A systems approach to evaluating rail life

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A SYSTEMS APPROACH TO EVALUATING RAIL LIFE

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ABSTRACT

Corus Rail Technologies (CRT) has undertaken a major project involving track studies of Rolling Contact Fatigue (RCF), with support from Manchester Metropolitan University (MMU).

The work takes a systems approach and involves the development and application of a suite of numerical models used to investigate the in-service conditions of track components with particular emphasis on RCF. The suite of models, called the Track System Model (TSM), comprises of vehicle dynamics models, developed by MMU, a Global Track model and a rail-wheel Contact model, developed by CRT. The modelling is being complemented through the monitoring of a number of RCF affected sites on the UK network to provide essential empirical data. A total of seven vehicle models have been developed using ADAMS/Rail, including two locomotives, two DMUs, two passenger coaches, and a freight wagon. Vehicle simulations were conducted for a range of UK sites and provided results such as wheel-rail contact forces and contact patch positions. The vehicle models have been validated using track measurements. The results were then used as inputs for the CRT Global Track and Contact models. The Global Track model is a finite element (FE) model that represents a length of railway track and includes the rails, sleepers and ballast. Forces from the vehicle simulations were applied to the Global model in order to predict the bending stresses in the rail head. This was conducted for a number of vehicles at seven sites and the predicted values showed good comparison with track measurements. The Contact FE model is a 3 dimensional (3D) representation of a wheel section rolling on a short length of rail. Wheel loads calculated from the vehicle dynamics simulations were applied to the contact model in order to predict surface and subsurface stresses, including directional and shear, in the rail head. Subsurface stress distribution is of primary importance for understanding the development of RCF and crack growth. The TSM successfully integrates the vehicle and track aspects of the railway system and provides an accurate method of predicting stresses in rails. When used in conjunction with the practical understanding of RCF, through site monitoring, it will enable the development of analytical fatigue life models that can be used by the track engineer to support future decision making for an optimum rail grinding strategy and rail renewal programme.

INTRODUCTION

The subject of Rolling Contact Fatigue (RCF) has been a research and development topic for several decades. Although, supported by the major railways, the work has primarily been undertaken by academic institutions and research organisations and has largely concentrated on laboratory studies using the "Twin-Disc" simulation of rolling contact conditions. Very significant progress has been made using this approach on the understanding of the development of RCF. However, it has become increasingly apparent that the development of a control strategy for this complex issue requires a practical track based investigation that is supported by detailed numerical analysis of the rail-wheel interface and the distribution of stresses within the rail head. A major project involving track studies of RCF has been undertaken by Corus Rail Technologies (CRT) with support from Manchester Metropolitan University (MMU). It adopts both a practical and scientific approach to understand the occurrence of RCF and behaviour of the railway as a system. The objectives of the project are to monitor a large number of sites that suffer from RCF and to develop and validate the CRT Track System Model (TSM) that will be used to evaluate the influence of a range of parameters related to traffic, track design and construction, track integrity and, in particular, the development of RCF.

The TSM comprises a suite of numerical models involving both vehicle and track aspects of the railway system and provides results that can be fed from one model to another. At the centre of the TSM are the track measurements conducted at additional monitoring sites that are being used to validate the models. The practical assessment of RCF sites used in conjunction with the track system modelling will aid the development of analytical based fatigue life prediction models that supports the track engineer to adopt an effective rail grinding and rail replacement strategy.

RCF SITE MONITORING

A total of 27 stretches of track are being monitored around the UK railway network. This provides essential information on the development of RCF cracks under different conditions. Some trends are beginning to emerge, although there is still insufficient data to establish any robust empirical relationships. The key issues that have been examined are the interrelationships between wear rate, RCF initiation and crack growth rate, traffic density, and track parameters such as radii.

