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The Effect of Profiles on Wheel and Rail Damage

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ABSTRACT:
This paper outlines the historical development of the wheel and rail profiles currently used on railway vehicles. It also presents the key damage mechanisms involved in wheel-rail contact and summarises the methods that have recently been developed by railway engineers to predict the level of wheel and rail damage from these mechanisms. Tools for predicting the key damage modes of wear and rolling contact fatigue (RCF) are explained. Methods of optimising the wheel and rail profiles to reduce the overall damage and therefore improve the efficiency of the railway system are discussed and a case study from the UK of an 'anti-RCF' wheel profile is presented. Finally a novel method using a genetic algorithm is discussed which uses a penalty index to optimise the wheel profile for good running, low track forces and rail stress, low wear and RCF.

KEYWORDS:
Railway wheel, Railway rail, wheel-rail interaction, wheel-rail damage, Rolling contact fatigue

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1. Introduction

The selection of the cross sectional profile for the wheel of railway vehicles is a typical engineering compromise and has challenged railway engineers since the time of George Stephenson. These early railway pioneers understood that a conical wheel profile would give better vehicle performance but could also lead to unstable behaviour when running at speed. A high level of conicity will allow good curving behaviour even in the tightest curve without flange contact. This could, however, lead to a relatively low critical speed and possibly dangerous hunting instability. A low level of conicity on the other hand will allow very high speed stable operation but the flange way clearance will quickly be used up in curves, resulting in flange contact and possible flange climb derailment. Flange angle and root radius are also variables that can have a significant effect on the possibility of derailment.

In practice most modern wheel profiles are a more complex shape and often based on an observed worn profile in an attempt to increase the interval between reprofiling. This increased complexity makes the problem of profile selection to ensure smooth and safe running even more difficult. In addition to the vehicle behaviour, engineers must consider the stresses on the wheel and on the rail. These have a major influence on the development of rolling contact fatigue which can have expensive and sometimes dangerous consequences.

Rail profiles for main line operation have also historically been developed according to fairly simple 'rules of thumb' with a large radius at the rail head where contact with the tread of the wheel normally occurs and a smaller radius at the corner of the rail head where contact with the flange occurs. In practice this pattern has been fairly stable as changes to the wheel profile have been easier to make. But changes to the both radii can have a big effect on stress levels in the contact patch and also on the likelihood of two point contact occurring.

It must of course be recognised that the wheel profile or the rail profile do not act in isolation but are two integral components in the wheel-rail system. Any serious study of the effect of changing one part of this system must include the other. A number of tools are available to help railway engineers select appropriate wheel and rail profiles. Computer softwares are now widely used to predict the interaction of railway vehicles with track. These usually allow full descriptions of the wheel and rail profiles and output of forces and stresses on the rail and various aspects of the vehicle behaviour.

2. Wheel Wear

The pattern of wear can vary significantly with vehicle and route type. A stiff yaw suspension or a route with tight curves will lead to high flange wear but a straight route or good curving will lead to tread wear predominating. For example, Fig. 1 shows the measured profiles on a modern passenger coach running on a main line. Excessive tread wear can lead to an increase in effective conicity and consequent unstable running even at relatively low speeds. Flange wear can lead to increased risk of derailment through flange climbing or switch splitting and in practice railway administrations set wear limits for these two parameters.

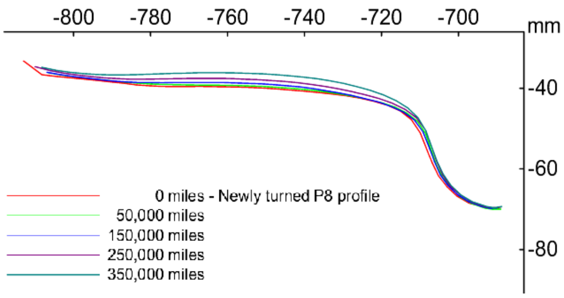

Fig. 1: Measured Wheel profile wear

3. Rolling Contact Fatigue

Rolling Contact Fatigue (RCF) is not a new phenomenon but has become a more significant problem in recent years partly due to increases in performance with higher axle loads, speeds and traffic and partly due to improvements in wear resistance of steels used in wheels and rails. The high stress levels present in the contact patch between a wheel and a rail cannot be supported by elastic deformation of the steel and plastic deformation therefore occurs. Due to the bulk stresses in the area of the contact, this plastic deformation is contained and the material dimensions are restored after the removal of the load. If the stresses are below a certain level (the shakedown limit) this plastic deformation may not result in crack growth. If this level is exceeded then cracks are likely to initiate and grow. These RCF cracks tend to appear in (see Fig. 2), or adjacent to the running band on the rail in groups at around 45^{o} to the direction of travel and in a similar band or bands around the wheel.

