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Effects of Gauge Widening and Wheel Wear on Low Rail Surface Damage of Heavy Haul Line

O. P. Yadav, J. Leung, S. Stichel and M. Berg

Department of Engineering Mechanics,
KTH Royal Institute of Technology
Stockholm, Sweden

Abstract

High axle load poses several challenges for infrastructure management. The introduction of 30-tonne axle load wagons on the Swedish iron ore line exacerbated rolling contact fatigue challenges. While infrastructure managers have effectively controlled rolling contact fatigue on the high rail of curves through the adoption of wear-resistant rail profiles and optimized rail grinding practices, mitigating rolling contact fatigue on the low rail remains a significant challenge. Particularly, tight curves with radii up to 850 meters are prone to spalling defects under widened gauge conditions. Therefore, this study investigates the impact of gauge widening and wheel profile wear on wheel-rail interaction and rail damage. A multi-body dynamic model of an iron ore wagon is implemented in the GENSYS software environment. Practical degradation parameters relevant to wheel-rail interaction are incorporated for both the vehicle and track. Simulations are conducted under normal and widened gauge conditions to assess the differences in severe gauge widening scenarios. The simulation results demonstrate that under widened gauge conditions, rolling contact fatigue on the low rail exhibit considerable increase compared to normal gauge operations. The combination of increased wheel hollowness and gauge widening further exacerbates rolling contact fatigue. Moreover, the effect of running speed indicates that reducing speed is advisable to minimize rail damage in widened gauge conditions.

Keywords: low rail rolling contact fatigue, spalling, rail surface damage, wheel hollowness, wheel-rail interface, gauge widening.

1 Introduction

The railway line under investigation in this study is the heavy haul iron ore line (Malmbanan) in Sweden. Malmbanan is a key heavy haul line connecting iron ore mines in northern Sweden to the ports of Luleå in Sweden and Narvik in Norway. It allows trains up to 750 meters long, consisting of 68 wagons with 30-ton axle load when fully loaded and two six-axle locomotives. Following the track upgrade, starting in the mid-2000s, there was a notable rise in damages associated with wear and rolling contact fatigue (RCF) on the rails. While infrastructure managers have successfully addressed RCF on the high rail of curves with wear-adapted rail profiles and optimized rail grinding practices, RCF remains a substantial issue on the low rail [1]. Specifically, tight curves with radii up to 850 meters exhibit spalling defects when subjected to widened gauge conditions.

Heavy haul operations (high axle load) impose substantial normal loads on the track, leading to increased stress and fatigue on track components [2]. The occurrence of RCF and wear on rails is influenced by several key factors linked with wheel-rail interface, for instance, curve design geometry and track condition [3], vehicle type [4], wheel and rail profiles [5], wheel and rail material [6], operational conditions, etc. [7].

Kuka et al. [3] examined the design and degraded parameters of the track, highlighting their significance in vehicle-track interaction. They concluded that track design and degradation exert a larger influence on vehicle-track interaction than the track characteristics itself. Asplund et al. [1] related the RCF on low rail with gauge widening through field observation data. These conclusions were recently corroborated by Flodin [8] in his thesis, which utilized multi-body dynamic simulations. Flodin´s findings indicated that the current maintenance gauge limit is appropriate; however, failure to adhere to it results in worsening the wheel-rail contact conditions.

While maintenance limits set by the operator and safety limits from infrastructure manager, for hollow wear are 1.5 and 2.0 mm, respectively, the measured data shows scattering of this parameter up to 5.0 mm [9]. It is evident that achieving fully effective maintenance is unattainable, and some wheels with hollowness exceeding the limits may persist. Therefore, understanding their impact on rail surface damage becomes crucial. Similar instances of wheel hollowness were observed in a study conducted by Sawley and Wu [10] in the North American railway system, where the effect of wheel hollowness was investigated. The study found that increasing hollowness results in a negative rolling radius difference, leading to elevated contact stresses on the top of the low rail in curves. Concurrently, Sawley et al. [11] conducted a study on the stability of vehicles with hollow wheel profiles. The study concluded that the amount of hollowness is not the sole indicator, but other wheel profile parameters and the gauge widening are also important.