TRACK SYSTEM MODEL

The Track System Model (TSM) comprises a series of separate numerical and analytical models that have been developed using commercial software packages. Each model is used to assess a specific part of the railway track system. The structure of the TSM is such that the results from one model can be fed into another allowing specific components to be assessed in more detail. The separate models, model developers, and the software used are as follows:

1. MMU Vehicle Dynamics Model – using Adams/Rail
2. CRT Global Track Model – using ABAQUS software
3. CRT Contact Stress Model – using ABAQUS software
4. CRT Detailed Sleeper and Component Model – using ABAQUS software
5. CRT/Irsid Fatigue Model – using Visual Basic

Together the models can be used as an effective tool for assessing the in-service performance of vehicle and track components and to optimise the track system. The TSM can also be used as a tool to investigate problems such as RCF to identify the root causes of failure and to evaluate the impact of the introduction of new vehicles. A flow chart of the TSM for the application of RCF is shown in Figure 1 overleaf. At the center of the TSM are the track measurements used to validate the separate models.

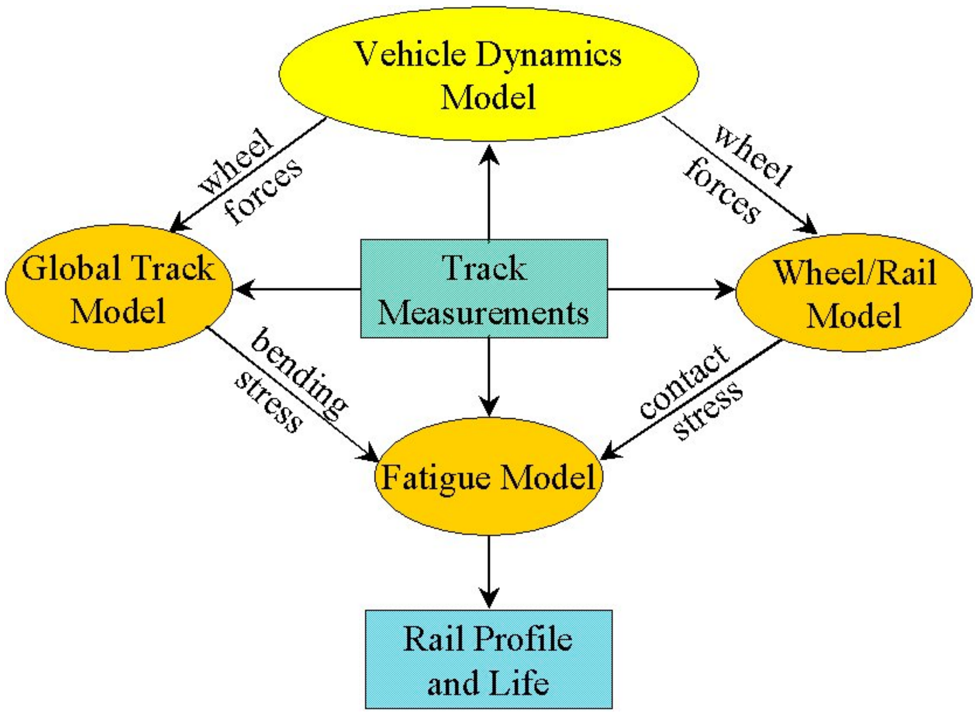

Figure 1 Flow Chart of Track System Model

The TSM has been developed and used as part of the current Railtrack Contact to investigate the in-service conditions and RCF of rails. This has involved the modelling of seven different vehicles and seven different sites located on the UK railway network.

Vehicle Dynamics Studies

Adams Rail allows construction of a railway vehicle computer model that is represented using rigid masses of individual components. The rigid elements of the vehicle body, bogies and wheel sets are connected together using force elements that define the suspension components such as springs, bushes, dampers and bumpstops. Vehicle models can then be simulated over different sections of track, taking into account track geometry, including rail irregularities as measured by the track recording coach, and cant. Complex algorithms based on theories developed by Hertz and Kalker (ADAMS/Rail 1999) handle the contact calculation of the wheel rail interface geometry and normal and tangential forces. The level of complexity can be varied from simple linear forces to a full non-linear, on-line calculation, using the wheel and rail profiles. Non-linear calculations are capable of handling multi-point contact. The simulations provide the predicted contact forces and creep forces as a function of track distance, as well as the position of the wheelsets relative to the rails and also contact patch locations.

