A New CAE Procedure for Railway Wheel Tribological Design

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Summary: New demands are being imposed on railway wheel wear and reliability to increase the time between wheel reprofiling, improve safety and reduce total wheelset lifecycle costs. In parallel with these requirements, changes in railway vehicle missions are also occurring. These have led to the need to operate rolling stock on track with low as well as high radius curves; increase speeds and axle loads; and contend with a decrease in track quality due to a reduction in maintenance. These changes are leading to an increase in the severity of the wheel/rail contact conditions, which may increase the likelihood of wear or damage occurring.

The aim of this work was to develop a new CAE design methodology to deal with these demands. The model should integrate advanced numerical tools for modelling of railway vehicle dynamics and suitable models to predict wheelset durability under typical operating conditions. This will help in designing wheels for minimum wheel and rail wear; optimising railway vehicle suspensions and wheel profiles; maintenance scheduling and the evaluation of new wheel materials.

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Index Terms: wheelset design, fatigue, wear

1. INTRODUCTION

There is a need to develop new design tools for railway wheelsets as new specifications are being imposed on wear and reliability to increase the time between wheel reprofiling operations, improve safety and reduce total wheelset lifecycle costs.

In parallel with these requirements, railway vehicle missions are changing due to the need to operate rolling stock on track with low radius curves as well as the high radius curves on high speed lines. This is coupled with increasing speeds and a decrease of track quality due to a reduction in maintenance. These changes will cause an increase in the severity of the wheel/rail contact conditions [1], which will increase the likelihood of wheel damage occurring in the form of wear or rolling contact fatigue.

Excessive wear can affect the dynamic behaviour of the railway vehicle and reduce ride comfort. This can then impact upon the potential for derailment and reduce the integrity of the wheel material [2]. Rolling contact fatigue is potentially more dangerous. The damage manifests itself in the initiation of cracks that will grow and, if not detected, cause fracture where a part of the wheel is detached. Consequences of such a failure normally include the formation of a non-round wheel. This non-roundness may cause secondary failures as well as give rise to increased wear and noise. More rarely the fatigue failure may be of such a type that it will cause derailment of an entire train. The best-known example is perhaps the tragic accident at Eschede, but other examples are reported in the literature (see [3]).

The aim of the work described was to develop a procedure for wheelset design by integrating advanced multi-body dynamics simulations of a railway vehicle with suitable wear and rolling contact fatigue models to predict wheelset durability. This will help in designing wheels for minimum wheel and rail wear, optimising railway vehicle suspensions and wheel profiles, maintenance scheduling. It will also help in the evaluation of new wheel materials.

2. MODELLING METHODOLOGY

The modelling methodology for the estimation of wheel profile evolution wear is made up of three main elements:

multi-body dynamics modelling of the railway vehicle, used to evaluate as function of time the number and position of wheel/rail contact points and the resulting global contact force and creepage components.

wear prediction involving contact modelling to derive the local pressure, traction and creepage distributions within the contact area using inputs from the multi-body modelling and a wheel profile evolution calculation based on the wear model developed from twin disc wear testing and using inputs from the local contact analysis.

rolling contact fatigue analysis in which inputs from the multi-body dynamics simulations are used to assess three fatigue factors relating to the most common failure modes.

The complete procedure is schematically represented in Figure 1. Starting from the vehicle characteristics and initial wheel and rail profiles, a sequence reproducing the vehicle mission profile is simulated using the multi-body vehicle model. For each time step of the simulation, the results in terms of *global* contact parameters (position of contacts, resulting contact forces and creepages) are derived.

In the wear analysis these are used to perform a local contact analysis, which provides as output the distribution of frictional work inside the contact patch. The modification to wheel profiles produced by the wear sequence is computed using a wear model based on experimental results obtained from twin disc wear tests. By subtracting this modification to the initial wheel profile, the worn wheel profile is determined. The wear loop can be repeated several times to predict wear progress on the wheel surface. In the RCF analysis the global contact parameters are used to calculate fatigue factors and compare them with given thresholds to evaluate the likelihood of RCF failure occurring and the severity of the fatigue impact.