Silva et al. [12] conducted a statistical simulation using a large set of worn wheel profiles to investigate the effect of tread wear on RCF of wheels. Their analysis revealed that within the wear range of 1.0 mm to 2.0 mm, the highest occurrences of maximum contact pressure were observed for both wheels. Furthermore, for tread wear values between 1.5 and 2.0 mm, the majority of observed occurrences corresponded to the highest contact pressures. Consequently, it can be inferred that beyond a wear depth of 1.5 mm, the contact pressure, and consequently the likelihood of RCF, increases.

Railway operation is a complex system involving vehicles, tracks, operational and environmental conditions, and maintenance activities. Modelling such a complex environment with changes in all associated parameters is beyond the scope of this study. Therefore, this study only focuses on vehicles and tracks. Furthermore, this study does not address the design parameters of vehicles and tracks; instead, the focus is on the degradation of relevant vehicle and track parameters. In this regard, the two degraded parameters under focus are (actual) track gauge and wheel wear.

This study provides insight into how wheel-rail interaction changes in real-world scenarios under operational conditions and how maintenance activities should be adapted for the given vehicle type. Suggestions for changes in vehicle or track design are costly and time-consuming. Therefore, the objective of this fundamental work is to contribute to assessing possible maintenance practices to extend rail life without necessitating changes in vehicle or track design.

2 Methodology and Simulation Cases

In this study, the Malmbanan line, specifically the segment spanning between Kiruna and Riksgränsen at the Norwegian border, is chosen. This section covers approximately 120 kilometers and features a significant number of curves. The research investigates rail damage occurring in tight curves due to iron ore trains operating under various conditions and maintenance statuses. The methodology relies on multibody dynamics simulations conducted using the GENSYS software platform, which employs comprehensive vehicle and track models, along with corresponding input data and representative operational scenarios.

Table 1 presents the distribution of curves along with important design parameters. To maintain a manageable number of simulation cases, only curve group 2 is considered, as it has the largest share among curves in the line. This choice provides sufficient information on vehicle behaviour in curves. The Malmbanan line is divided into northern and southern loops. The northern loop which has been considered in this study, primarily handles cross-border traffic and is predominantly utilized for exporting iron ore to other European countries from the port in Narvik. In order to reduce the number of simulation cases, this study exclusively analyzes the contribution of iron ore wagons under loaded conditions.

Table 1: Curve distribution in the selected line.

Group No.	Radius [m]	Frequency	Mean radius [m]	Mean curve length [m]	Mean transition curve length [m]	Actual percent share	Mean cant [mm]
1	<550	12	496	249.2	86.8	4.08%	58.8
2	550-650	82	594	226.3	102.8	28.50%	62.7
3	650-750	16	691	129.3	101	4.26%	52.8
4	750-850	17	780	230.8	97.7	5.82%	49.7
5	850-1500	42	1112	213.2	90.5	13.32%	36.8

The maintenance limit for hollowness is set at 1.5 mm, while the service limit is 2.0 mm. However, real-time data indicates the presence of some wheels with hollowness values as high as 5.0 mm. Therefore, multiple levels of wheel hollowness have been taken into account. Analysis of experimental data also revealed variations in the amount of hollowness among all the wheels of each wagon. Conducting an extensive investigation into the effects of each axle and wheel side is beyond the scope of this study and will be addressed in future research. However, to develop a basic understanding of the effect of hollowness alone and in conjunction with other parameters, a simplification was necessary. Thus, we assumed all wheels have the same worn profile. Figure 1(a) illustrates the nominal and worn wheel profiles with their approximate hollowness values. The wheels of iron ore wagons feature special profiles known as WP4. The rail profiles on the high rail and low rails, are designated as MB1 and MB6, respectively, which are modified forms of UIC60 rails achieved through grinding (Figure 1(b)). Only nominal rail profiles are considered in this study.