A total of seven railway vehicles were modelled including two locomotives (class 43 and 91), two passenger coaches (Mk3 and Mk4), two multiple units (class 158 and 170), and a freight container wagon running on Y25 bogies. The vehicles were selected as representative of the wide range of vehicles currently running on the UK network and probably account for over 50% of vehicle passages on mainline track. A MiniProf device was used to measure the wheel profiles from one axle of each vehicle at the particular site of interest. The profiles were then imported into the Adams/Rail vehicle model. An example of a Class 91 locomotive model is shown in Figure 2 overleaf.

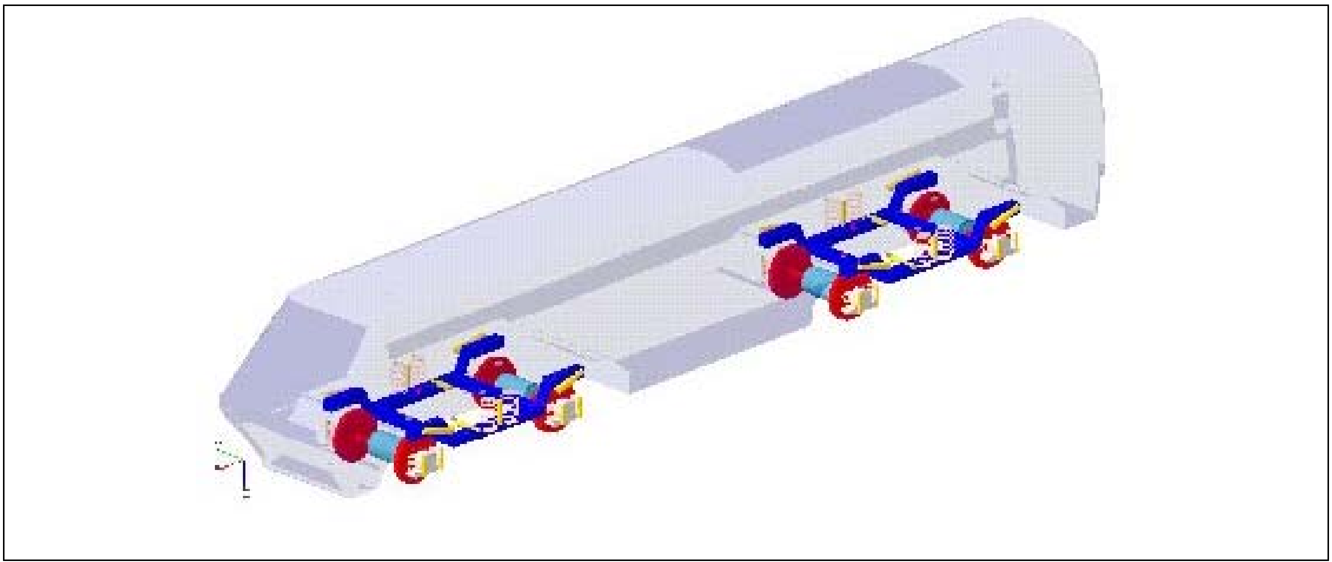

Figure 2 Class 91 Locomotive Model Developed Using ADAMS/Rail

The models were validated against static test measurements that form part of the UK Railway Group Standards acceptance test for new vehicles, these include:

- ΔQ/Q (wheel unloading test) using specified twisted track geometry.
- X-factor (bogie rotational resistance test).

