

Technical and Economic Evaluation of Maintenance for Rail and Wheels on Malmbanan

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Summary: This paper provides an overview of how maintenance costs for rails and wheels are distributed between infrastructure owner and rolling stock owner on the basis of a study performed in close co-operation with MTAB (Malmtrafik i Kiruna AB, iron ore transportation company), Banverket and Duroc Rail AB. This paper presents a technical and economic correlation between maintenance activities and decisions performed by MTAB, Banverket and Jernbaneverket. Technical aspects are generated by controlling rolling contact fatigue (RCF) failures and wear in combination with grinding. RCF damages such as head checks are a common problem on high rails gage corner, causing the main replacement cost for rails. To reduce replacement of rails caused by RCF a grinding program started 1997. The balance between controlled wear, with or without lubrication and grinding, are very important tools to ensure long life and effective maintenance operation for both the infrastructure and rolling stock. Rail profile measurement since 1997 gives an indication of parameters that have to be taken into account when choosing grinding strategy at Malmbanan.

Economic aspects are generated from different maintenance activities such as grinding and re-profiling wheel sets. The results give an indication of how different parameters affect maintenance performance. Aspects such as wheel/rail interface and car steering ability affect maintenance costs over the studied period.

Index Terms: Grinding, Wear, Costs, Wheel, Rail, Maintenance.

1. INTRODUCTION

In railroad heavy haul applications, grinding and lubrication are routinely used as a maintenance tool in curved track sections in order to reduce friction, wear and rolling contact fatigue (RCF). The cost of maintenance of wheel and rail for heavy traffic such as ore lines can be up to fifty per cent of the total maintenance cost of the rail/wheel system. For instance, proper lubrication can reduce wear rates by a factor of 20, Elkins et al. [1] and Waara [2]. Grinding programs can also produce significant cost savings for both the wheel and infrastructure owner, see Grassie et al. [3].

During the past 30 years axle loads have increased from 25 tons to 32.5 tons per axle, Allen [4]. This has been possible due to improvements in metallurgy, larger rail cross sections standardization of heat-treated wheels, development of new rail/wheel profiles and the extensive use of track lubrication and grinding.

Wear of rails and wheels has long been identified as a major reason for the high maintenance costs of rail infrastructure. A second major cause of the degradation of rail is rolling contact fatigue (RCF). As the wear rates of rail have decreased due to the factors described above and the axle loads have increased, RCF has become a more important problem.

If the wear rate drops below a certain value the rail surface reaches its fatigue limit before it can be worn away. Preventive grinding programs are designed to grind away a thin layer of material from the rail surface before RCF cracks can develop. The depth to which RCF cracks penetrate determines the amount of material that has to be removed. Lubrication can slow the initiation of surface and contact fatigue cracks, but it might accelerate crack propagation.

To optimize the life of railway infrastructure, wear rates, the development of RCF cracks and grinding have to be carefully balanced. The rate of wear is larger if softer rail steel is used and any damage or cracks are worn away before the critical deformation is reached. However, while no

cracks are observed in the softer rails, they are consumed earlier by wear, see Pointner and Frank [5]. A hard rail will not wear as much, but after a certain time it will suffer from RCF and may need replacement having suffered only a small amount of wear. Also, lubrication, which reduces wear, shifts the failure mode from wear to crack formation.

A systematic experimental test program of wheel/rail adhesion and wear was undertaken using the Illinois Institute of Technology's 1/4 scale wheel rail simulation facility, see Kumar et al.[6]. The tests determined the effects of axle load, adhesion coefficient, angle of attack, class of wheels and mode of operation. Wear was measured by overlaying profiles of the wheel/rail surface at different stages of wear and measuring the change in cross-section area. The hierarchy of influencing parameters for wheel/rail wear in order of priority was given as:

- 1) rail curvature or angle of attack
- 2) adhesion coefficient
- 3) axle loads

Lubrication improves interactions at both micro and macro level of the wheel/rail interface. However, today no general model or strategy that describes the interactions between wear, lubrication and grinding at the wheel/rail interface exists, see Clayton [7] and fundamental studies have only been carried out during the last thirty years. Models that have been developed to simulate real field phenomena are often designed for specific problems and cannot be extrapolated to the general situation.

More studies have to be completed before a general model can be developed to treat combination of technological-economic maintenance activities such as grinding and lubrication correlated with stringent cost efficiency evaluation. The challenge is in combining the outcomes of technical maintenance activities with an economic analysis.