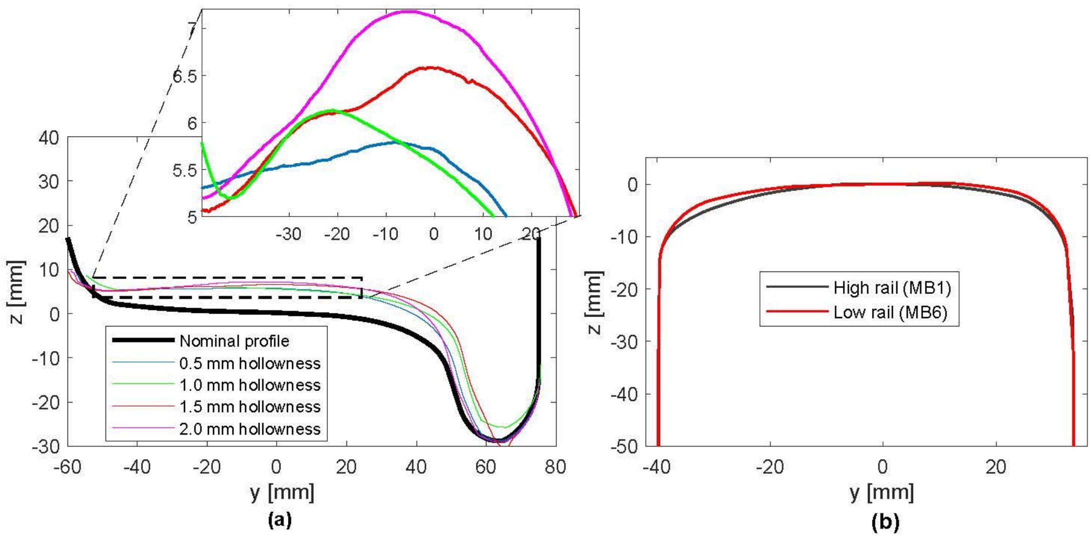

Figure 1: (a) new and worn wheel profiles and (b) rail profiles.

The track under consideration is a standard gauge track with a nominal gauge value of 1435 mm. However, under practical conditions, this gauge value is never exactly 1435 mm, not even during the design phase. Furthermore, operational conditions often result in significant gauge widening, particularly on tight curves. Experimental observations indicate that the mean gauge value in tight curves can reach as high as 1470 mm. The current maintenance limit for tight curves is set at 1450 mm. In our study, we accounted for variations in the average gauge up to 1465 mm. To conduct a parametric study with variations in track gauge, the average gauge was manually adjusted. Additionally, to incorporate the dynamic effects of track irregularities, track irregularity data before tamping was selected, as presented in Figure 2.

