Rail grinding as an integral part of technically and economically efficient track maintenance

A high level of reliability and availability is demanded of the railway track. In order to guarantee a high track quality, cyclical maintenance and renewal interventions are required. This article addresses rail grinding as an integral part of technically and economically efficient track maintenance. The evaluation of the cost efficiency of the different rail grinding strategies requires a consideration of the grinding costs versus the long-term benefits. By means of the LCC (life cycle cost) analysis method, the long-term benefits of cyclical rail grinding, within the framework of track maintenance, can be verified. Thus, recommendations can be derived for technically and economically efficient rail grinding strategies, as well as optimisation potentials.

Dr.-Ing. Thomas Hempe
Track Technology Management
DB Netz AG, Frankfurt/Main
Germany

Prof. Dr.-Ing. Thomas Siefer
Institute of Transport, Railway Construction and Operation
Leibniz University Hannover
Germany

The dynamic loading of the track due to train traffic causes various damage processes that, at regular intervals, necessitate maintenance and renewal interventions. Typical damages are high initial wear (early failures, 'teething troubles'), and function limitations at the end of the technical working life that are normally accompanied by a rapid wear. Fig. 1, for instance, shows the wear curve over time for engineering installations with respect to different maintenance intervals.

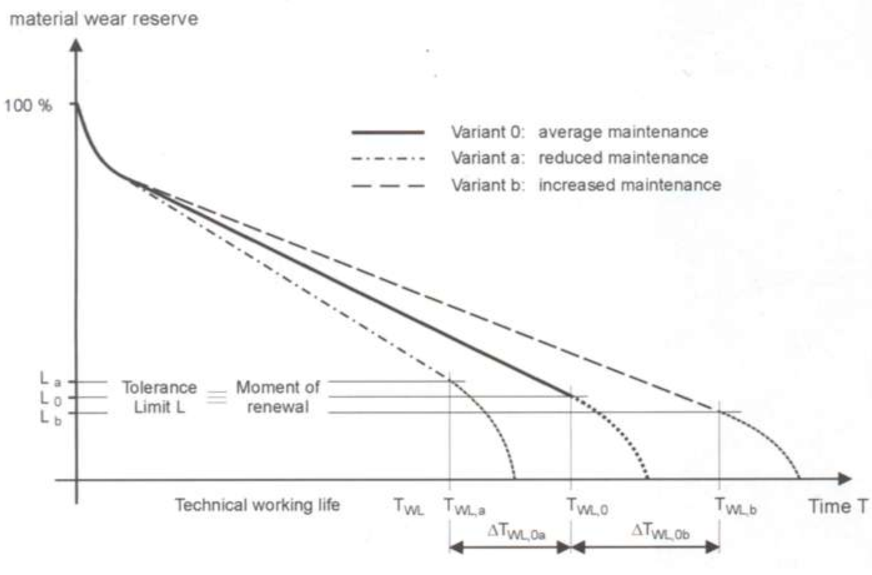


Fig. 1: Wear curve over time for engineering installations with respect to different maintenance intervals

By means of targeted maintenance, wear can be delayed and the technical working life extended, thus resulting in lower life cycle costs. Furthermore, a high level of reliability and availability of the engineering installations is achieved.

Well organised, technically and economically efficient track maintenance is characterised by:
— a timely and targeted (carefully planned) performance of maintenance and renewal interventions;
— an optimal utilisation of the deployed resources;
thus resulting in a minimum of life cycle costs.

RAIL GRINDING STRATEGIES

Faster train running speeds, increased axle loads and a growing demand for a high track quality and availability led, in the 1950s, to the development of track-borne rail grinding machines [1].

Initially, the aim of rail grinding was to eliminate rail corrugation, in order to reduce track stresses and to extend the service life of the rail, as well as to ensure ride comfort [2].

After more than fifty years of experience gained in practice, there is a consensus amongst engineers that mechanical rail grinding leads to:

— an extension in the service life of the rails;
— an extension in track maintenance intervals;
— an improvement in vehicle running properties and, thus, ride comfort;
— a reduction in noise emission levels.

Rail grinding is, thus, applied to eliminate various types of rail defects, to achieve a rail profile that optimises wheel/rail contact and combats noise and vibration.

Grinding new rails

The aim of grinding new rails is:

— *to remove the low-carbon boundary layer formed during the rail manufacturing process:* the low-carbon boundary layer, which is approx. 0.15 mm to 0.30 mm thick, is formed when heating the ingot to rolling temperature, as a result of oxidation of the carbon close to the rail surface. Experience gained in practice has shown that by removing the low-carbon boundary layer, the formation of rail corrugation can be delayed (Fig. 2, [3]);

— *to create a uniform rail head cross-section, thereby taking into account the as-laid position of the rails:* by creating a uniform rail head cross-section in accordance with the target geometry, differences in rail cant following installation are neutralised. In doing so, an optimal wheel/rail contact zone is created, thus ensuring optimal vehicle running properties;

— *to eliminate damage to the running surface of the rail caused during installation:* damage to the running surface caused during installation, such as ballast stone imprints, constitutes an initial damage that must be eliminated, in order to ensure an optimal long-term behaviour of the rail.

