT compared to standard grade R260 is about 3 times for wear and 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) may result in extension of RCF to track segments currently RCF free if the rail grade remains unaltered.

3.1.2 Literature Review – Site Tests

The beneficial behaviour of premium grade rail steels in respect of their degradation behaviour has been published many times over the preceding decades (the following selection is only a rough overview and not exhaustive).

A comprehensive study of the test results from FAST (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. RCF was not a topic of 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 than a head hardened one with moderate lubrication and nearly 2 times for the more extensive lubrication. The effect of lubrication in reducing wear is higher for the standard rail grade.

Similar results were reported by Muster [3] with slightly less benefit of a head hardened grade of hardness 370HB versus standard UIC900A (equivalent to R260 in EN13674-1:2003[4]) with double the wear resistance without lubrication and less improvement for a lubricated curve (1.5 times). The hardened steel grade showed in general 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 [5] reported on tests performed on high-speed tracks of DB where the main degradation mechanism is head checking. On grade UIC800 (equivalent to R220) rails the depth of rail damage, due to head checks, was twice as much as for grade 900A (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 R260 and one-third compared to grade R220. 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 [6].

The results of the track tests and site monitoring of wear and head checking that have been reported in the literature show in general similar results where the relative degradation behaviour of one rail steel grade is compared with a different one at specific test sites. Nevertheless the absolute degradation rate will vary from site to site. But there are different opinions regarding the influence of rail grades on singular faults such as squats. For example Deroche [7] observed that squat occurrence could be solved by changing the rail from grade UIC700 (R200) 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 lead 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 reduce degradation due to wear and RCF crack growth compared to standard grades. The consequence for the railways is that less maintenance would be required and the total lifetime of the rails would increase.

3.1.3 Literature Review – Laboratory Tests

At present only the R260 rail grade has been tested in WP4.3 at the DB and VAS test rigs while twin disc tests have only been performed on Corus 400HB rail steel, additional tests are planned imminently. Thus these results cannot be used to predict degradation at the moment but will be considered for the final deliverable.

Therefore the following is a review of the literature on laboratory tests performed to investigate the wear and RCF behaviour of rail steels, the vast majority of which supports the observations made in track.

Garnham and Beynon [8] performed rolling sliding twin disc tests on bainitic and pearlitic steels and emphasised 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 [9,10] 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.* [11] 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 decreased wear rate realised 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 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 [8] 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.

Cyclical torsion testing of grade R260, hardened rail grade R350HT and further non commercial trial steel grades have been performed by Stadlbauer [12] and Tapp [13]. The results show that the high strength steels withstand load levels over several hundreds of cycles where the standard grade fails after the initial cycles and 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 uncritically 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.

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

3.2 Current Selection Guidelines

The present guidelines or national regulations for rail grade selection[1] on mixed traffic lines with up to 22.5 tonne axle load and at least 20 MGT annual load show a wide variation between the different railways, especially for the shallow curves with radius less than 1500 m. While in Italy, Ireland and the UK, grade R260 is recommended for the whole range of curvature, several countries use R350HT up to 500 m or 700 m wide curves to combat wear. DB recently increased their guidelines for the use of R350HT to 1500 m while ProRail in The Netherlands and OeBB in Austria recommend heat treated rail for curves up to 3000m to combat RCF. Banverket in Sweden also use heat treated rails for curves up to 3000m for the heavy haul Malmbanan line.

There has been much research interest in steels with bainitic microstructures over the past 25 years to combat both wear and RCF. The results of trials have never conclusively demonstrated their superior performance over heat treated grades in terms of wear but the current generation have shown promise in their resistance to RCF. Trials with them are still ongoing, including in Switzerland where bainitic steel is proposed for curves between 700 m and 1200 m radius to combat RCF.

The guidelines are summarised in Table 1 below.