2. WHEEL/RAIL INTERACTION

The ore car is a four-axle heavy-haul freight wagon specifically designed for the transportation of ore. This so-called BoBo vehicle contains a car body sitting on two two-axle bogies. A side view of an ore wagon is shown in figure 1.

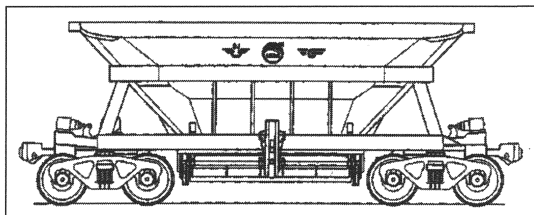


Figure 1. Four-Axle Ore Wagon with Three-Piece Bogies.

The bogies are so-called three-piece bogies, where the bogie frame consists of two side frames and a bolster coupled together into a bogie frame.

In service, the wheel and rail profiles change substantially due to wear and the fleet of trains passing over a section of rail will have a range of wheel profiles at any one time, ranging from new to worn. Simulations have been performed in order to investigate the wear rate sensitivity as function of the wheel/rail profiles. In this investigation steady-state curving of a Malmbanan ore car was investigated using a multi body dynamics model and the numerical algorithms implemented in the commercial software GENSYS [8]. The model was validated using field measurements, see Berghuvud [9]. Seven different wheel profiles, including a nominal S1002, were used to compare the influence of wear rate as function of wheel profile status. The vehicle is run on designed track with new (nominal) UIC60 rail profile, see figure 2.

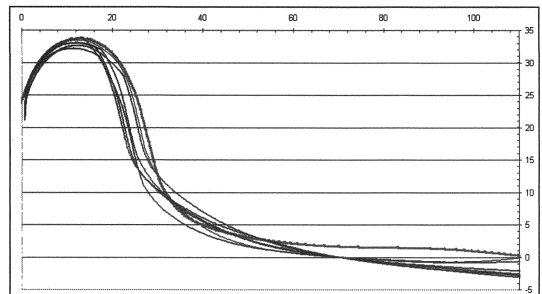


Figure 2. Measured in service measured wheel profiles (dark) and a new nominal (gray) wheel profile S1002. The scales is in mm.

2.1 Simulation Results

Changes in wheel profile have only a small influence on the contact forces, contact dimensions and positions on the high rail for the trailing wheel set. The contact conditions for the other contacts are significantly influenced by the change of wheel profile. Calculated energy dissipation is used as an indication of the amount of expected relative change of wear for the different profiles, [9]. High difference in creepage and tangential forces gives high difference in energy dissipation at the wheel/rail interface. Some combinations of profiles produce more severe wear than with a single contact patch, see table 1.

The results presented here should be viewed upon as examples of what types of results the developed model can support used in maintenance planning.

Table 1. Energy dissipation for different wheel/rail profiles.

Nominal rail profile		
	High Rail (J/m)	Low rail (J/m)
Leading wheel set	180-245	90-135
Trailing wheel set	45-55	45-130
Worn rail profile		
	High Rail (J/m)	Low rail (J/m)
Leading wheel set	50-250	75-175
Trailing wheel set	10-50	10-75

3. RAIL PROFILE MEASUREMENT

Transverse profile measurements of outer and inner rails were performed at 60 positions along the rail located on Malmbanan. Banverket used the MiniProf Rail system to measure the profiles. The profiles were measured shortly before and after the grinding of the rails. Results of these measurements are presented in different ways and the MiniProf Rail system provides an easy, portable tool to monitor and evaluate rail profiles. The system is a useful aid for rail grinding operations, providing instant information on profile and metal removal.

MINIPROF is a standard system for the determination of rail profiles in the field. The sensing element consisted of a magnetic wheel 12 mm in diameter attached to two joint extensions. When the magnetic wheel was moved manually over the rail surface, two angles were measured and stored in a computer. The profile was then transformed to Cartesian co-ordinates. Marks on the edge of the rail were used to ensure that the measurements were performed at the same location each time. Further information on the MINIPROF system can be found in Esveld and Gronskov [10]. The accuracy of the MINIPROF system is of the order ± 0.015 mm for similar profiles.