The Sites

A total of seven individual sites were selected by Corus to give a broad range of characteristics, details of these sites are shown in Table 1. At each site, strain gauges have been attached to the rail to validate the models; these are referred to as track force detectors (TFD) and are discussed in a later section. The track geometry data was recorded by a track recording coach and processed by SERCO Railtest and AEA Technology. This includes the track distance, cross-level & curvature irregularities, lateral & vertical irregularities and gauge variation. The data around the measuring site location was selected and further processed for inclusion in ADAMS/Rail. The general design layout was defined (curvature and cant elevation), and the irregularities were converted to vertical and lateral irregularities at each rail. Measurements of the rail profiles were taken on-site, by Corus personnel, using a MiniProf device and a selected profile was used in ADAMS/Rail for both left and right rails.

Sites	**Monitoring Location**	**Curve radius (m)**	**Curve cant (mm)**	**Balance speed (mph)**	**Rail inclin-ation**	**Total track length (m)**
Silverton	MLN – 186m. 27ch.	2000.00	85.05	76.28	1/20	800
Wellingbr' Up	SPC - 63m. 48ch.	1428.57	139.98	82.71	1/20	1738
Conington Up	ECM – 67m. 30ch.	tangent	9.76	182.71	1/20	3000
Hatfield Up	ECM – 17m. 5ch.	1428.57	144.69	84.09	1/20	3020
Hatfield Down	ECM – 17m. 5ch.	1428.57	160.00	88.43	1/20	2000
Aycliffe Down	ECM – 49m. 5ch.	763.35	154.96	63.61	1/20	1186
Coning' S&C	ECM – 67m. 35ch.	tangent	-	-	Vertical	3000
Aycliffe S&C	ECM – 49m. 45ch.	tangent	-	-	1/20	200

Table 1 Site Data

Simulation and Output

A total of 19 simulations were performed using different vehicles at selected sites. Each simulation provides the predicted forces and contact information at each output time step for use by both the CRT

Global Track and Contact Stress Models. Predicted values were extracted for a limited section of track around the TFD monitoring site and the outputs for each model are listed below:

For use in the CRT Global Track Model:

- Average, minimum and maximum vertical forces at all 8 wheels.
- Average, minimum and maximum lateral forces at all 8 wheels.

For the CRT Contact Stress Model, the outputs were generated only for the leading axle. The maximal, minimal, average and a selected snapshot values were extracted for:

- Total vertical and lateral forces.
- Wheel lateral displacement and roll angle relative to the rail.
- Contact patches lateral position on wheel and rail profiles coordinate systems for up to three contact patches.
- Contact patches surface areas for up to three contact patches.

<u>Validation</u>

The vehicle models have been validated using strain based track force detector equipment. Strain gauges were attached to both cess and six foot rails, above and halfway in between the sleepers. The strains are then converted to stresses and subsequently converted to vertical and lateral forces, they are then compared with the vehicle dynamics predictions. Figure 3 shows an example vertical force output from ADAMS/Rail and the relative location of the TFD site.