Fig. 2: RCF cracks on a rail

In practice the rate of wear is also an important factor in the growth of RCF, as wear tends to remove the cracks and their growth is then the result of a combination of growth at the crack tip through RCF and removal of material at the surface through wear.

4. Rolling Radius Difference Graphs

One way of assessing the effectiveness of the wheel and rail profiles is by constructing a rolling radius difference graph. This allows the effective conicity at any lateral displacement of the wheelset on the rails to be evaluated and indicates the level of steering and stability that will be provided. An example rolling radius difference graph is shown in Fig. 3 for new and worn wheels and rails.

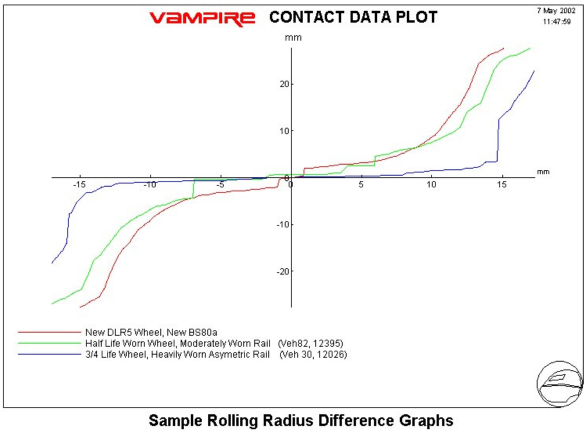

Fig. 3: Rolling radius difference graph for new and worn wheels and rails

5. Computer Simulation Tools

Vehicle dynamics analysis softwares have been developed by research institutes and railway administrations around the world. Examples are: VI-Rail, Vampire, Gensys, Nucars and Simpack. These have often grown out of the in house software tools that were developed to solve specific problems and are thus different in their operation and capability. Benchmarking of the main vehicle system dynamics packages has been carried out at Manchester Metropolitan University (MMU) and can be found in [1]. Using these computer softwares, it is possible to simulate the contact behaviour in some detail including location of the contact on wheel and rail (see Fig. 4), the dynamic behaviour of the vehicle and the forces at the wheel-rail interface.

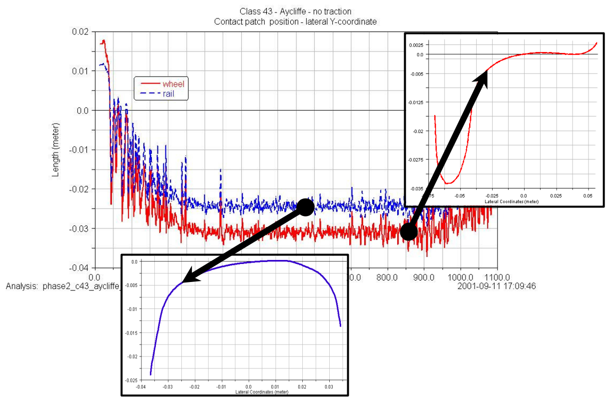

Fig. 4: Computer simulation of vehicle dynamics

6. Prediction of Wear

The prediction of wheel profile wear has been an area of investigation for many years. A great deal of previous work, such as that conducted by Pearce and Sherratt [2], Zobory [3] and Jendel [4], has looked at the prediction of both wheel and rail wear. From this work, a number of computational tools have emerged for predicting wheel profile wear over time (or distance). Using these tools, it is possible to study the evolution of wheel wear quickly and effectively through computer simulation providing numerous analysis benefits including the estimation of wheel and rail wear rates and the effectiveness of different lubrication strategies.