3.1 Rail profile results

A grinding program was initiated by The Swedish National Rail Administration (Banverket or BV) 1997 at Malmbanan, the Swedish ore track between Kiruna and Riksgränsen. The grinding is primarily to remove RCF, which has been an increasing problem in recent years. In the seventies, the axle load was increased on this track to 25 tonne and again in 2001 a new ore care was introduced giving 30 tonne axle loads. This rise in axle load increases the susceptibility of the rail to RCF. In 1997 a new asymmetric profile MB1 was introduced. As the contact path in this profile is wider than previous profiles, the onset of RCF should be delayed. Before the grinding program started the curved track was prepared with 60 measurement points and 10 points on the tangential track. BV has carried out rail profile measurements before and after the grinding activities every year since 1997. The grinding campaign is here evaluated at

the ore track between Kiruna and Riksgränsen with a total length of 127 km.

To evaluate the combined effects of the track wear and the grinding, the track is divided into three categories: track curves with radius under 800 m, track curves with radius over 800 m is another group and tangential track, see table 2. In this paper, the yearly wear and the amount of material removed due to grinding is evaluated at these points. The yearly wear and grinding indicate the proportion of the life of the rail consumed according to BV's regulations (BVF 524.1 [11]), which indicate when the rail should be replaced.

Table 2. Grouping of grinding for Malmbanan.

	Length [m]	Grinded/year
Radius<800	51 791	100%
Radius>800	30 526	100%
Tangential track	48 220	33%

The tolerances for the ground profile compared to the reference profile have been changed during the period from 1997 to 2001 and nowadays the high rail diverge should be within +0.3/-1.0 mm on the railhead between -20/50 Miniprof degrees. A minimum metal removal is set to be of at least 0.2 mm in the area between 0° and 45° every 23 MGT.

The grinding results were evaluated over year 2000 and the wear over 10 months in 1999/2000. The wear results over 10 months are afterward compensated to correspond to wear per annum based on ore traffic volume.

The results of grinding and wear from traffic at the high rail for curves under 800 m is summarized in figure 3. The mean yearly traffic wear was around 0,18 mm at β=10° (β is Miniprof degrees according to figure 3). As the figure shows, the average material lost on the railhead to grinding per annum was 0.4 mm and when coupled with the wear, 0.6 mm was lost on the railhead per annum.

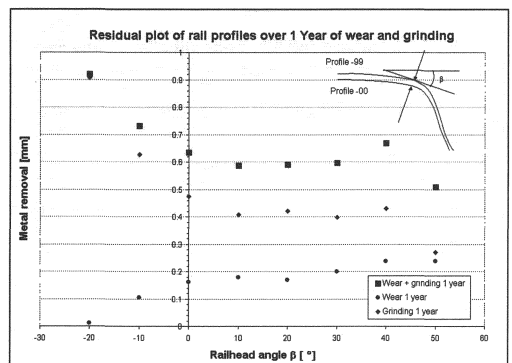


Figure 3. The mean wear for one year and the amount of removed material during one grinding campaign is presented in this diagram.

The measurements in figure 3 also show that traffic wear and grinding wear is of the same order in the 45-50 degree region. Grinding wear (0.4 mm) is twice as much as traffic wear (0.18 mm) for the 10-40 degree region. The train/track simulations, table 1, indicate that it could be possible to use an other portion of the existing worn wheel profile population distribution to increase the traffic wear to the same amount as the total wear presented in figure 3. This might produce higher rail wear in the 10-40 degree region and hence save costs by prolonging the grinding intervals. The rail profile was evaluated due to the rail grinding campaign year 2000 as well as the wear for one year. This yearly rail profile evaluation will help to predict future renewal of rail. Around 20 profiles for high respective low rail and 10 profiles at tangential track were measured and used in this investigation. The profiles used here were measured before and just after a grinding campaign each year. The profiles were considered of measuring quality chosen among 60 profiles in curves and 20 profiles at tangential track. When evaluating the rail wear there are two measurement values to consider according to the Swedish standard for railhead wear measurement. The vertical wear on the railhead h and the flange wear s , 14 mm down from the top of a new rail profile ($\beta=36.4^\circ$), see equation 1.

$$H = h + \frac{s}{2} \tag{1}$$

Once H reaches a critical value, H_{limit} determined by a rail classification system, the rail must be replaced. The rail life is separated into 5 different groups, high and low rail under 800 m curve radius, high and low rail over 800 m curve radius and tangential track. One third of the tangential track is ground each year. The yearly wear on the tangential track railhead is estimated to be the same as low rail in curves with radius > 800 m. The cost of replacing the one rail side was 800 SEK/m rail (high rail=one side, low rail=one side) (87,5 USD\$/m). The rail life is evaluated in the Miniprof software and presented in table 3.