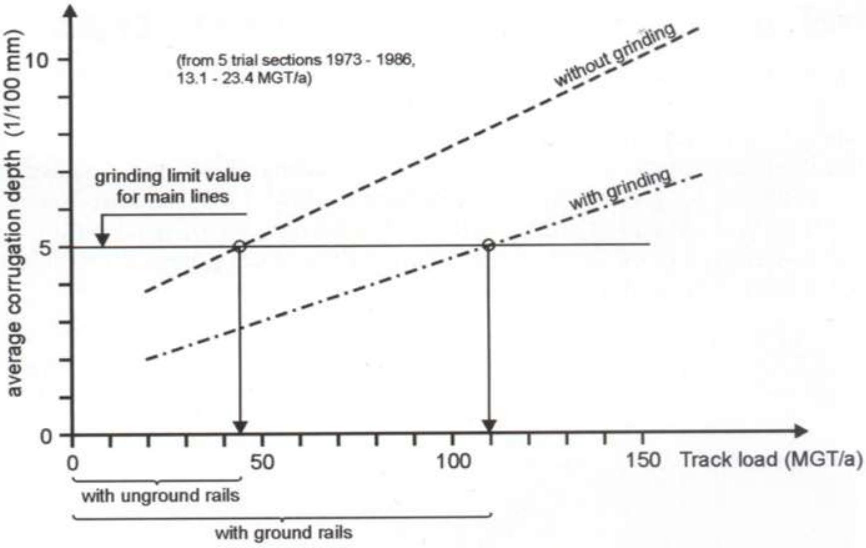


Fig. 2: Cumulative track load at the time of first corrugation grinding, for the situation with and without previous grinding of new rails [3]

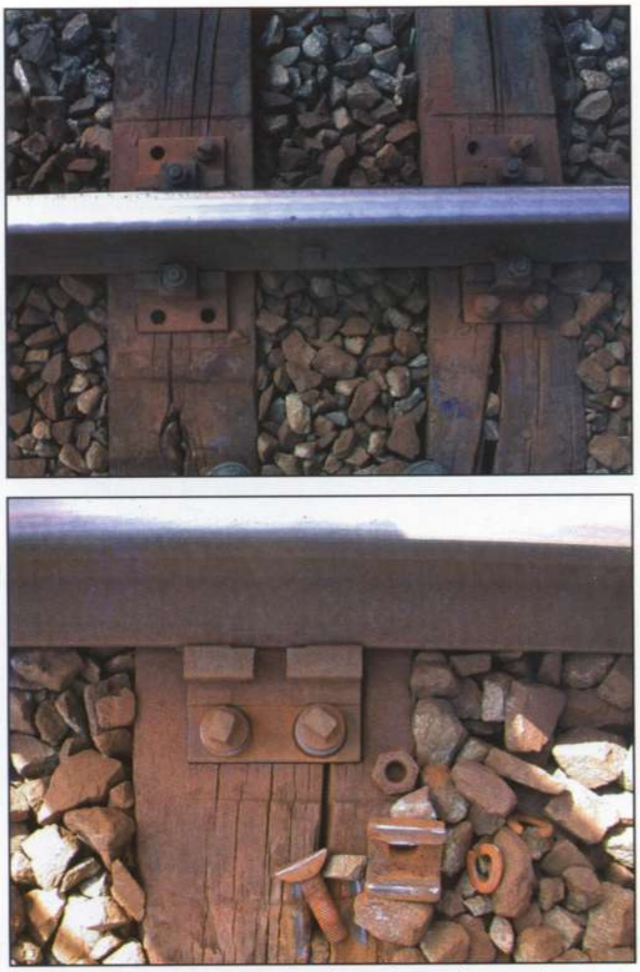


Fig. 3: K-fastenings that have become loose due to rail corrugation

Corrugation

Corrugation concerns periodic irregularities in the longitudinal plane of the rail head, featuring typical wavelengths of between 1 and 30 cm, which result from the dynamic wheel/rail forces. They can be distinguished between:

— short-pitch corrugation featuring wavelengths from 1 to 10 cm;

— long-pitch corrugation (slip waves) featuring wavelengths from 3 to 30 cm.