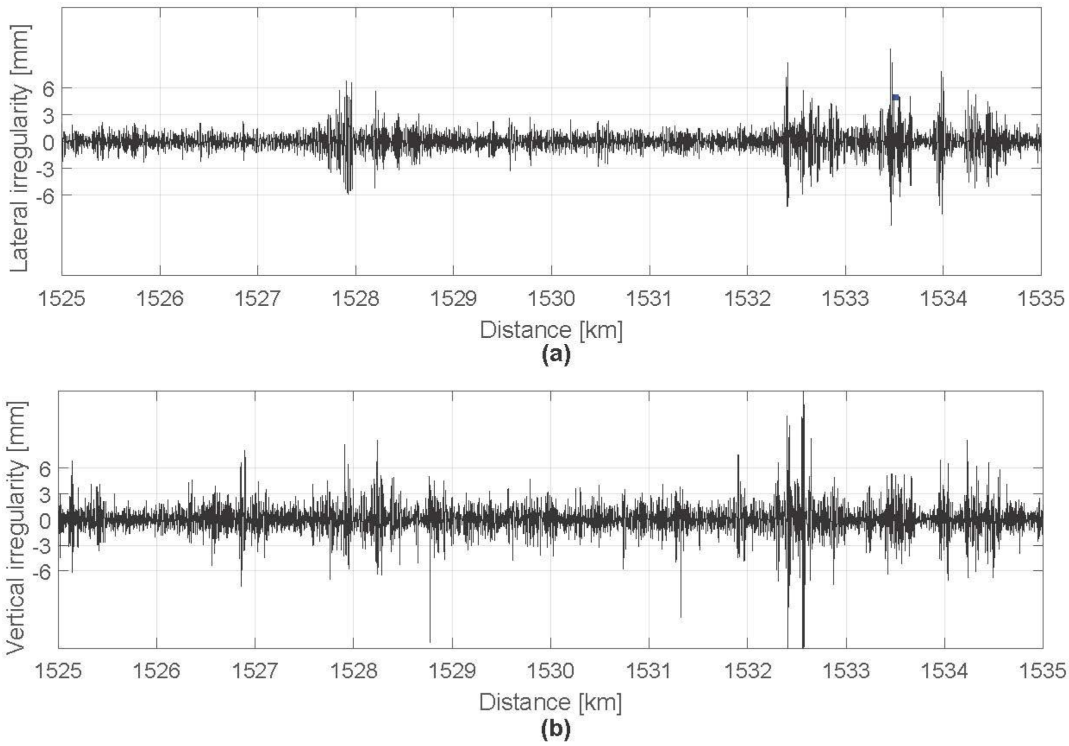

Figure 2: Measured lateral and vertical track irregularities before tamping.

The maximum permitted speed for loaded trains on the selected line is 70 km/h; however, actual train speed profiles indicate an average speed of 60 km/h. Running speeds of 70 km/h and 50 km/h are also taken into account in the study. For the curve under consideration, the balance (equilibrium) speed is approximately 60 km/h. Consequently, at 70 km/h, there is a cant deficiency of around 30 mm, while at a running speed of 50 km/h, there is a cant excess of about 15 mm. Therefore, the effects of both cant deficiency and excess are also considered.

3 Results

Spalling is the main issue with low rails, which is a surface fatigue phenomenon. The surface fatigue index developed by Ekberg et al. [13] is used. A positive value of this index indicates a likelihood of RCF. Since the entire curve length cannot be under the likelihood of RCF, an average RCF index alone is not sufficient. Therefore, to accommodate the average RCF index and the affected curve length to better represent the severity of RCF, a new RCF indicator is defined. It is defined as the average value of positive surface fatigue indices multiplied by the percentage of curve length with positive surface fatigue index.

The time series data for RCF index was collected corresponding to the times between right side wheel of leading axle just entered the curve and left the curve. Then following equation (Eqn. 1) was used to estimate the defined indicator:

$$RCF\ indicator = AVERAGEIF(\text{RCF index}(1\text{:end}) > 0) \times \frac{\text{COUNTIF(RCF index(1:end)>0)}}{LENGTH(\text{RCF index(1:end)})} \times 100 \tag{1}$$

The operational parameters are varied individually, keeping other parameters constant. One set of results was produced for the nominal case, i.e., nominal wheel profile, 1435 mm gauge, UIC irregularity level QN<1, friction coefficient 0.5, and running speed of 60 km/h. Other sets of results were produced for the degraded case, mostly considering maintenance limits, i.e., 1.5 mm wheel hollowness, 1455 mm gauge (greater than 1450 mm), irregularity level QN<1, friction coefficient 0.5, and a running speed of 60 km/h. The presented results are extracted from the wheel-rail contact at the low rail due to the inner wheel of the first axle of the leading bogie.

3.1 Wheel Hollowness

The overall results observation shows that the RCF indicator for degraded cases is higher than under nominal conditions. The difference is not only in terms of magnitude but also in terms of trend. Thus, consideration of actual degraded conditions is important. An increase in wheel hollowness while keeping other conditions at nominal levels (1435 mm gauge, irregularity level QN<1, friction coefficient 0.5, and running speed 60 km/h) results in an overall increase in the RCF indicator (Figure 3). However, for the case with degraded conditions (1455 mm gauge, irregularity level QN<1, friction coefficient 0.5, and running speed 60 km/h), it is very pronounced and increases at faster rates.