Radius [m]	≤ 300	400	500	600	700	800	1200	1500	2500	≤ 3000	> 3000
UIC	R350HT		R350HT/R260			R260					
Germany	R350HT (≥ 30 MGT)					R260					
Germany - New Track	R350HT (≥ 50 MGT)								R260		
Switzerland	R350HT		R320Cr/R350LHT				R260				
Switzerland (Trial)	370LHT		R350LHT		Bainitic			R260			
Austria	R350HT	R260									
Austria (New) Single Track	R350HT	R260									
Austria (New) Double Track	R350HT										R260
Sweden	R350HT	R260									
Sweden (Malmbanan)	R350HT										R260
Norway	R350HT					R260					
UK	R260										
Ireland	R260										
Italy	R260										
Belgium	R350HT					R260					
Luxembourg	R350HT					R260					
Netherlands	R350HT/400HB	370LHT/400HB									R260
Denmark	R350HT					R260					
Poland	R350HT					R260					
Hungary	R350HT					R260					
Romania	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[1]

[1] Since the numbers given in this section are based on the information known by VAS/Corus technical customer service they need not exactly reflect the internal guidelines of the railways and have to be proved by the railways themselves.

A summary of the current pearltic rail steels in use in Europe is given in Table 2 below. The grades are designated according to their minimum hardness (see Table 2 below). The grades R200 and R220 are still found in track but rarely used for new build tracks.

Rail Grade	EN13674 - 1: 2003[4]	Running Surface Hardness Range (HB)	Min. Ultimate Tensile Strength (MPa)	Min. Fracture Toughness K_{IC} ($MPa.m^{1/2}$)		Description	Chemistry	Branding lines
				Single	Mean			
R200	Yes	200-240	680	30	35	C-Mn		None
R220	Yes	220-260	770	30	35	C-Mn		
R260	Yes	260-300	880	26	29	C-Mn		
R260Mn	Yes	260-300	880	26	29	C-Mn		
R320Cr	Yes	320-360	1080	24	26	1%Cr		
R350HT	Yes	350-390	1175	30	32	C-Mn Heat Treated	R260 + up to 0.15%Cr	
R350LHT	Yes	350-390	1175	26	29	Low Alloy Heat Treated	R260 + 0.30%Cr	
370LHT	No	370-400		Equal to or better than R350HT		Low Alloy Heat Treated	R260 + 0.50%Cr	Depends on Manufacturer
400HB	No	381-408	1280			Alloy Heat Treated	R260 +Cr+Si	Depends on Manufacturer

Table 2: Pearlitic rail steel grades available in Europe

UIC leaflet 721 gives recommendations for the selection of rail grades[14]. The criteria for the choice of rail grades for mixed passenger and freight traffic railways with a maximum axle load of 22.5 t include:

- Local parameters (radius, tonnage carried, gradients (20‰ and more), speed and cant, axle load, type of rolling stock;
- Rail maintenance methods (lubrication and rail grinding)
- Economic assessment (investment cost, annual maintenance cost and service life time)

As it is almost impossible to produce guidelines for every situation UIC leaflet gives guidance based on track curvature and annual traffic in million gross tonne(MGT). The UIC leaflet 721 gives recommendations for the rail grades that can be classes as standard and hard, Figure 1. The standard grades are R260 and R260Mn and the hard grades are R350HT, R350LHT and R320Cr (see Figure 1). The grades R200 and R220 are not recommended anymore for mainline railways. Tables 1 and 2 demonstrates that there are also other pearlitic rail steel grades available and in current use, as well as bainitic steels that are in the stage of moving from trial to commercial products; none of these are included in these recommendations.