Corrugation does not affect the functionality of the rail. However, they lead to an increase in the dynamic loading of the track. The resulting forces accelerate damage to the rail, rail fastenings, sleepers and ballast, thus increasing maintenance expenditure and reducing ride comfort. They also lead to an increase in noise emission levels and vibration.

The dynamic wheel force in the vertical direction is a determining factor for changes in track geometry quality. For instance, in shallow curves, long-pitch corrugation leads to an increase in ballast compression of at least 50%. Considering the exponential relationship between ballast compression and the deterioration in track geometry quality, this leads to a more than twice as rapid deterioration in track geometry quality [4]. This corresponds to a halving of track maintenance intervals.

The dynamic forces resulting from short-pitch corrugation lead to increased stressing of wheel and rail. This has a major impact on the long-term behaviour of rail fastenings (Fig. 3) and also leads to fatigue cracks on the rail surface.

Rolling contact fatigue

Rolling contact fatigue leads to rail surface cracks in the wheel/rail contact zone. Since the mid-1980s, rolling contact fatigue has become an increasing problem for rail maintenance. In 1984, the presence of cracks on the gauge corner of the high rails in curves was reported [5], and it was predicted that such damage would occur with increasing frequency, as traction forces of locomotives increase. In 1990, rolling contact fatigue was the cause of 30% of all reported rail damage in Germany [6] and, at the end of the 1990s, it was 60% in Japan (JR East) [7].

Head checks

The most frequently occurring form of rolling contact fatigue is head checks, which mainly occur on the gauge corner of the high rails in curves featuring radii of between 300 and 5,000 m (Fig. 4).

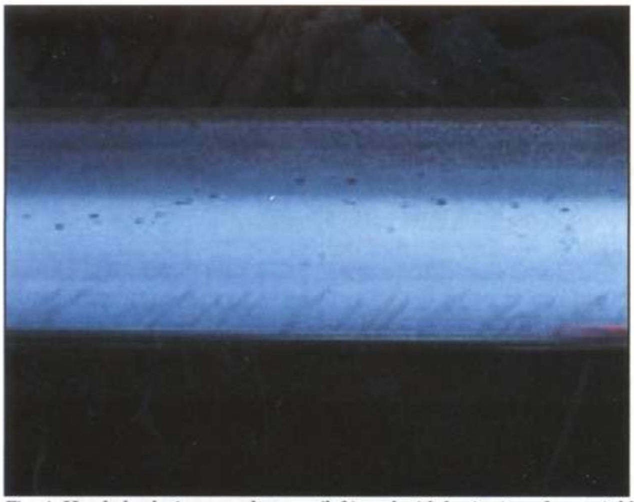


Fig. 4: Head checks in an early stage (left) and with beginning of material break-up (right)

Head checks are caused by high shear stresses on the rail surface that, again and again, exceed the yield strength of the rail surface material. The accumulation of plastic flows leads to surface cracks that increase in depth. If not removed in time, this will lead to a transverse breakage of the rail [8].

Belgrospis
In 1996, a new form of rolling contact fatigue was observed on the high-speed lines in Germany, known as "Belgrospis", named after the three persons who discovered it (Belz, Grohmann and Spiegel). Belgrospis are networks of cracks that occur periodically, in conjunction with short-pitch corrugation, between the centre of the rail head and the gauge corner of the rail. If not eliminated, they can lead to a transverse breakage of the rail [9].

Squats
Squats are individual semi-circular cracks on the running surface of the rail, which extend towards the gauge corner. As with head checks and Belgrospis, squats too can result in a transverse breakage of the rail.

The importance of rail grinding to combat rolling contact fatigue
With the occurrence of rolling contact fatigue defects becoming more frequent, rail grinding has gained in importance in recent years. A cyclical removal of fatigued rail surface material and a reproduction of the nominal rail geometry by means of profile grinding are, at present, the only possibilities to control the formation and growth of rolling contact fatigue.

Experience gained internationally has indicated that the service life of the rail can be extended significantly by the cyclical removal of fatigued rail surface material. According to trials conducted by the Railway Technical Research Institute (RTRI) in Japan, even a material removal of 0.1 mm after every 50 MGT of traffic reduces the occurrence of rolling contact fatigue by 50% [10]. On the Burlington Northern Santa Fe Railway (BNSF), USA, for instance, in curves with radii R > 1,000 m, the service life of the rail of initially 15 to 40 MGT was extended to more than 1,000 MGT, as a result of cyclical grinding [7].

Transverse rail profiles
The geometry of the transverse rail profile influences wheel/rail contact. Any deviations from the nominal geometry of the transverse rail profile can lead to a deterioration in vehicle running properties, which would necessitate speed restrictions. By means of profile grinding, flattened rail heads are re-profiled and gauge corner lips removed and, thus, good vehicle running properties are re-established.