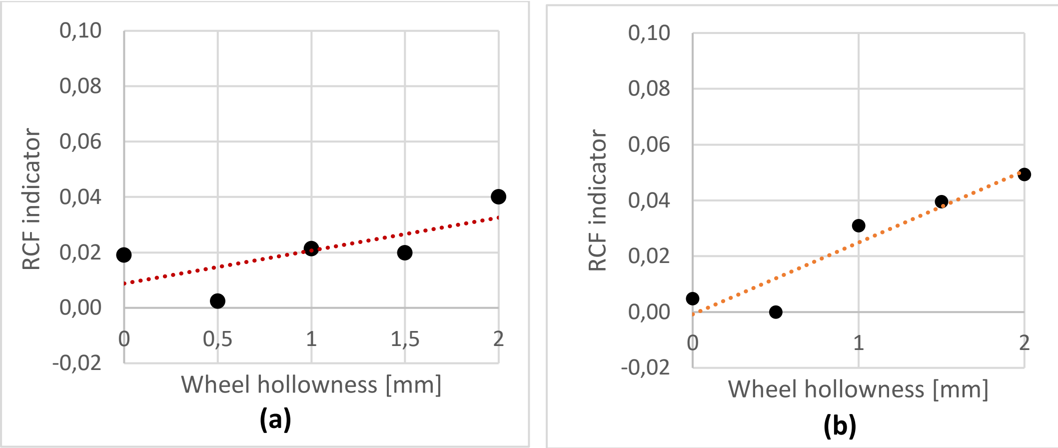

Figure 3: Variation of wheel hollowness under (a) nominal conditions (1435 mm gauge, irregularity level QN<1, friction coefficient 0.5 and running speed 60 km/h) and (b) degraded conditions (1455 mm gauge, irregularity level QN<1, friction coefficient 0.5 and running speed 60 km/h).

3.2 Gauge Widening

In the nominal wheel profile case, gauge widening is helpful as the RCF indicator shows a decreasing value (Figure 4). However, in the degraded case, with a wheel hollowness of 1.5 mm, it is observed that the trend is completely different. The RCF indicator is very low except in the gauge range of 1445 to 1455 mm. Within this range, a sudden increase in the RCF indicator is observed. This observed behaviour requires detailed investigation to understand such a trend. However, a preliminary observation is that beyond the gauge value of 1445, the rolling radius difference becomes negative with lateral displacement, for the considered worn wheel and nominal rail profiles presented in Appendix. The negative rolling radius difference causes a complete change in vehicle running stability and the rail-wheel forces.