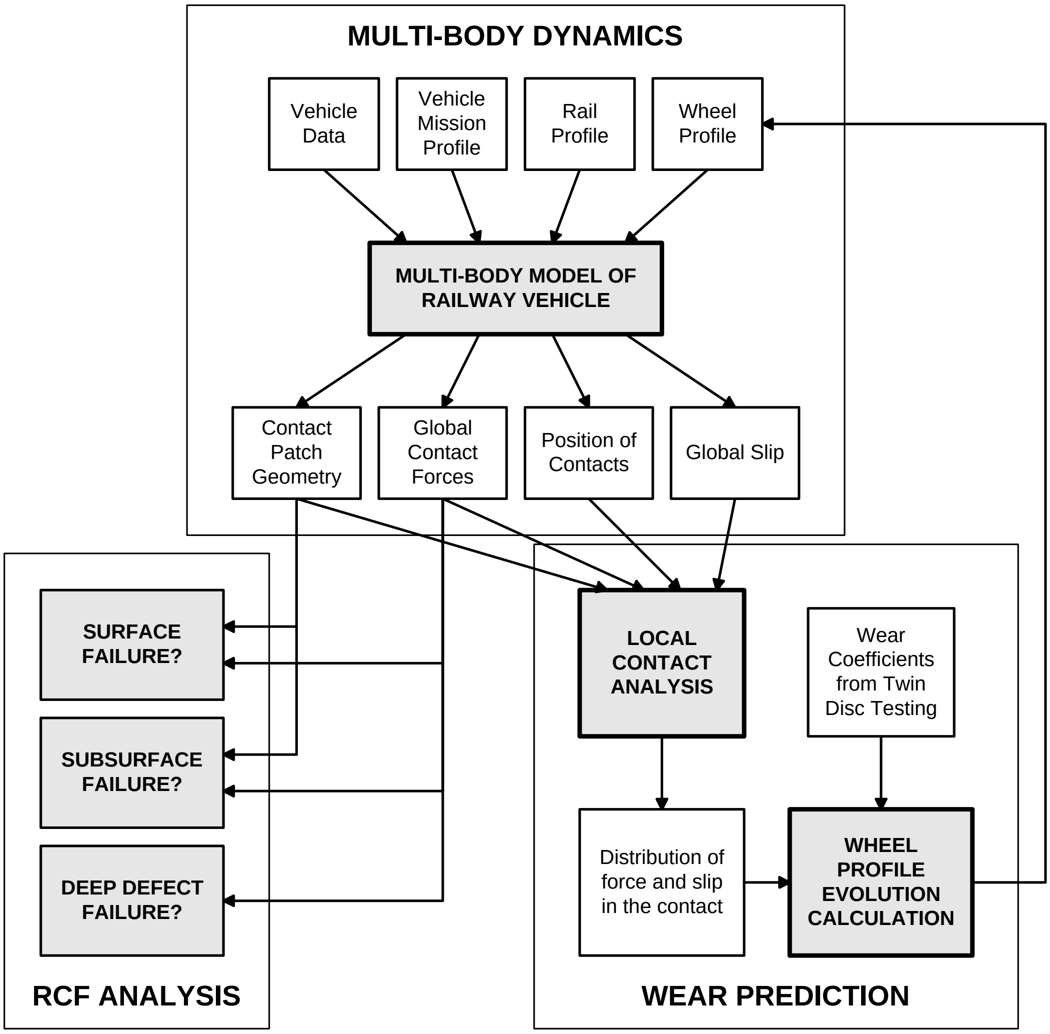

Figure 1. Wheel Damage Modelling Strategy

3. ADAMS/Rail MULTI-BODY DYNAMICS SIMULATION

The railway vehicle model used to evaluate wheel/rail contact forces as a function of wheelset mission profile was developed in the ADAMS/Rail environment. The model includes a mathematical description of the full vehicle where car body, bolsters, bogie frames and wheelsets are treated as rigid bodies, while primary and secondary suspensions are represented by means of linear and non-linear elastic and damping elements (Figures 2a and b).

Vehicle parameters were defined with reference to an *ETR470 Pendolino* railway vehicle. This kind of vehicle is particularly interesting for wheel wear analysis because it can be operated at high levels of cant deficiency, which leads to high values of lateral contact forces and creepages and therefore to accelerated wheel wear [4]. More details about the vehicle model are reported in [1].
Methods of dynamic analysis are used within ADAMS/Rail to evaluate, as a function of time, all quantities related to the dynamic behaviour of the vehicle and the wheel/rail contact. In order to integrate the wheel wear calculation and dynamic analysis results these have been enhanced to include quantities such as contact patch dimensions and actual rolling radius, necessary for wear evaluation.

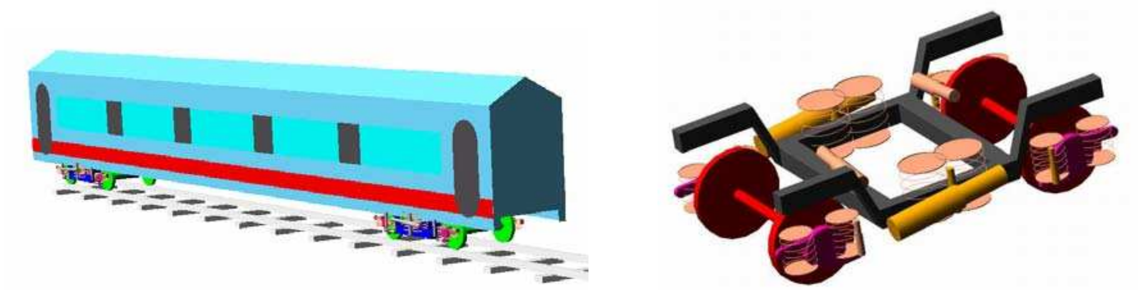

Figure 2. (a) Railway Vehicle Model; (b) Bogie Model

4. WHEEL PROFILE EVOLUTION PREDICTION

4.1 Wheel Wear Mechanisms

Wheel wear is closely related to conditions of force and slip in the wheel/rail contact. Three wear regimes for wheel materials have been defined as a result of laboratory twin disc experiments [5, 6], *mild*, *severe* and *catastrophic*. The regimes are described in terms of wear mechanism as well as wear rate.
In the mild regime at low load and slip conditions, typical of those in the tread contact, oxidative wear was seen to occur. The wheel disc surfaces turned a rusty brown colour. Closer examination of the wear surfaces revealed abrasive score marks and evidence of a thin oxide layer breaking away from the surface. A small amount of deformation just below the wear surface of the discs was also apparent.
As slip and load in the contact was increased (towards those actually experienced in a flange contact) severe wear occurred. The wheel material appeared to be wearing by a delamination process. It could be seen that a larger amount of plastic deformation was occurring below the wheel disc wear surface and crack formation just below the surface was visible which was leading to thin slivers of material breaking away from the surface.
As the contact conditions were made more severe, in the catastrophic regime, these cracks were seen to alter direction from running parallel to the wear surface and turning up to turning down into the material causing larger chunks of material to break away. The mechanisms are described in more detail in a companion paper [7].