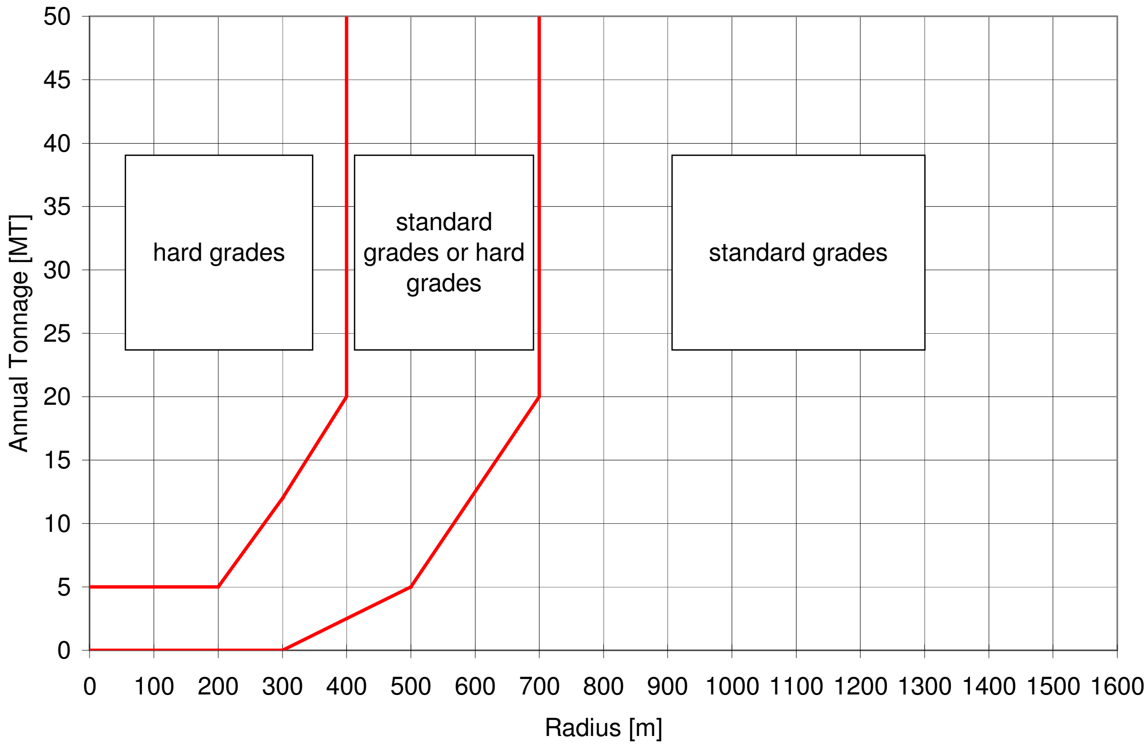


Figure 1: Recommendation for the use of standard and hard steel grades according to UIC Leaflet 721

3.3 Criteria for Rail Grade Selection

The criteria described in the UIC leaflet 721 should be kept as an accepted basis. The strongest criteria will be the economical issues, which will be considered by LCC and RAMS analysis. More explicit guidance on the rail grade selection especially for the overlap zones will be given in the final document in month 36.

3.3.1 Local Parameters

- Curve radius is one of the most influencing parameters on wear and RCF and thus the technical recommendations will use it as its initial parameter.
- The actual amount of tonnage carried over a time interval does not influence the kind of failure occurring, but defines the degradation rate and thus influences the maintenance strategy, the total life time of the rail and finally the economical justification of rail grade selection.
- Gradients and locations where acceleration and braking occur, e.g. stations, signals, increase the longitudinal traction forces on the railhead. Degradation at these locations includes: wear, corrugation, wheel burns and RCF. The degradation mechanism at these locations is also influenced by the curvature as well. On tangent tracks with high line speed it has to be considered, that the engines run with high power and under full slip conditions while running with constant speed to overcome the aerodynamic and rolling resistance of the train. RCF like Head Checks and Squats or Corrugations may therefore initiate.
- The actual driven speed and its distribution along with cant influences the transverse position of the vehicles in track and thus the loading and degradation mechanisms of high and low rail. An example of damage arising because of high cant, low speed and high axle loads is field flow and crushing of the rail head for the low rail of curves.
- The axle load together with the wheel rail profiles and tangent contact forces defines the working point according to Johnson's shakedown map leading to different material behaviour[15]. In the

regimes of cyclic plasticity and ratchetting the material will fatigue and the degradation mechanism observed on the rail will be both wear and RCF or severe wear without crack propagation if the slip is high enough to remove initiated surface fatigue cracks.