A procedure for predicting wheel wear has been developed by MMU and Royal Institute of Technology (KTH) [5]. The general methodology behind the wear prediction tool is shown in Fig. 5. This wear prediction tool is split into three stages as: (1) Vehicle dynamic simulation, (2) Wear calculation and (3) Wheel profile updating. As the change in wheel profile shape affects the vehicle-track interaction, an iterative procedure must be used, as shown by the feedback loop in Fig. 5, where the updated profiles are used as the starting profiles for the following wear iteration.

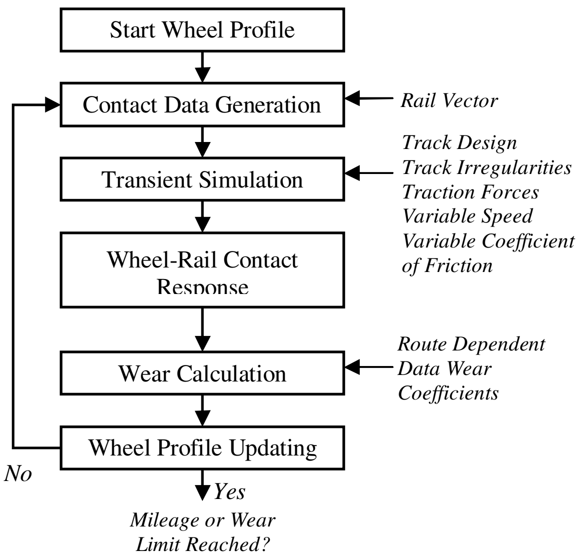

Fig. 5: Wear prediction methodology flowchart

Vehicle dynamic simulation is undertaken using the VAMPIRE software. MATLAB sub-routines are used during each wear iteration to call the VAMPIRE programs required for generating wheel-rail contact data and performing a transient simulation. Route dependent data such as track geometry, speed variation along the track, traction forces and varying coefficient of friction, which are important to the wear prediction, are included in the vehicle dynamic simulation.

The contact conditions, such as the contact shape, size and location on the wheel profile, are very important to the wear prediction routine. These properties are governed by the shape of the wheel and rail profiles and therefore must be determined prior to each wear iteration. Like most simulation tools used to analyse the dynamics of rail vehicles, VAMPIRE has a pre-processor for calculating the properties of the wheel-rail contact. This pre-processor is called at the beginning of each wear iteration to calculate the contact data tables for each wheel-rail profile combination.

The wear calculation is based on the Archard wear model [6]. This model can predict the volume of material removed based on the normal force, tangential forces, creepages and the material properties using:

$$V_{wear} = k(Ns/H) \tag{1}$$

Where V_{wear} is the volume of wear, k is the wear coefficient, N is the normal force, s is the sliding distance, and H is the hardness of the softer material.

The wear coefficient, k, in Eqn. (1) is a function of the slip velocity and contact pressure. Laboratory tests have been undertaken by KTH on typical wheel and rail steels to determine the wear coefficients [7]. Results from these and similar tests have been used to generate a wear chart, as shown in Fig. 6. This wear chart shows the values of the Archard wear coefficients (k) for typical wheel and rail steels for dry contact separated into regions for tread and flange contact. The wear chart is divided into four regions, indicated by *k1*, *k2*, *k3* and *k4*, to describe different states of wear, with the most severe wear occurring in the upper region.

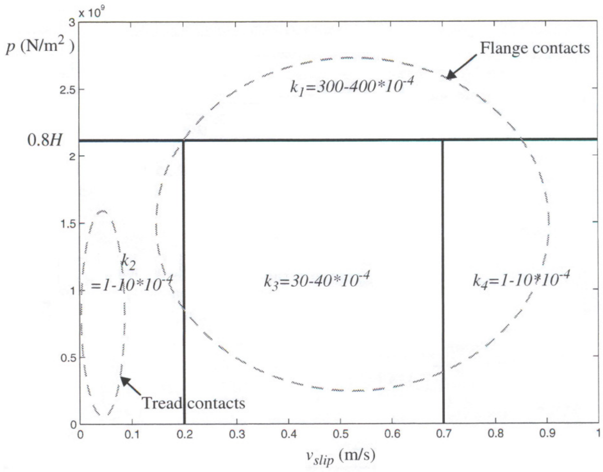

Fig. 6: Wear chart showing typical regions of tread and flange contacts [6]

Following the calculation of the wear distribution some smoothing of profile must take place. This smoothing is undertaken to ensure that the predicted profiles are physically plausible and to retain program stability during the calculation of the contact tables. Therefore the wear distribution is firstly smoothed and the updated wheel profile is calculated by subtracting the smoothed wear distribution from the start profile. The updated wheel profile is also smoothed. Typical results from this procedure are shown in Fig. 7, where the predicted profile shape and the material removed is compared with the measured profile from a vehicle at this mileage.