4.2 Wear Modelling

The wear modelling approach adopted for this work is an energy based wear index [8]. It is assumed that wear rate is related to work done at the wheel/rail contact (wear rate = $T\gamma/A$, where T is tractive force and γ is slip at the wheel/rail interface, K is a wear coefficient and A is the contact area). Various researchers have reported wheel/rail wear results using twin disc test machines of varying geometries, as well as full scale test results, that support this approach [6, 9, 10]. The approach, however, has limitations. It was found to break down at high slip and contact stress conditions [6]. Twin disc work, carried out to characterise the performance of a new wheel material, R8T, has shown a strategy to overcome these deficiencies [5]. Wear coefficients were defined for each of the wear regimes outlined above, which are illustrated in Figure 3.

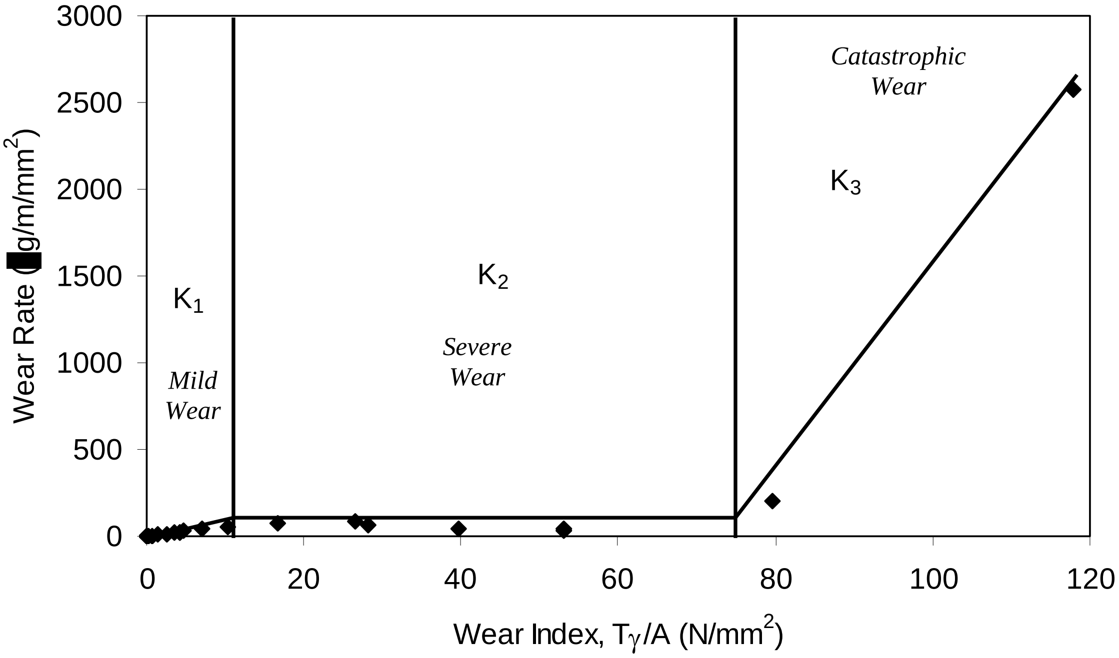

Figure 3. Wear Regimes and Coefficients (Lewis et al., 2003)

4.3 Local Contact Analysis

ADAMS/Rail provides information about the load and tractions applied to the whole wheel/rail contact patch and its location. In this model it is assumed that the contact between the wheel and rail can be approximated by an elliptical contact patch. This allows the use of a faster solution method to determine the traction and slip distribution within the contact.

ADAMS/Rail provides the total normal force, the traction applied and the semi-axes a and b for each elliptical contact patch and it is from these values that local contact analysis is performed. Each elliptical contact patch is discretised into strips. Each strip is then divided into equal sized cells. The contact analysis calculates traction, T, pressure, p, and slip, γ, for each cell (see Figure 4) from the leading edge of the contact, sequentially to the rear. The forces determined for each cell are compared to slip/adhesion criteria enabling slip and adhesion regions to be identified and the slip magnitude and direction to be determined. This approach is similar to the method employed in the FASTSIM algorithm [11].