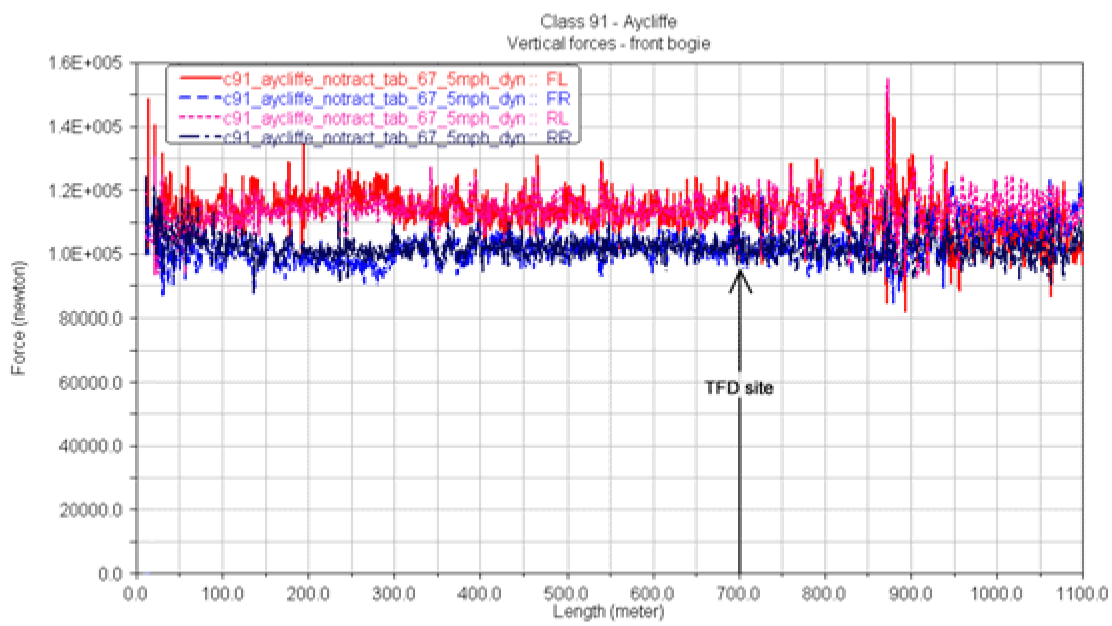

Figure 3 Vertical Forces Predicted at the Front Bogie

Figures 4 and 5 show the comparison between predicted and measured forces on the six foot rail at Aycliffe for two locomotives. It can be seen that in general the comparison is good with simulated values reasonably close to or overlapping the measured values. This indicates that the simulations are producing similar behaviour that matches that of the vehicles on the measurement site. Overall, the comparison between different vehicles and sites has shown that there is a lot of variation in both the simulated and the measured forces. However, further investigations are being conducted to assess vehicle model accuracy in more detail.

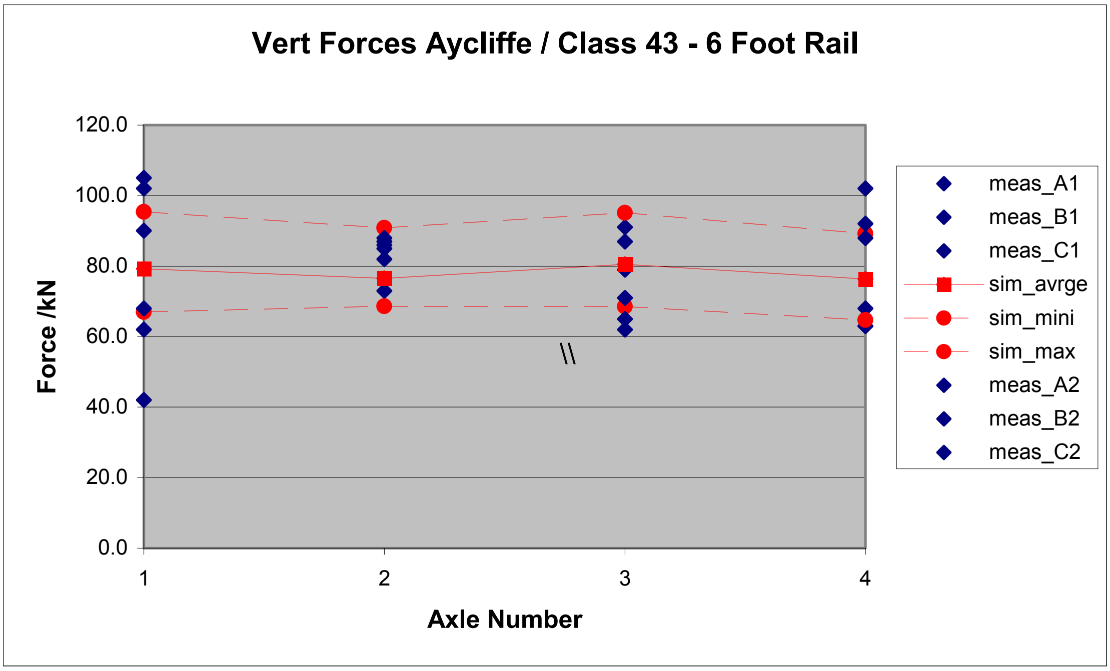

Figure 4 Measured and Simulated Vertical Forces for the Class 43 on the 6 Foot Rail