Grinding special profiles
Individual control of the angular position of the rotating grinding stones allows the production of any special rail profile required. The cross-sectional geometry of such special profiles deviates from the symmetric profile of newly rolled rails and, thus, their production is also known as asymmetric grinding.

The application of asymmetric grinding is aimed at [11]:

— *reducing lateral wear of the high rail in sharp curves:* relocating the wheel/rail contact zone at the gauge corner of the high rail results in an increase in the rolling radii difference and an improvement in the guidance of the wheelsets;
— *preventing rolling contact fatigue:* grinding the rail below the nominal geometry (undergrinding) at the gauge corner results in the relocation of the wheel/rail contact zone towards the centre of the rail head, away from the fatigue endangered contact zone;
— *producing gauge-widening profiles:* whenever the rail gauge is insufficient, gauge-widening profiles can be ground, in order to allow smooth self-centring of the wheelsets and, thus, avoid hunting;
— *influencing the equivalent conicity of rails on high-speed lines:* by grinding targeted rail profiles on high-speed lines, vehicle running properties can be improved.

Specially monitored track (BüG)
In Germany, there are various sections of track that are specially monitored, so-called 'specially monitored track' (BüG). This embraces the application of preventive rail maintenance by means of early detection and timely elimination of corrugation, in order to reduce noise levels caused by rail traffic, and thus keeping them within those set by rail traffic noise regulations. The checking of the running surface condition takes place at six-month intervals with a noise measuring coach, specially designed for this purpose. As an active noise protection measure, the 'specially monitored track' (BüG) enables dispensing with constructional noise protection measures. By specially monitoring a section of track, a reduction in noise emission of at least 3 dB(A) can be achieved [12].

INTEGRATED MAINTENANCE
Integrated maintenance is the coordinated performance of tamping and rail grinding [13]. The aim is to carry out rail grinding immediately after tamping, if possible during the same track possession. Elimination of running surface irregularities and restoration of the nominal cross-section of the rail, reduces track stresses and improves the durability of track maintenance. The execution of tamping and rail grinding during the same track possession leads to a reduction in planning costs, worksite costs (track signalling equipment only has to be removed once), and costs associated with operation hindrances.

EVALUATION OF THE COST EFFICIENCY OF RAIL GRINDING STRATEGIES BY LCC ANALYSIS

The analysis of different rail grinding strategies according to their economic efficiency requires long-term evaluations. An adequate instrument for the economic evaluation of long-life systems, such as the rail, is the calculation of life cycle costs (LCC). Depending on the question posed, it is possible to consider either all costs during the entire life cycle or only individual cost blocks within defined life cycle phases.

In order to be able to evaluate the effects of varying rail grinding and renewal intervals, the LCC analysis considers the time of payments. In this respect, each payment during the life cycle is discounted to a reference year, which is normally the year of the LCC study. In this way, the present value of future payments is calculated. The sum of present values indicates the LCC (see Fig. 5).

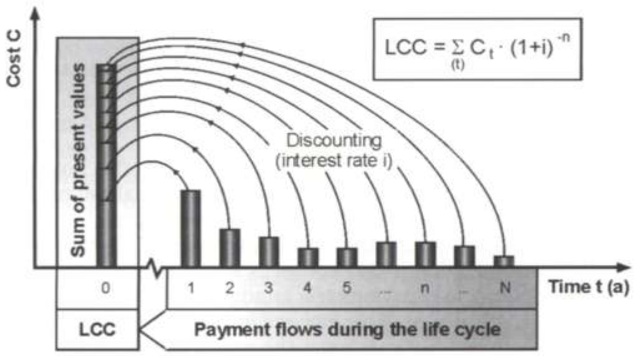


Fig. 5: Calculation of LCC

Cost efficiency of eliminating corrugation

Using the LCC analysis method, it is possible to determine the cost efficiency of eliminating corrugation by means of cyclical rail grinding.

In the following application example of the LCC analysis method, the cost efficiency of long-pitch corrugation elimination was considered, using the example of a curve with a radius R = 450 m that is affected by long-pitch corrugation.

In this example, the average growth rate of the corrugation was taken as being 0.02 mm/10 MGT of traffic, the cumulative traffic load, for various train types, was assumed to be 23 MGT per annum (23 MGT/a) [14], and the tamping interval was taken as being six years (reference cycle). The costs of rail grinding were estimated to be between 4.40 and 5.05 EUR/m, depending on the amount of metal removed. A theoretical cost of 28.14 EUR/m was determined for tamping of the curve (including preparatory work and material costs) [14]. The life cycle costs were regarded as annuities, i.e. equal annual payments over the time period under consideration; in this case, 50 years. Calculations were based upon a calculated interest rate of 8% and an annual inflation rate of 2%.