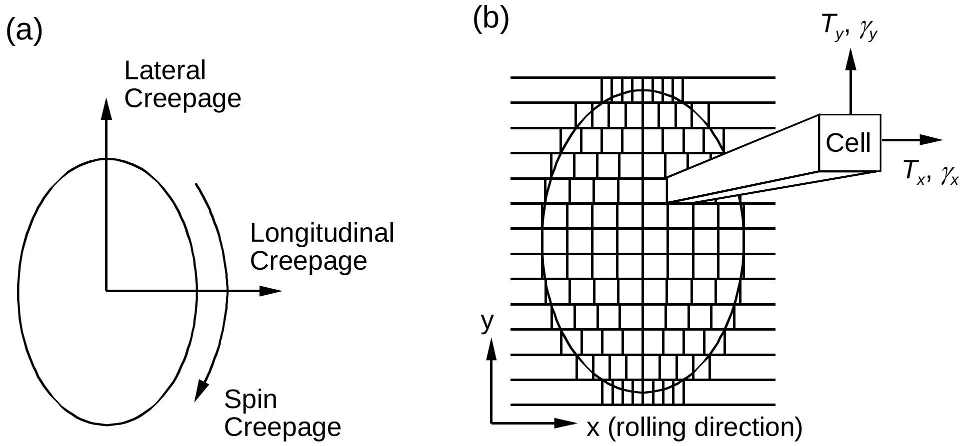

Figure 4. Output from: (a) ADAMS/Rail and (b) local contact analysis

4.4 Wear Determination

To determine the evolution of the wheel profile as it wears, it was discretised into circumferential strips. This enabled the elliptical contact patches to be located on the wheel circumference. The discretisation of the contact patches could then be made to coincide exactly with the strips of the wheel (see Figure 5). By aligning the discretisation strips in this way, wear calculated for each strip could be summed to calculate the wear depth for that region of the wheel profile.

A value for $T\gamma/A$ was calculated for each cell in the local contact analysis and compared to the wear regimes identified from wear test data (as shown in Figure 3). The corresponding wear coefficient, K, for each wear regime was used to calculate the wear depth per cell, WD_{cell}:

$$WD_{cell} = \frac{T\gamma}{A} K \frac{V\Delta t}{\rho} \tag{1}$$

where V is the rolling velocity, ρ is the density of the wheel steel and Δt is the duration of the contact time step.

Each cell in the contact ellipse has an associated wear depth. The wear on each strip (in the rolling direction) is summed and that depth removed from the corresponding circumferential strip on the wheel. The contact time interval, Δt, in the output data from ADAMS/Rail is not necessarily equal to one revolution of the wheel. It is generally observed that wear occurs uniformly over a wheel circumference. Therefore it is reasonable to proportion the wear caused by a given patch location over the time, Δt, equally over the whole circumference of the wheel according to the ratio $V\Delta t/2\pi R$, where R is the wheel radius. This is carried out for each strip in the contact patch to determine the wear caused by that contact over the time, Δt. Each contact patch obtained from the ADAMS/Rail simulation is treated in the same way to obtain the worn wheel profile. This procedure is shown schematically in Figure 5.

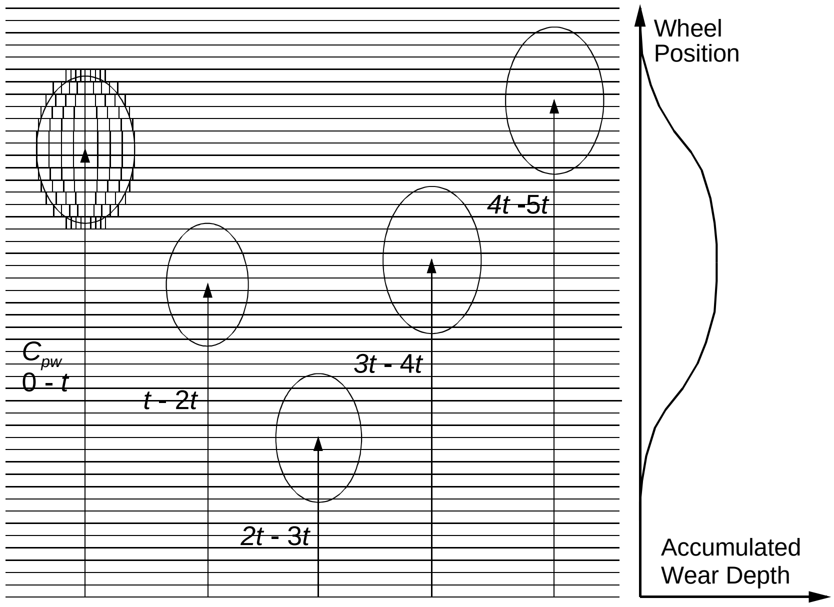

Figure 5. Summation of the Wear per Strip to give Total Wear Depth

5. ROLLING CONTACT FATIGUE (RCF) PREDICTION

5.1 RCF Failure Modes

In developing prediction tools for RCF, it was recognised that it might manifest itself in (at least) three different forms: surface fatigue; subsurface fatigue and deep defects, each corresponding to different underlying mechanisms.

In surface initiated fatigue of railway wheels, fatigue cracks result from excessive plastic flow of the surface material. This will cause crack initiation due to ratchetting and/or low cycle fatigue of the surface material. Once initiated, the cracks typically grow into the wheel material to a maximum depth of some 5mm. Final fracture occurs as the cracks branch towards the wheel tread. The typical appearance of surface initiated fatigue failure is shown in Figure 6a.