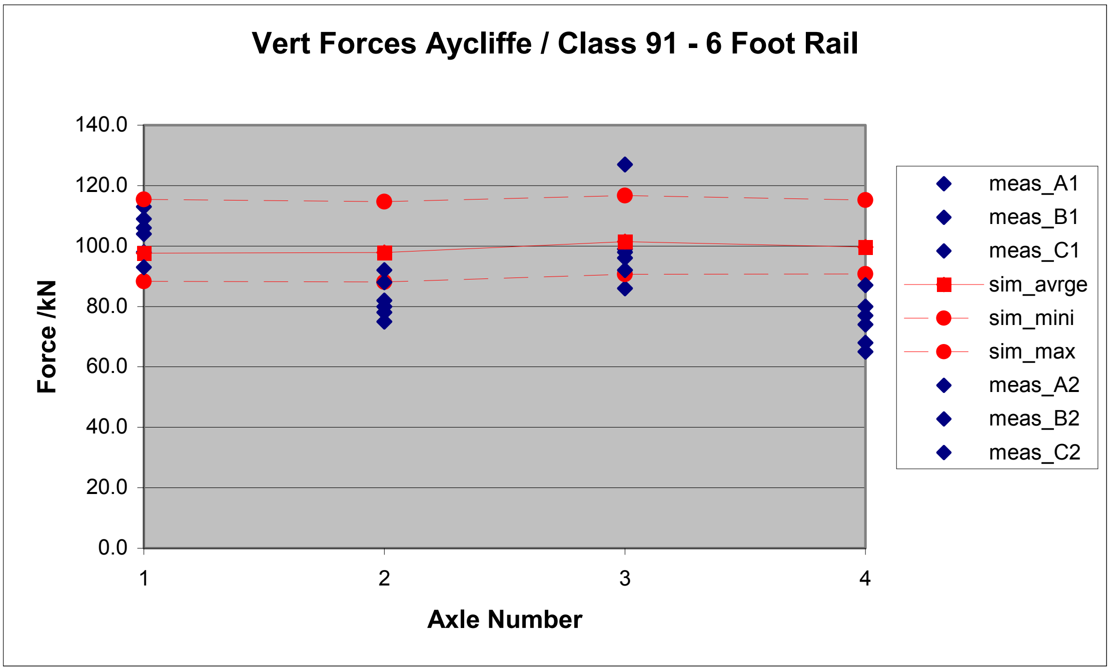

Figure 5 Measured and Simulated Vertical Forces for the Class 91 on the 6 Foot Rail

Global Track Model

A model of the railway track has been developed in order to quantify the in-service conditions of track components. Referred to as the ‘Global Model’ it includes the rail, sleeper and rail pad components and also provides representation of the ballast and subgrade. The CRT Global Model is defined as a mechanistic model that reacts to loading in the form of an interconnected structure. It is an excellent tool designed to investigate ‘what if’ sensitivity studies such as vehicle loads, track geometry, component type and support conditions. The Global Model can be used to accurately predict track response and hence can be used to provide useful information on track deterioration and subsequently to support future maintenance or renewal strategies. In the context of this work, however, the primary objective of the Global Model is to predict the bending stresses and displacements in the rail component when subjected to a variety of vehicle forces. The Global Model enables the stress cycle to be characterised and therefore help predict the fatigue life of components. Additionally, the predicted displacements of the rail and sleeper components can be used to feed into more detailed models in order to produce more accurate results.