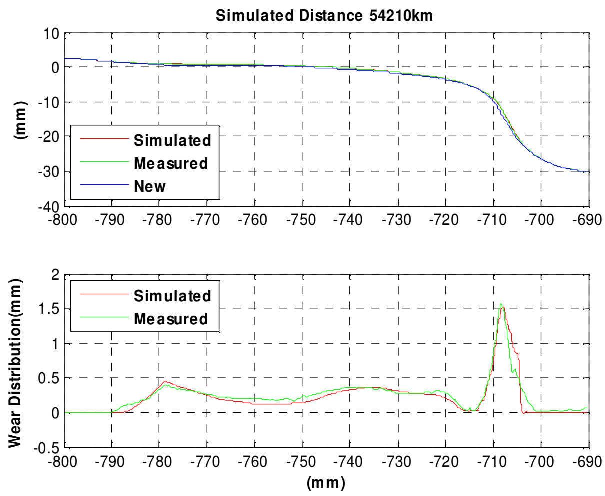

Fig. 7: Comparison between predicted and measured wheel profile and wear distribution after 54000 km.

7. Prediction of Rolling Contact Fatigue

Prediction of rolling contact fatigue is in practice extremely difficult due to the complex nature of this phenomenon and its dependence on small changes in material properties and applied forces. Partly due to the difficulty in practical inspection and also due to the extremely serious consequences that can arise from an RCF failure, a great deal of effort has recently gone into finding effective RCF prediction methods. Two key methods are presented here: the shakedown limit and the Tgamma method.

The shakedown method defined by Johnson [8] uses a plot of contact stress against traction coefficient (defined as the ratio of the tangential to normal forces) as shown in Fig. 8. The tangential force is given by the vectorial sum of the longitudinal and lateral creep forces. The material properties set the 'shakedown limit' and exceedence of this means that RCF crack initiation is likely to occur.

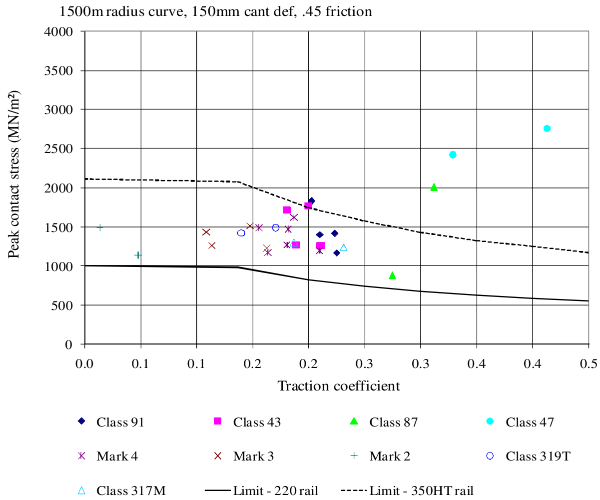

Fig. 8: A shakedown plot [9] to predict RCF

Another method that has recently been developed [10] uses the 'Tgamma' number which is the product of the tangential or creep forces and the slippage or creepage in the contact patch between wheel and rail. Tgamma was originally used to predict the wear but when combined with a non-linear damage function produces a RCF damage index as shown in Fig. 9. This index is then used to interpret whether the vehicle is damaging the track due to wear, RCF or more commonly, a combination of both. With reference to Fig. 9, wear and RCF damage rates is combined to develop the RCF damage function. The operation of the damage function is as follows:

- As Tgamma increases from 0 to 15 N, no RCF damage is generated as there is insufficient energy to initiate RCF cracks
- As Tgamma increases from 15 to 65 N, the probability of RCF initiation increases, to a maximum of 10 at a Tgamma value of 65 N.
- As Tgamma increases further from 65 to 175 N, the level of energy is such that the dominant form of surface damage is wear (rather than crack initiation). Therefore the probability of RCF damage decreases as wear increases.
- Negative values of RCF damage index indicating the values of Tgamma greater than 175 N, results in wear and no RCF initiation.
- The units of the RCF damage index are 10^{-5} per axle. This indicates that for a damage index of 1, 100000 (One hundred thousand) axle passes would result in RCF initiation.