Surface initiated cracks are normally not a safety issue. However, they are the most common type of fatigue damage in wheels. They are costly in requiring reprofiling of the wheel and causing unplanned maintenance. Further, if not attended to, the non-round wheels may cause secondary damages to rail, bearings etc.

In the case of subsurface fatigue, cracks will initiate several millimetres below the surface. They continue to grow under the surface and final fracture will normally occur due to branching towards the surface. Such a failure will break off a large piece of the wheel surface, see Figure 6b.

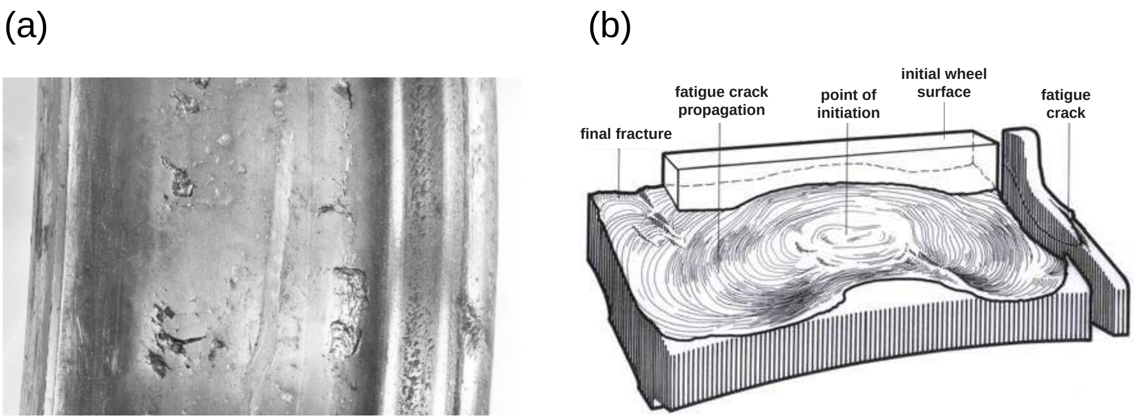

Figure 6. RCF Damage: (a) Surface Fatigue; (b) Crack Morphology for a Subsurface Induced Fatigue Failure

Materials defects will have a strong effect on the resistance against subsurface initiated RCF. Below 10mm, nominal stresses due to rolling contact are very low, and fatigue can only occur if promoted by a material defect of sufficient size. Subsequent propagation occurs at approximately the same depth as the initiation. Due to the deep initiation point, such cracks are very dangerous. Final fracture may well occur as a branch towards the wheel hub and cause a derailment [3].

5.2 Modelling RCF

In the CAE tool the three mechanisms of fatigue initiation should be considered separately and quantified by three fatigue indices as described below.
It was decided to, as much as possible, avoid the introduction of material parameters in the models. In order to achieve this, the models predict the fatigue impact of a certain combination of load and contact geometry. The question of the material's resistance to this impact is then a separate issue. This strategy has the benefit of allowing fatigue assessments at the design stage where the wheel material is not specified. Further, statistical uncertainties in the predictions normally introduced by material fatigue parameters are limited. Scatter due to random variations in load and contact conditions will, of course, still exist.
The fatigue index for *surface initiated fatigue* is based on the theory of elastic and plastic shakedown in general and shakedown map theory in particular (see [12]). The index is expressed as:

$$FI_{\mathrm{surf}} = \mu - \frac{2\pi abk}{3F_z} \qquad (2)$$

Here, μ is the traction coefficient ($\mu = \sqrt{\left(F_x^2 + F_y^2\right)/F_z^2}$), F_z the magnitude of the vertical load, *a* and *b* the semi-axes of the Hertzian contact ellipse and *k* the yield limit in shear of the material (including material hardening). Fatigue is predicted to occur if the inequality $FI_{\mathrm{surf}} > 0$ is fulfilled.

The index for *subsurface initiated fatigue* is based on the Dang Van equivalent stress (see [13]). It is an approximation of the largest occurring equivalent stress during a wheel revolution. The index is expressed as:

$$FI_{\mathrm{sub}} = \frac{F_z}{4\pi ab}\left(1+\mu^2\right) + a_{\mathrm{DV}}\sigma_{\mathrm{h,res}} \tag{3}$$

Here, $\sigma_{\mathrm{h,res}}$ is the hydrostatic part of the residual stress (positive in tension). The parameters F_z, a, b and μ are the same as above and a_{DV} is a material parameter that may be evaluated as:

$$a_{\mathrm{DV}} = \frac{3\tau_{\mathrm{e}}}{\sigma_{\mathrm{e}}} - \frac{3}{2} \tag{4}$$

where τ_{e} is the fatigue limit in alternating shear and σ_{e} is the fatigue limit in rotating bending.

Fatigue is predicted to occur whenever the inequality $FI_{\mathrm{sub}} > \sigma_{\mathrm{EQ,e}}$ is fulfilled. Here, $\sigma_{\mathrm{EQ,e}}$ is the fatigue limit in shear. To account for material defects, a reduced fatigue limit, σ_{w}, can be estimated as:

$$\sigma_{\mathrm{w}} = \sigma_{\mathrm{EQ,e}}\left(\frac{d}{d_0}\right)^{-1/6} \tag{5}$$

where d is the diameter of the occurring defect and d_0 the defect size corresponding to the unreduced fatigue limit [14].