Fig. 6 shows the tamping and grinding intervals for five variants. The results indicate the cost efficiency of eliminating rail corrugation by means of cyclical grinding.

As can be observed from Fig. 6, shortening the grinding interval from four to two years leads to a cost saving of 7.35 EUR/(m·a). When taking into account the operation hindrance costs of the track section under consideration, cost efficiency was further increased by an additional cost saving of 10.74 EUR/(m·a).

Var	year	1	2	3	4	5	6	7	8	9	10	11	12	...
1	grinding	x	x	x	x	x	x	x	x	x	x	x	x	...
	tamping						x						x	...
2	grinding		x		x		x		x		x		x	...
	tamping				x				x				x	...
3	grinding			x			x			x			x	...
	tamping			x			x			x			x	...
4	grinding				x				x				x	...
	tamping			x	x			x	x			x	x	...
5	grinding					x					x			...
	tamping			x	x	x			x	x	x			...

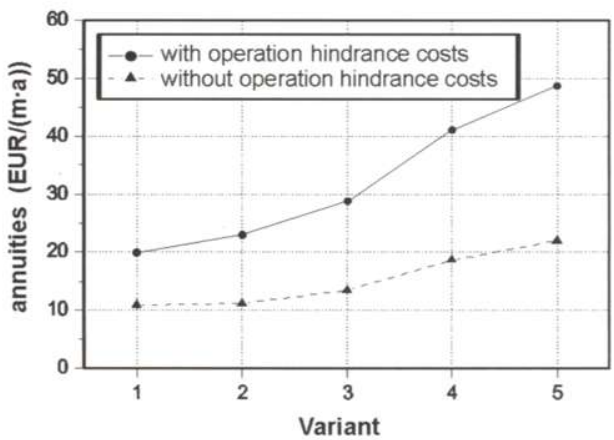


Fig. 6: Tamping and grinding intervals for five variants

The difficulty with LCC analysis is predicting the long-term behaviour of the installation under consideration for a given level of loading, and in deriving appropriate intervention intervals.

On the basis of comprehensive data analyses, literature research and interviews with experts, empirical damage functions have been developed at Leibniz University Hannover, Germany, and incorporated into the LCC analysis method that enable the long-term behaviour of the rail to be predicted. Further, a cost catalogue was developed for determining the payment flows which, in addition to the costs of the renewal and maintenance interventions to be taken, include worksite-specific costs [14].

Cost efficiency of eliminating rolling contact fatigue

To evaluate the cost efficiency of eliminating rolling contact fatigue by means of cyclical rail grinding, a curve with a radius R = 1,500 m featuring head checks on the high rail was considered. For the low and high rails, a wear rate of 1.0 mm/100 MGT of traffic was assumed. Further, a track load of 20 MGT per annum and a tolerable damage depth of 14 mm (i.e. DB AG limit for UIC 60 rail, up to 160 km/h) was assumed.

In practice, the service life of the high rail in curves featuring radii of between 300 and 5,000 m is shortened by the occurrence of head checks. The growth rate of head checks is dependent on the stress status of the rail head and the material characteristics of the crack surroundings.

The rate at which head checks increase in depth cannot be predicted yet, because it depends on a variety of influencing parameters. In this example, based on experience gained in practice, an exponential function is used to describe the development of crack growth. The tolerable damage depth is taken as 2.7 mm from the rail surface; this being the maximum depth that can be detected using the eddy-current testing method of DB AG. It should be noted that deeper cracks cannot be monitored by eddy-current testing and, thus, an imminent rail breakage cannot be detected. Therefore, rails featuring cracks exceeding the limit of 2.7 mm should be replaced.

By means of cyclical removal of the fatigued material, the crack growth can be kept under control and the service life of the rail extended. Fig. 7 shows the superposition of wear and crack growth for the high rail. As can be observed from the top diagram, which shows the situation without cyclical grinding, the rail reaches the end of its service life after 140 MGT of traffic. The bottom diagram shows the same situation, but now with cyclical grinding. As can be observed, the artificial removal of material controls the crack growth and extends the service life of the rail until the tolerable wear limit (in this case, 14 mm) is reached. For a grinding interval of 60 MGT (corresponding to every three years) and a tolerable wear limit of 14 mm, the service life of the rail can be increased to 800 MGT (corresponding to 40 years). Because of the exponential crack growth, the theoretical service life of the high rail depends on the grinding intervals. The more often the rail is ground, the less material has to be removed and the longer the lifespan will be.