- The type of rolling stock is also a factor on the degradation of the rail. The severity of impact depends on the wheel diameter, the curving behaviour (including primary yaw stiffness) and, for the driven axles, on the kind of traction control. This may result in full rolling, stick slip or full sliding conditions at the contact patch.

The aforementioned parameters are not known exactly in many cases, so pragmatic estimations for upper and lower boundaries have to be made.

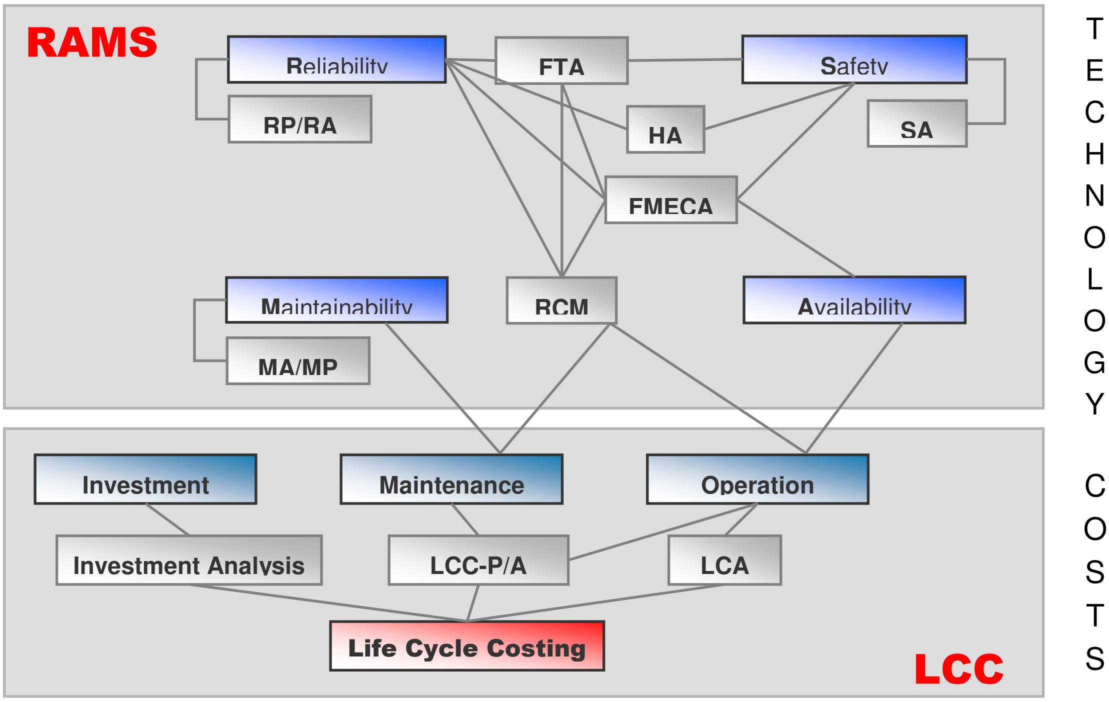
3.3.2 Rail Maintenance Methods

Properly applied lubrication of the high rail leads to a significant reduction of side wear on the high rail and some reduction vertical wear and prevents the so called “rutting” corrugations [16] on the low rail of tight curves too. Due to the reduced wear by applied lubrication an increased growth of RCF-cracks might occur. The efficiency of lubrication depends strongly on the operating conditions and can reach 200 times under some instances [16]. When the wear rate falls below a certain value – the so called magic wear rate – the rail surface may reach its fatigue limit before the highly strained layer will be worn out [17]. Initiated Head Checks will propagate. This seems to be plausible if the initial situation is severe wear or with the designation according to Bolton [18] Type 3 wear and would be reduced to moderate wear (Type 2 wear). The same situation referring to the shakedown map would be described by a shift of the working point from ratchetting regime to plastic shakedown. By the choice of a material with high initial yield and ultimate strength a shift to elastic shakedown should be proved for the actual contact conditions. This would result in light wear (Type 1 wear) without RCF-failures.