For fatigue initiation at *deep defects*, the index given below is used:

$$FI_{\mathrm{def}} = F_z \tag{6}$$

where F_z is the magnitude of the vertical load. Fatigue is predicted to occur when this magnitude exceeds a threshold. To quantify this threshold is a complicated task and the topic of current research [15, 16]. Further details of the fatigue model can be found in [17].

6. INTEGRATION OF DAMAGE MODELS INTO ADAMS/Rail

The wear prediction algorithm has been introduced as a built-in tool in ADAMS/Rail, and it is accessible through the graphic user interface. Results of wear evaluations are available in graphic format (for the overall amount of worn material), as shown in Figure 7, and as an ASCII file for the evolution of wear during the simulation.

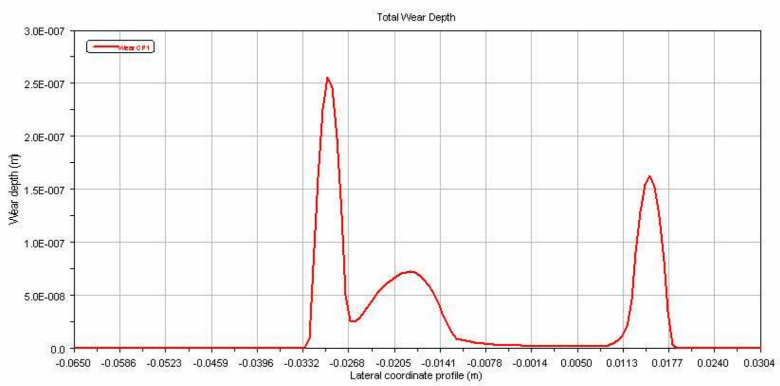

Figure 7. An Example of the Graphical Output for the Wear Modelling in ADAMS/Rail

The RCF predictive model is implemented as a post-processor to ADAMS/Rail (named FIERCE for Fatigue Impact Evaluator for Rolling Contact Environments).
In Figure 8, fatigue indices evaluated by FIERCE are represented as histograms. In addition, the surface fatigue impact may also be represented in the form of work-points plotted in a shakedown diagram.

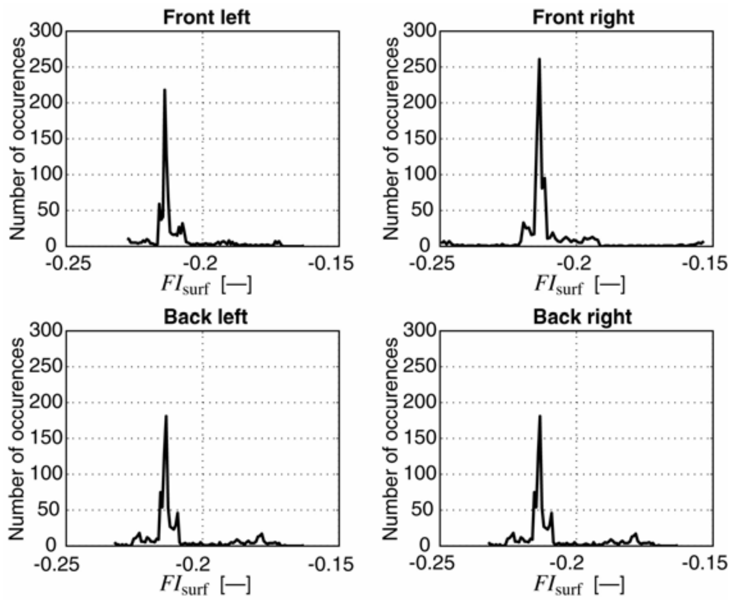

Figure 8. Examples of Rendering of Surface Fatigue Histograms in FIERCE (in this case surface fatigue indices for all four wheels of a train bogie are shown)

7. VALIDATION

Sample runs of the wear modelling procedure have been carried out as outlined previously [5]. An example of predicted wear is shown in Figure 9 and an example of a recalculated wheel profile is shown in Figure 10. These predictions have been used to validate the model at a basic level. Work is currently underway to carry out validation over longer vehicle routes for comparison with wheelsets in service and shorter runs to compare with results from a full-scale wheelset test-rig.

The task of validating the RCF models is very difficult. Part of the reason is the complex interaction between a wheel and rail and the uncontrolled environment the operational wheels are subjected to. To avoid these problems, laboratory experiments (such as twin disc tests) can be carried out. However, these tests also have their drawbacks. For instance, a twin disc test will introduce scale effects. How to deal with these scale effects is far from obvious. A thorough study has been devoted to the issue [18], which concluded that there is no fully satisfactory way of validating the model. The current model is, however, based on verified and documented fatigue criteria, which should provide a measure of validation. In order to prescribe operational limits on the fatigue indices, empirical knowledge from train operations are needed.