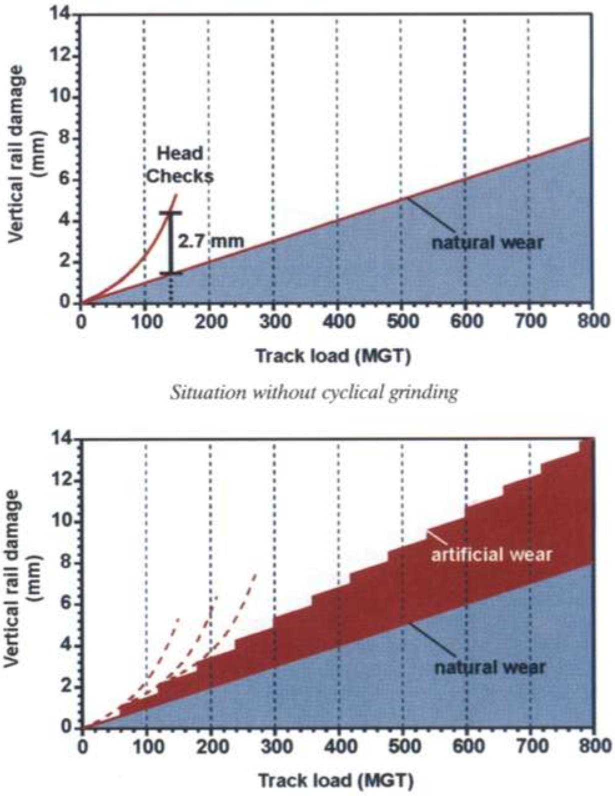
In order to assess the cost efficiency of cyclical grinding, the grinding costs were compared to the costs of rail renewal, using the LCC analysis method. Fig. 8 shows the development of the LCC over a time period of 50 years for the following three scenarios:
— Variant 0: no grinding;
— Variant 1: cyclical grinding every 60 MGT (3-year interval), grinding cost 5.05 EUR/m;
— Variant 2: cyclical grinding every 120 MGT (6-year interval), grinding cost 13.82 EUR/m.

The grinding costs depend on the amount of material removed and include the costs of machinery and staff, site supervision, safety arrangements and site planning. The costs of rail renewal are considered to be 100.52 EUR/m for the renewal of a single rail and 149.26 EUR/m for the renewal of both rails (values for a 1,000 m site length).

In Variant 0, the service life of the low rail is assumed to be 25 years. In Variants 1 and 2 it is justified to give the low rail at least the same service life as the high rail. Thus, in Variants 1 and 2, both rails are renewed at the same time. The summation of present values in Fig. 8 illustrates the discounting effect. The later a payment takes place, the lower the steps of the cost function are. At the end of the 50-year time period, the remaining value of the rails have to be considered as credits.

The results of the LCC calculation show the economic efficiency of cyclical rail grinding to extend the service life of the rail. Already, the six-year grinding interval extends the service life of the rail to 27 years. Payments for grinding at an amount of 2.55 EUR/(m·a) (annuity) lead to a LCC reduction of 12.25 EUR/(m·a). The shorter grinding interval of three years leads to a service life of the rail of 40 years. The annual payments for grinding are nearly the same, while the LCC is reduced by 2.29 EUR/(m·a).

The 40-year service life of the rail corresponds to that of concrete sleepers, which is also predicted to be at least 40 years. This means that cyclical rail grinding would allow the track to be renewed completely after 40 years, thus minimising track possessions and operation hindrances.



Situation without cyclical grinding

Situation with cyclical grinding

Fig. 7: Superposition of wear and crack growth on the high rail for the situation without cyclical grinding (top) and with cyclical grinding (bottom)

Vertical rail damage (mm) / artificial wear / natural wear / Track load (MGT)

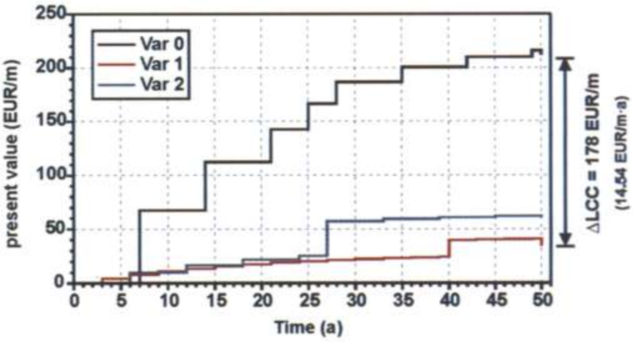


Fig. 8: LCC development over a 50-year period for three variants (interest rate 8%, inflation rate 2%)

It is interesting to observe the congruent LCC development of Variants 1 and 2 during the first years (see Fig. 8). Regarding annual costs, it does not make a major difference whether or not the rails are ground every three years or every six years. However, because of the extension of the service life of the rail, a three-year grinding interval is much more efficient. A further shortening of the grinding intervals leads to a further extension of the service life of the rail. However, the reduced LCC for rail renewal does not compensate the higher annual costs of grinding.