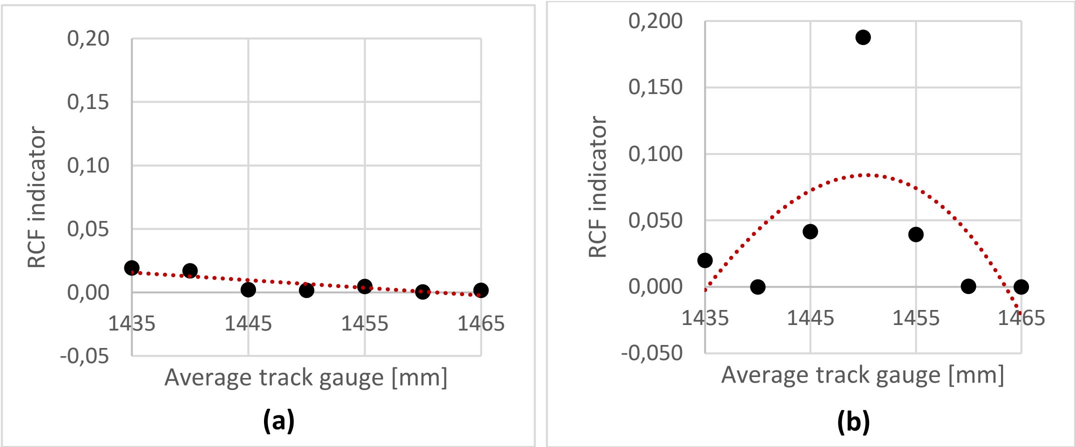

Figure 4: Variation of gauge under (a) nominal conditions (nominal wheel profile, irregularity level QN<1, friction coefficient 0.5 and running speed 60 km/h) and (b) degraded conditions (worn wheel profile with hollowness of 1.5 mm, irregularity level QN<1, friction coefficient 0.5 and running speed 60 km/h).

3.3 Speed Limitation

In nominal conditions, variation in running speed exhibits no significant impact on RCF. However, in degraded conditions, RCF indicator values rise with higher running speeds (Figure 5). Consequently, it can be inferred that when a significant portion of a train's wagon wheels exhibit high hollowness values and the gauge is widened, speeds exceeding 60 km/h should be avoided.

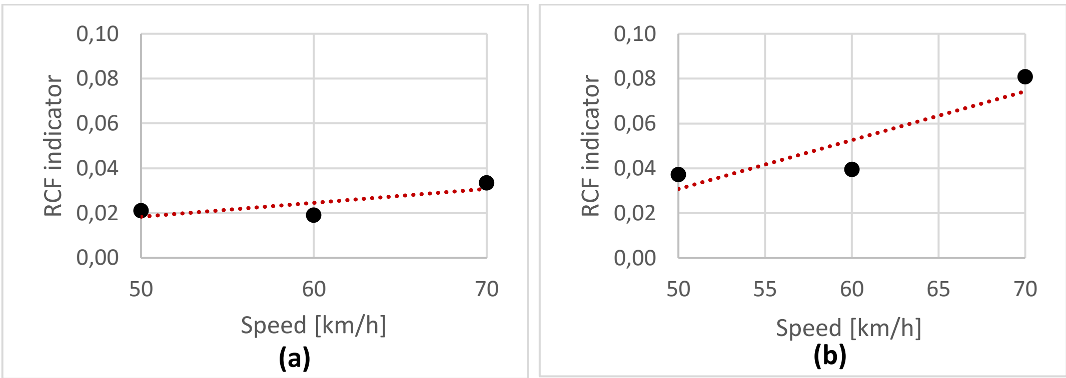

Figure 1: Variation of running speed under other (a) nominal conditions (nominal wheel, 1435 mm gauge, irregularity level QN<1 and friction coefficient 0.5) and (b) degraded conditions (wheel hollowness of 1.5 mm, 1455 mm gauge, irregularity level QN<1 and friction coefficient 0.5).

The impact of both gauge widening and wheel hollowness on RCF likelihood is evident. However, this study solely focuses on selected wheel profiles determined by their hollowness values. Yet, it's crucial to note that different wear profiles are possible even for identical hollowness values. Hence, statistical analysis provides more precise insights. Furthermore, this study assumes uniform worn wheel profiles across all wheels, which may not reflect real-world scenarios. Therefore, a future investigation with actual profiles for all wheels is recommended. Nonetheless, these initial findings serve as a foundation for understanding how these two parameters influence RCF likelihood.

4 Conclusions and Contributions

RCF on low rails remains a significant challenge in heavy haul freight lines, impacting operational safety and maintenance costs. Continued research efforts focused on understanding the underlying mechanisms, implementing effective mitigation strategies, and exploring innovative solutions are essential to address this persistent issue and optimize the performance of heavy haul railway networks.

This foundational study concludes that both wheel hollowness and gauge widening significantly impact the likelihood of RCF occurring on wheels and rails by altering the contact conditions between the wheel and rail. The combination of gauge widening and wheel hollowness can lead to a negative rolling radius, thereby altering the vehicle dynamics and increasing the likelihood of RCF.

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Appendix

A. Rolling radius difference plot for the wheel profile with hollowness of 1.5 mm.