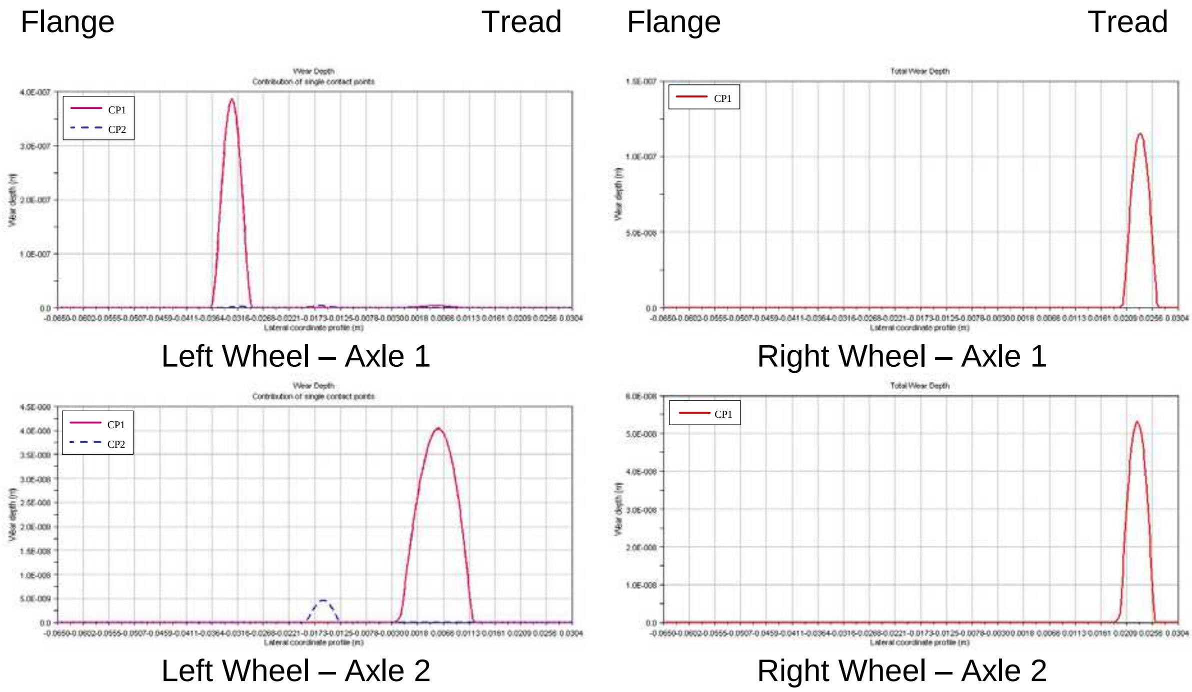

Figure 9. Sample ADAMS/Rail Output for a 370m Radius Curve

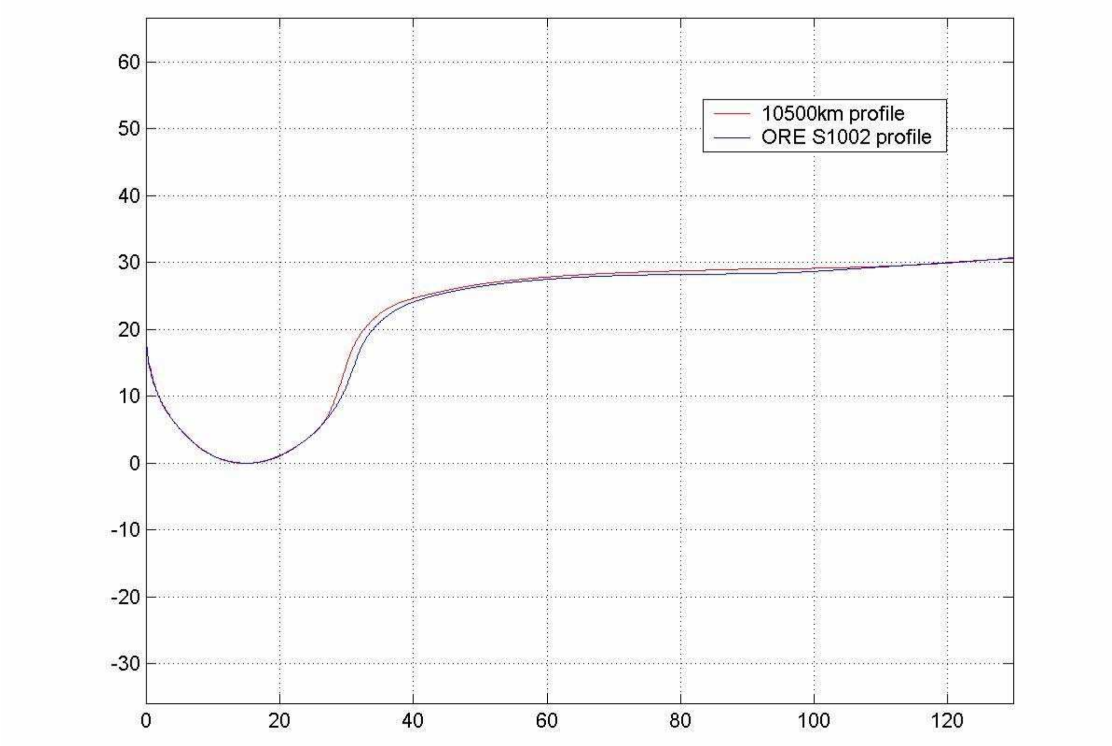

Figure 10. Example of a Worn Wheel Profile

8. CONCLUSIONS

Models have been developed to predict the wear and rolling contact fatigue (RCF) of railway wheels. The wear model assumes that wear is related to $T\gamma/A$, where T is tractive force, γ is slip at the wheel/rail interface and A is contact area. Twin disc testing of rail and wheel materials was carried out to generate wear coefficients for use in the model. The RCF model quantifies fatigue impact by three fatigue indices, which are based on existing scientific knowledge of rolling contact fatigue. The time evolution of the indices may be employed to assess the likelihood of RCF occurring due to surface fatigue; subsurface fatigue and fatigue initiated at deep defects.