Rail grinding is a common maintenance procedure to improve contact conditions and extend rail life by reaching the magic wear rate with artificial metal removal. The improvement would be enforced further by parallel use of a higher steel grade. Maintenance strategies are studied in detail in WP4.5 and the accompanying deliverables.

3.3.3 Economical Issues

The economic consideration is the most relevant criteria (main task of Innotrack is a 30% reduction in LCC). The present work of SP6 shows that LCC is used to evaluate investment alternatives by the IMs, but the participating IMs do not consider RAMS issues in all phases of the system life cycle, even if they use RAMS technology (see Figure 2). There are several hidden costs which can be described by the RAMS-technology but they are harder to quantify. Two fields of RAMS, safety and availability, strongly influence the acceptance of private and business customers for railway services. Including cost figures for these subjective items will increase the maintenance and operation cost on a more advanced LCC calculation. The increased investment cost of premium steel grades for rails will be justified by decreased cost figures for maintenance and operation by better performance, better safety and better availability. The result is a reduction of total LCC.



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

Figure 2: Flow chart to visualise the relation of the fields of RAMS-Analyse on LCC calculation

3.4 Recommendations

The rail grade classes recommended in UIC Leaflet 721 have to cover a wide field of loading conditions. The worst conditions where standard grades are recommended (>700m for more than 20MGTPA) is located within the range of curvature where the present study on rail degradation (D4.1.1 and D4.1.2) shows RCF being the dominating problem (500m to at least 5000m). Since the results from field test show both a reduced wear and RCF-crack growth rate for the head hardened pearlitic grades (see section 3.1.1) an improvement in LCC could be expected especially for high annual tonnage by the use of R350HT/R350LHT in this range. Wear resistance, yield limit, ultimate tensile strength and simultaneously fatigue resistance for pearlitic steels increases with decreasing lamella spacing and grain size and/or increasing the carbon content or micro alloying the steel. Assuming that the expectation of doubling passenger traffic and tripling freight traffic by 2020 would occur, we can summarize some obvious consequences:

- The annual tonnage on railway lines rises.
- The maximum axle load would be exploiting by an increased proportion of traffic or would rise.
- The higher line efficiency requires shorter time slots for maintenance.

Thus to ensure sustainability, for tighter curves where higher contact stresses occur the higher hardness grades are recommended for both high and low rail. The grades recommended include those with a hardness of approximately 400HB, which are not currently specified in EN13674-1. To ensure safety it is important that these grades have sufficient fracture toughness to withstand operational conditions. This is also related to the work in WP4.2 on different defects and the effect of fracture toughness on the criticality of them. This new recommendation shifts the boundaries for the selection of hard steels to higher radius and lower total load compared with the present UIC Leaflet 721. A graphic illustration is shown in Figure 3.