Table 3. Calculated rail life, using equation, 1 and costs evaluated from one year of wear and one grinding campaign.

	Curve radius <800		Curve radius >800		Tangential track
	High rail	Low rail	High rail	Low rail	
Life [years]	13,6	17,7	19,6	23,9	38,9
Length [m]	51791		30526		48220
Cost [MSEK]	3,05	2,34	1.25	1,02	1,98
Yearly needed rail investment cost [MSEK]					9,6

These lives are derived from equation 1 and assume that railhead material is removed only by traffic wear and

grinding. Using both traffic and grinding wear rates from rail profile measurements i.e. figure 3 is one example, it is possible to predict the total yearly vertical railhead wear (h mm/year) and the total flange wear (s mm/year) and hence calculate H mm/year for the different track sections. The safety wear limit H_{limit} is set to 11 mm for the 50 kg/m BV50-rail profile used. The average rail life is then calculated as the ratio between the safety limit H_{limit} and the measured H value of the studied section. Using this approach it is also possible to estimate the number of meters of rail in each section, that needs to be replaced due to railhead material loss each year. These calculations suggest that 12000 ± 1900 m rail need to be replaced each year average, which corresponds to a yearly investment of 9,6 million SEK (1,05 million USD\$). The yearly cost of grinding this track should be around 4 million SEK, giving a total yearly maintenance cost of 13,6 million SEK.

4. ECONOMIC EVALUATION

An economic analysis of Malmbanan made 1995 indicates that about 50% of the total cost for maintenance and renewal was related to traffic and 50% was related to other factors such as signaling, electricity, snow-clearance etc. Costs for maintenance and renewal of rails on some lines account for more than 50% of the costs related to traffic. The results from this analysis have made it possible for the mining company LKAB to start up the 30 tons traffic with new wagons and locomotives on the Malmbanan line in year 2001. The focus in this economic evaluation is therefore to examine the costs generated by maintenance and the replacement of rails and wheels.

The approach is to combine the technical and economic modelling to determine how decisions based on technical activity affects the economy of the wheel/rail interface. In this case the technical activity of concern is rail grinding.

4.1 Data collection

Data were collected from a literature search, different databases at MTAB, Duroc Rail, BV and Norwegian Rail and from interviews with personnel at the different companies. It was found that primary data is located at different levels for each company, depending on internal needs and demands. It was also found that economic costs and results are presented and based on technical aggregated data, resulting in difficulties in comparing between different companies at primary information levels. Therefore it is not possible to determine how every technical detail affected the system.

4.2 Infra structure maintenance activities and costs

The rail-grinding project on the Malmbanan line between Kiruna and Riksgränsen reduced the requirement for rail

replacement from approximately 25 000 meter to 5 000 meter annually, as shown in figure 4. In this paper the rail life due to wear and grinding was evaluated on the basis of material loss rates and the mean renewal level is suggested to be 12000±1900 m over the same distance. In figure 4 it is possible to see a very significant reduction of rail renewal during the first years after the grinding campaign started. However, it is likely that this effect is transient and is simply delaying the requirement for track replacement. After some years of grinding the track will become degraded and an accumulated volume of rail will need to be replaced. The track status is not considered in this paper and therefore it is not possible to make any more exact investment calculations. However it is likely that the cost level will be a bit over 13,3 million SEK. However this cost level is significantly reduced when compared with the years 93,94,95 and 96. The result so far in economic terms is a reduction in rail maintenance costs of approximately 50%.

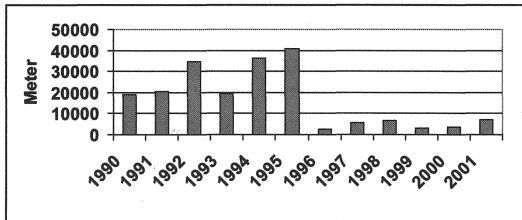


Figure 4. Quantity of annually rail renewals on the ore track between Kiruna and Riksgränsen.

In 2000 Norwegian Rail changed their maintenance strategy, deciding that renewal of rails shall be done only on the basis of MINIPROF data or similar objective measures. This new strategy has halved rail renewal demands. So far, economic results indicate reduced maintenance costs, but no deeper analyses are made to confirm new cost levels.