In order to identify the optimal grinding interval, the annuities of rail renewal and grinding were calculated for a bandwidth of different head check growth functions. The tolerable damage depth of 2.7 mm was reached as follows:
— after 90 MGT of traffic (Variant 1);
— after 135 MGT of traffic (Variant 2);
— after 180 MGT of traffic (Variant 3).

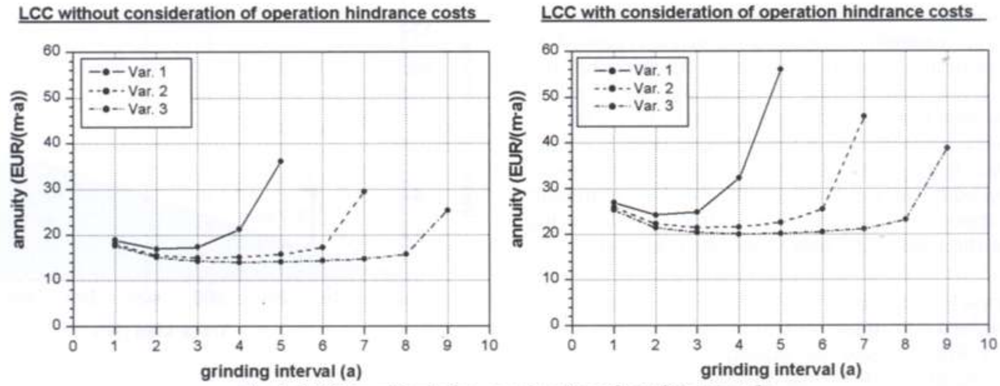


Fig. 9: LCC for rail grinding as a function of grinding intervals, for the situation without operation hindrance costs (left) and with operation hindrance costs (right)

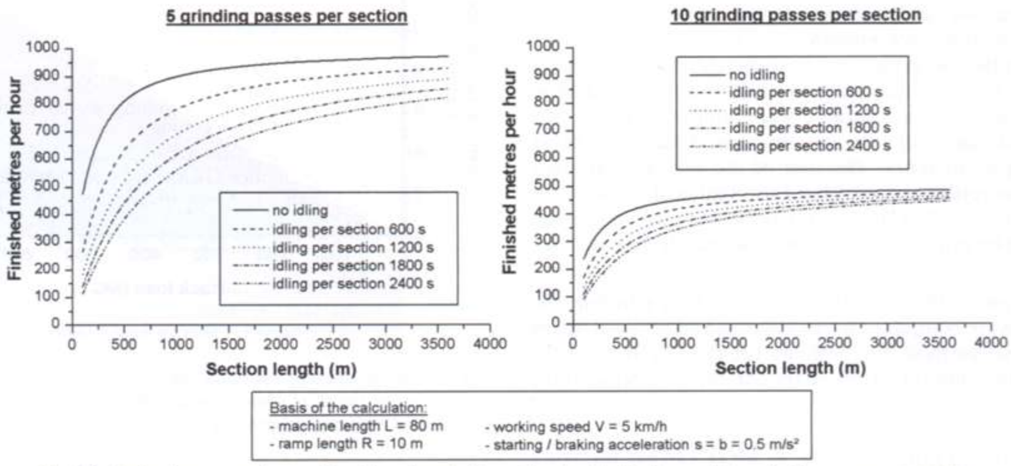


Fig. 10: Production capacity as a function of worksite section length, for five and ten grinding passes per section

The results shown in Fig. 9 again highlight the high cost efficiency of cyclical rail grinding. Any grinding strategy - at whatever interval - is better than doing nothing at all. For rails featuring rolling contact fatigue, grinding intervals of 40 to 80 MGT lead to the best economic efficiency. More frequent grinding does not increase cost efficiency. For instance, when grinding annually, the savings from an extended service life of the rail do not outweigh the grinding costs.

Operation hindrance costs do not affect the choice of grinding intervals. However, due to the high operation hindrance costs involved in rail renewal, the cost efficiency of cyclical grinding is increased further.

Optimal grinding intervals

The example applications of the LCC analysis method have shown that the optimal grinding interval is dependent upon the type and extent of the rail defect, and the costs of its elimination. Curves featuring long-pitch corrugation and head checks should be cyclically ground based on tonnage borne. For curves with rolling contact fatigue, the results show that optimal grinding intervals lie between 40 and 80 MGT, and for shallow curves and plain track between 80 and 120 MGT.

High-speed lines require special attention. To avoid overstressing of the rail, the running surface must always be totally level and, thus, grinding intervals of between 10 and 50 MGT are recommended.