The models have been incorporated into ADAMS/Rail to develop a CAE package for assessing durability in the design of new wheelsets. ADAMS/Rail carries out a multi-body dynamics simulation of a railway wheelset operating over a track section. The outputs from this modelling are then used as inputs to the wear and RCF prediction tools.

The wear model has been applied to multi-body simulation of a passage around sample track curves. For a simple validation case the worn profile is quantitatively similar to published data. Validation of the RCF model is a more complex process, which will require empirical data from train operations.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

[1] Stanca., M., Stefanini, A., Gallo, R., "Development of an Integrated Design Methodology for a New Generation of High Performance Rail Wheelsets", *Proceedings of the 16th European MDI User Conference*, Berchtesgaden, Germany, 14-15 November, 2001.

[2] Jendel, T., "Prediction of Wheel Profile Wear - Comparisons with Field Measurements", *Proceedings of the International Conference on Contact Mechanics and Wear of Rail/Wheel Systems*, Tokyo, Japan, 25-28 July, 2000, pp117-124.

[3] Ekberg, A., Marais, J., "Effects Of Imperfections on Fatigue Initiation in Railway Wheels", *Proceedings of the IMechE Part F, Journal of Rail and Rapid Transit*, Vol. 214, 1999, pp45–54.

[4] Roberti, R., Bruni, S., "Development of Operations of Tilting Train on Italian Network", *Proceedings of the WCRR*, Köln, Germany, 25-29 November, 2001.

[5] Lewis, R., Braghin, F., Ward, A., Bruni, S., Dwyer-Joyce, R.S., Bel Knani, K., Bologna, P., "Integrating Dynamics and Wear Modelling to Predict Railway Wheel Profile Evolution", *Proceedings of CM2003*, *6th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems*, 2003, Vol. 1, pp7-16.

[6] Bolton, P.J., Clayton, P., "Rolling-Sliding Wear Damage in Rail and Tyre Steels", *Wear*, Vol. 93, 1984, pp145-165.

[7] Lewis, R., Olofsson, U., Dwyer-Joyce, R.S., Hallam, R.I., "Wheel Material Wear Mechanisms and Transitions", accepted for presentation at the *14th International Wheelset Congress*, Florida, 17th-21st October 2004.

[8] Elkins, J.A., Eickhoff, B.M., "Advances in Non-Linear Wheel/Rail Force Prediction Methods and their Validation", ASME Winter Annual Meeting, 1979.

[9] McEwen, I.J., Harvey, R.F., "Full-Scale Wheel-on-Rail Wear Testing: Comparisons with Service Wear and a Developing Theoretical Predictive Method", *Lubrication Engineering*, Vol. 1, 1985, pp80-88.

[10] Zakharov, S.M., Zharov, I.A., "Simulation of Mutual Wheel/Rail Wear", *Proceedings of the 5th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems*, Tokyo, Japan, 25-28 July, 2000, pp125-130.

[11] Kalker., J.J., "A Fast Algorithm for the Simplified Theory of Rolling Contact", *Vehicle System Dynamics*, Vol. 11, 1982, pp1-13.

[12] Johnson, K.L., "The Strength of Surfaces in Rolling Contact", *Proceedings of the Institution of Mechanical Engineers*, Vol. 203, 1989, pp151–163.

[13] Dang Van, K., Cailletaud, G., Flavenot, J.F., Le Douaron, A., Lieurade, H.P., "Criterion for High Cycle Fatigue Failure under Multiaxial Loading", in Brown, M.W., Miller, K.J., Editors, *Biaxial And Multiaxial Fatigue*, Mechanical Engineering Publications, London, 1989, pp459–478.

[14] Ekberg, A., Sotkovszki, P., “Anisotropy and Fatigue of Railway Wheels”, *International Journal Of Fatigue*, Vol. 23, No. 1, 2001, pp29–43.
[15] Kabo, E., Ekberg, A., “Fatigue Initiation in Railway Wheels – A Numerical Study of the Influenece of Defects”, *Wear*, Vol. 253, No. 1-2, 2002, pp26-34.
[16] Kabo, E., “Material Defects in Rolling Contact Fatigue – Influence of Overloads and Defect Clusters”, *International Journal Of Fatigue*, Vol. 24, No. 8, 2002, pp887-894.
[17] Ekberg, A., Kabo, E., Andersson, H., “An Engineering Model for Prediction of Rolling Contact Fatigue of Railway Wheels”, *Fatigue & Fracture of Engineering Materials & Structures*, Vol. 25, No. 10, 2002, pp899-916.
[18] Ekberg, A., Lundén, R., “Rolling Contact Fatigue of Railway Wheels – Towards Validation of a Predictive Model”, *Proceedings of Fatigue 2002*, Vol. 2, 2002, pp843-850.