4.3 Ore car maintenance activities and costs

MTAB's maintenance program is based on experience and relates to driven distance for the ore car. In practice this means that the ore car wheel set is checked every 30 000 kilometer. Normally the wheel profile lasts for approximately 120 000 kilometer, after which it is necessary to re-profile the wheel and its geometry. Each wheel can be re-profiled 4 or 5 times. The type of wear/damage that dominates changes over time, but analyses shows that as one wear mode decreases another mode increases. More important is that the total number of wheel sets replaced per annum decreased, as shown in figure 5. However, at this stage it is too early to link the reduction in wheel set replacements to the ongoing grinding program.

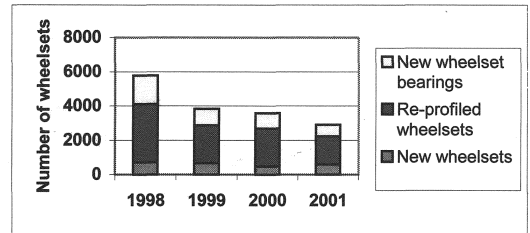


Figure 5. Number of worked/shifted wheel sets

The major problem for MTAB is that the cost of replacing wheels is at least ten times more than re-profiling an old wheel. During the last year, MTAB has introduced a new wheel material with better wear resistance. This could be one of the explanations why the turnover of wheel sets decreased. The distribution of wheel age in the population of wheels is not constant over the years and this will affect the cost levels between different years. Different wheel wear modes will require different re-profiling. If one wear mode is very fast for short periods this can result in high maintenance costs if that particular wear mode results in shifting to new tires. Therefore it is possible for MTAB to incur higher overall costs even if the total number of worked and shifted iron ore wheel sets decreases, which also happened in year 2001.

4.4 Results from an economic perspective

Analysis made from an economic overview perspective for the Malmbanan as a transporting system, shows that maintenance processes and strategies related to rail/wheel interaction do not seem to affect the total system in a negative way. However, once again the problem is that all comparisons have to be made at high aggregated data levels, which make it possible for subsystems to show different results.

5. DISCUSSION

Using train/track simulation in maintenance planning provides a powerful tool to predict changes in wear due to different rail/wheel profile strategies. Simulations and field observations clearly suggest that, by altering load traffic direction of cars would produce longer wheel life. The results in table 1 indicate that for the same three-piece bogie a leading wheel set can have up to five times higher wear than a trailing wheel. Some years ago MTAB had problems with high leading wheel set wear. They introduced a logistic change of loaded car direction and hence prolonged the leading wheel life. This kind of train/track simulation is a powerful low cost tool for estimating and predicting traffic wheel and rail wear. It can be used in the optimization of wheel and rail profiles on a traffic routes such as Malmbanan. A technically optimized wheel/rail profile

combination can be used in maintenance planning to decide on new strategies such as maintenance intervals for both rail and wheels.

The grinding project was an important step to make it possible to increase the axle loads to 30 tonnes. The grinding program was also one of the main strategies to prolong the renewal of existing 50 kg rails. Even after only a short time, there are measurable costs savings for both infrastructure and traffic. However, this procedure may simply be delaying the costs and an accumulated rail renewal will appear in the future due to degradation of the rail. It is too early to suggest, that for the long time run, the introduction of grinding has led to decrease costs and an increase in rail and wheel life. Maybe future life cycle cost analysis can provide an answer. However, ultrasonic inspection is indicating that grinding has increased the number of rails replaced due to rolling contact fatigue.

This rail life investigation indicates that the maintenance program has delayed maintenance costs to the future and a suggested mean level of rail renewal is suggested. Optimizing the grinding process by for example using train/track simulations is one possible step to increase rail life, however it is uncertain if the economic potential is enough.

6. CONCLUSIONS

- The grinding campaign delays major replacement of rail to the future.
- The grinding program is evaluated to give a yearly cost of 13,6 million SEK included rail renewal and grinding campaign.
- Train/track simulations can be used as a tool in maintenance planning.
- Train/track simulation clearly suggests that by altering the load traffic direction of the cars it would be possible to obtain longer wheel life.
- Neither grinding campaigns on the Swedish side or objective measurements to increase rail life on the Norwegian side seems to affect the total system in a negative way.

7. ACKNOWLEDGEMENT

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