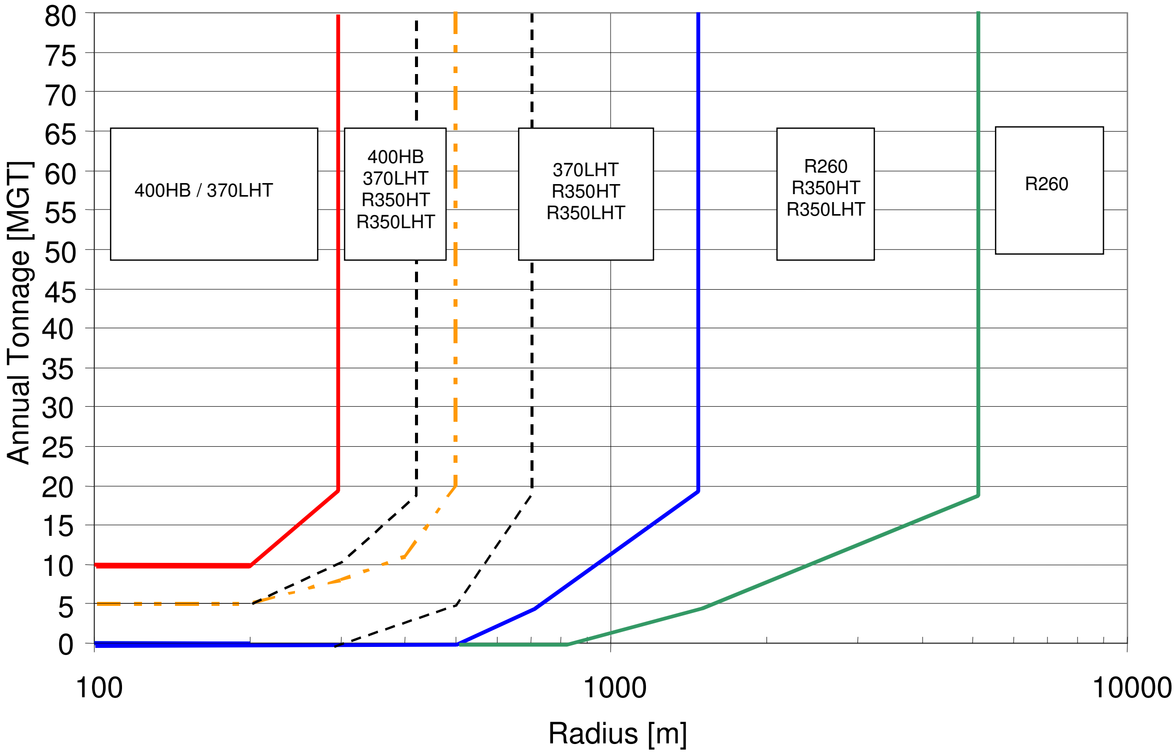


Figure 3: Recommendation on the selection of standard and different hardened rail grades. The dashed black lines mark the boundaries shown in Figure 1.

The next steps on elaborating final guidelines are the discussion with all railways involved in Innotrack and other expert groups and the calculation of LCC for the proposed optimisation within WP6.3.

The request by WP6.3 for a calculation of the expected LCC improvement (see Table 3) splits the curvature ranges according to the segmentation analyse done in SP1 and hence the numbers only basically reflects the recommendations given above. The actual cost figures will be considered for the final deliverable.

			Reference system	**Optimized system (alternative 1)**	**Remarks**
Description of the track elements, boundary conditions and track condition					
Track elements - Alignment					
curve	radius	<300 m	R350HT	400HB/R370LHT	Each individual rail grade and radius class of the optimised system can be interpreted as an own alternative
		300 - 700 m	R260	R350HT/R370LHT	
		700 - 1500 m	R260	R350HT	
		1500 - 5000 m	R260	R350HT	
		>5000 m	R260	R260	

Table 3: SP6 LCC table for rail grade recommendations

4. Conclusions

In recent years the amount of traffic that the railways have to carry has increased and this is expected to continue into the future, combined with higher speeds has meant that the duty conditions of rail have become more severe. To combat this new harder rail grades have been developed by the rail manufacturers, which have become better understood through extensive laboratory and track testing.

The results from the site monitoring and the initial rail degradation data analysis (D4.1.1 and D4.1.2) are supported by the results from a literature search in that:

- Curves of low radius demonstrate higher wear than higher radius curves while the higher radius curves exhibit RCF.
- Harder rails are more resistant to wear and rolling contact fatigue than standard grade rails.

The results for the benefits of harder rails have also been supported by a literature search of laboratory testing results.

To maximise assets and minimise life cycle costs it is therefore vitally important that these premium grade rails are used at appropriate locations within track. This is the basis for the guidelines on the selection of rail grades. It is also important to note that the use of premium rail grades is not a replacement for effective maintenance. The maximum benefits will arise from an optimised lubrication and grinding strategy for the different rail grades.

The results of the work so far have demonstrated that the use of the high strength/hardness heat treated rails are beneficial in combating both RCF and wear, therefore their use is recommended on curves with higher radius than have been previously recommended.

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