Fig. 9: The Tgamma RCF damage index

Both the Shakedown and Tgamma methods can be used to assess the output from a vehicle dynamics simulation run and to give a prediction of the likelihood of RCF cracks initiation and their growth to dangerous levels. These methods are currently being incorporated into user friendly tools for track engineers. It should be stressed that careful calibration will be required as these methods are very much dependent on detailed and accurate information about the system properties and operating conditions which may vary locally.

8. The WRISA2 Anti-RCF Wheel Profile

As an example, a brief case study of a wheel profile development to solve a specific problem is presented by using the tools discussed in previous section. Shortly after the introduction of a new fleet of vehicles onto a line in London, significant RCF was observed on the rails. A range of vehicle and track properties are identified as being factors [11] to cause the RCF.

The solution proposed was a new wheel profile which would avoid highly stressed contact in the specific gauge corner area of the rail. The 'WRISA2' profile, as developed by NRC [12], can be seen in Fig. 10 when compared to new P8 and RD9 profiles. The designed anti-RCF relief can be clearly seen in the flange root area when the profile is matched with a BS113a rail as shown in Fig. 11. This relief was designed to reduce the contact stress approximately 25mm from the gauge face of the rail where RCF typically initiates in mild curves.

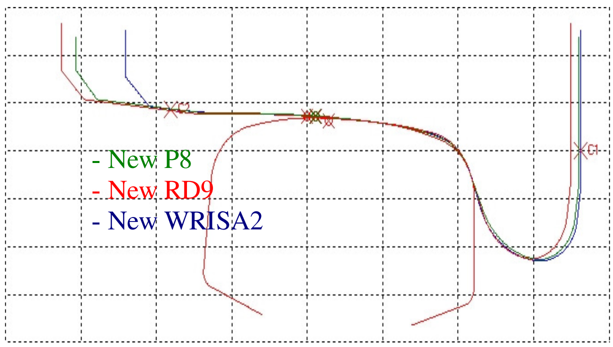

Fig. 10: Overview of new WRISA2, P8 and RD9 wheel profiles.

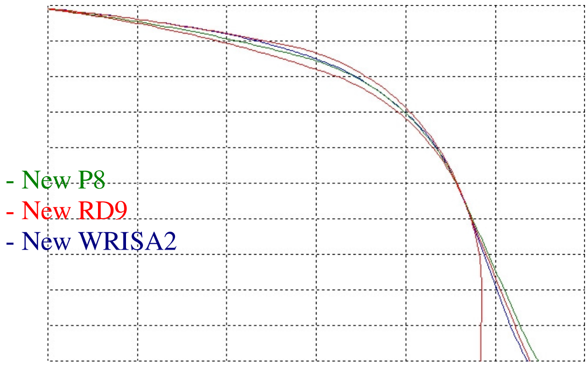

Fig. 11: Close-up view of anti-RCF relief at the gauge corner of a new BS113a rail.

9. Optimisation of Wheel and Rail Profiles

The issue of wheel and rail profile optimisation is briefly discussed in this section. This is an important area and many people have developed methods to optimise the profiles for better life and resistance to damage. The author together with Dr. Ingemar Persson of DE Sover, has developed a novel genetic algorithm method for designing wheel and rail profiles for railway vehicles [13]. In this method, two existing wheel profiles are chosen as parents, and genes are formed to represent these profiles. These genes are mated to produce offspring genes and then reconstructed into profiles that have random combinations of the properties of their parents. Each of the offspring profiles are evaluated by running a simulation of the vehicle behaviour with these profiles and a penalty index. The inverted penalty index is used as the fitness value in the genetic algorithm. The method has also been used for rail profiles [14].