Optimal planning of grinding interventions

Grinding interventions should be planned in such a manner that the highest possible productivity is achieved by the rail grinding machine deployed, in order to minimise the cost per metre of track treated. With shift costs for grinding ranging between about EUR 20,000 and EUR 25,000, this means that every single minute costs between EUR 40 and EUR 50. Thus, it should be a priority to plan an efficient use of the full machine capacity, and machine idle times should be avoided as much as possible.

Fig. 10 shows the finished metres per hour against the worksite section length being ground for different machine idle times, for five and ten grinding passes per section. As can be observed from Fig. 10, an adequate machine capacity utilisation is not possible for section lengths of less than 500 m. It is also important to ensure that travel times between consecutive worksites are kept as short as possible. In the case of consecutive worksites along a given route, the question to be answered is when the intermediate sections will require grinding. If a track section between two consecutive worksites has to be ground in a year's time, it may be economically viable to grind the intermediate section as well. If, however, grinding of the intermediate section is not due until after a few years, then a separate treatment at a later date could be more suited.

Using the LCC analysis method, the viability of grinding intermediate sections can be determined. In Fig. 11, for instance, the costs for grinding the consecutive sections (L1 and L2) and the intermediate section (LZ) at time t = 0 (at the present time) were compared with those of grinding LZ at t = n (after n years), for different machine lengths. A shift price of EUR 25,000 was taken as a basis for calculation in this LCC analysis. It was also assumed that there were five grinding passes per section. The results for the different section lengths are shown in Fig. 11.

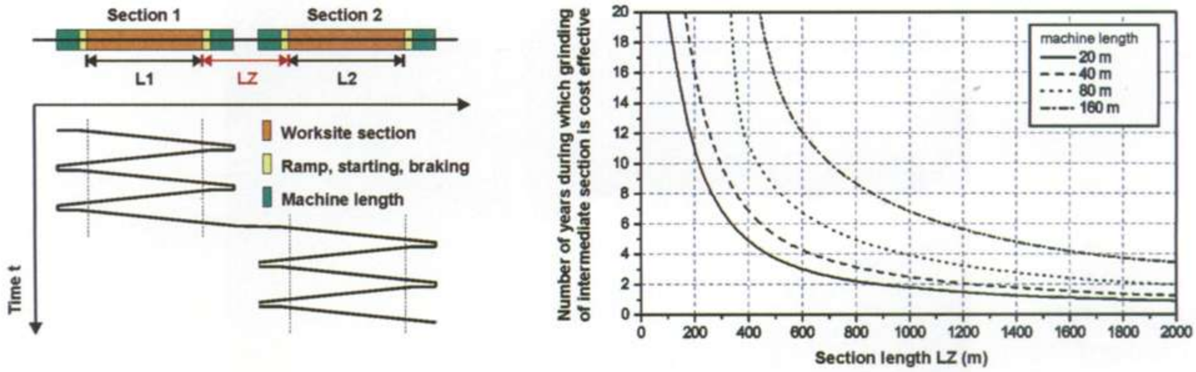


Fig. 11: Cost efficiency of grinding intermediate sections

Recommendations

For technically and economically efficient planning of rail grinding interventions, the following recommendations should be taken into account:

- *conduct cyclical grinding, instead of corrective grinding following the detection of rail defects:* track sections that exhibit predictable behavioural characteristics, especially track sections featuring rolling contact fatigue and sharp curves featuring long-pitch corrugation, should be ground cyclically;
- *conduct efficient route planning and linking of worksites:* in order to optimally utilise the high machine capacities and to minimise machine idle times, a careful route planning is required. Wherever possible, worksite lengths of less than 500 m should be avoided;
- *optimally coordinate track possessions:* cyclical treatment of defined sections of track facilitates the planning of track possessions, thus leading to a better coordination of maintenance and train traffic and, consequently, a reduction in operation hindrance costs;
- *provide machine parking facilities:* in order to minimise machine idle times, if possible, parking facilities should be provided along the line.

CONCLUSIONS

As the LCC analysis method described in this article has shown, by means of cyclical rail grinding, the costs of controlling head checks in curves can be reduced by 50% and the service life of the high rail in shallow curves of main lines be extended to about 40 years. Also, a smooth rail running surface leads to a reduction in track stresses. Thus, by means of cyclical grinding, the service life of a track featuring concrete sleepers can be increased to 40 years. An essential precondition for achieving this, is a targeted, i.e. carefully planned and timely, maintenance.

Carefully planned machine deployments lead to further cost reductions. Internationally, production time (time for grinding, reversing, measuring, cleaning) amounts to about 60% of the machine deployment time. If the ratio production time/deployment time could be increased to 70%, from the present 60%, this would lead to a cost reduction of 14%. Thus, in Germany, for a calculated budget requirement of EUR 50-60 million per annum [15], this would lead to an immediately achievable saving of EUR 8.4 million per annum.

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Website: www.speno.ch