The cross sectional profile of the wheel is initially described with a series of x,y coordinates and these are converted into a binary sequence – the 'gene' for this profile. The genes for the two parent profiles are mated by taking random sections from each gene to make the offring genes. The children will represent different profiles to the parent but will share some similar characteristics. Mutations are also made by randomly changing the genes to introduce occasional larger variations.

To test the proposed genetic algorithm based optimisation method, the selected wheel profile was incorporated into a simple motored bogie vehicle model with an axle load of 20 tonnes. The vehicle bodies are assumed to be rigid and the main primary and secondary suspension stiffness is linear. The vehicle has vertical primary dampers as well as secondary lateral, vertical and yaw dampers. Traction rods and anti-roll bars are included in the model and the yaw dampers have blow-off valves and include a series stiffness. The nominal wheel diameter is 1 m. For these tests two versions of the vehicle were set up, one with soft primary suspension and the other with a stiffer primary suspension with no yaw damper. The track selected for the tests was a section of Swedish main line. The vehicle was run at 160 km/h on straight track for 275 m then into a 120 m linear transition into a curve of 1000 m and cant of 150 mm (130 mm cant deficiency). The rails are inclined at 1:40, measured track irregularities are included and the average gauge is 1430.76. After running for 227 m around the curve, the simulation was stopped.

In order to evaluate the effectiveness of each profile, a penalty index is calculated after each simulation run. The aim of this penalty index is to provide an assessment of the vehicle behaviour including the most important factors in a single optimisation. It currently includes the following forces and indices:

- Maximum contact stress
- Maximum lateral track-shift force
- Maximum derailment quotient
- Total wear index
- Total ride comfort index

Each of the factors that make up the penalty index can be weighted to reflect their importance to the operator or the particular vehicle/track combination. Other factors could also be included in the penalty index if they were felt to be critical. The following results were produced for the two vehicles (see Fig. 12 and 13) after 21 mating and selection generations of the optimisation. It can be seen that the genetic algorithm has selected a profile with higher conicity for the softer bogie and vice-versa for the stiffer bogie.

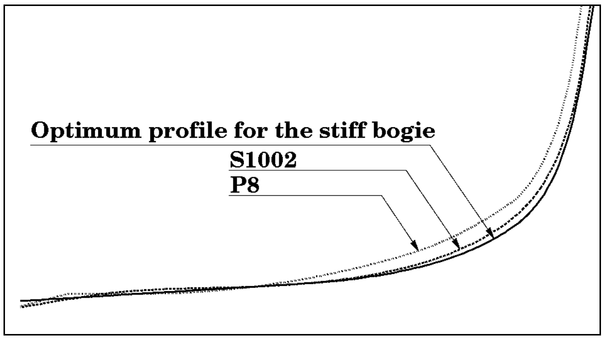

Fig. 12: Vehicle with stiff primary suspension

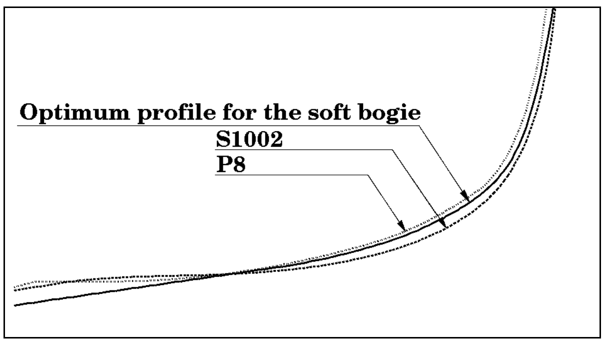

Fig. 13: Vehicle with soft primary suspension

10. Conclusions

The design of wheel profiles for the conflicting requirements of stability and derailment resistance as well as low wear and resistance to rolling contact fatigue is a significant engineering challenge. Some fairly effective methods now exist to predict the wear and RCF damage. But these methods rely on detailed and accurate information about specific railway system. Computer simulation is a useful tool to assist in this process. Optimisation of profiles for best possible performance on a specific railway system can now be carried out. A new method using genetic algorithms has been developed for optimising the wheel profiles and is being tested. This method takes into account the effect of the wheel-rail interaction and can be tuned to reflect the importance of the various requirements.

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