The Global Model is a finite element (FE) model that represents a section of railway track. It has been developed using the software package MSC Patran and is analysed using ABAQUS Standard Version 6.2. Two models have been developed, one with a track length of 50 metres and one with a track length of 20 metres. The 50 metre model allows the forces from all eight wheels of a single locomotive to be applied simultaneously whereas the 20 metre model allows only four, i.e., one bogie. The forces can be applied as a single set of forces, i.e., to produce a ‘worst case’ snapshot, or as a series of forces to simulate the effect of a vehicle moving over a specified distance. Currently, the Global Model simulates the static response of a railway track and uses linear elastic values for the individual components. However, it can also be modified to simulate dynamic train-track interactions and include both linear and non-linear track responses.

Track Representation
The individual track components are modelled using a range of elements in order to model them in an accurate but efficient manner. The rail and sleeper components are modelled as Timoshenko beam elements, that rely on beam theory to describe the elastic deformation of a particular shape when forces are applied. The beams are one-dimensional line elements in a 3-dimensional space and their stiffness is defined by material and section properties. Bending stresses can be calculated for the head, web and foot areas of the rail section. The rail pad, ballast and subgrade are represented using spring elements that have an appropriate stiffness as defined by test measurements (Tiflex 2001) or through existing literature data (Hunt 1995, 1998). Site-specific stiffness values for the ballast and subgrade are currently being determined using falling weight deflectometer (FWD) measurements and these values will be incorporated into the models. A section of the Global Model is shown in Figure 6.

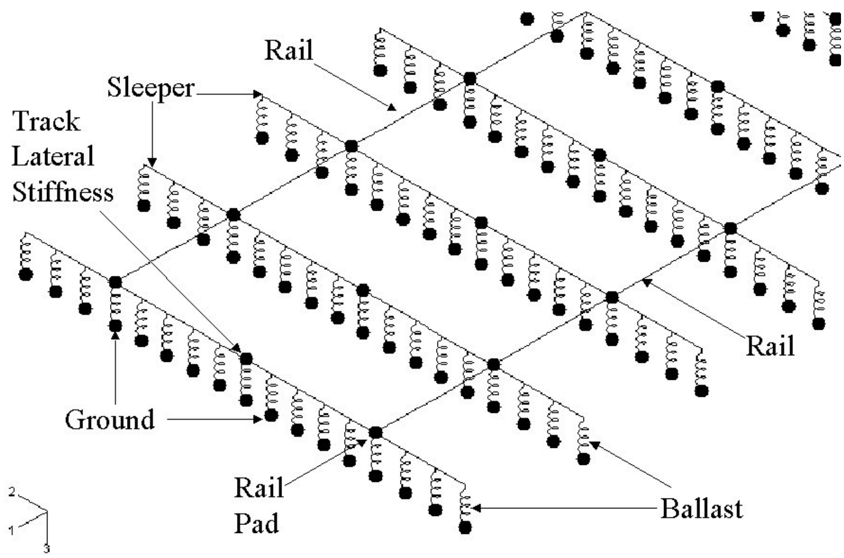

Figure 6 A Section of The CRT Global Model

<u>Simulation and Results</u>
The Global Model has been used to quantify the rail bending stresses and displacements when subjected to a number of vehicle loads at representative sites. A total of 22 simulation runs were performed using the 20 metre model, this involved two runs per vehicle and other investigations. The average vertical and lateral wheel forces for each wheel, calculated using ADAMS/Rail, were applied to the rail component at their appropriate locations.

Bending stresses have been calculated for both the high and low rails. In most cases the highest stress occurs in the high rail due to the centrifugal force acting on the vehicle and the cant deficiency. Vehicle dynamics results of the Class 43 locomotive simulated at Aycliffe predicted average vertical wheel forces of 95 kN. The resulting rail head bending stresses for a BS113A 'high' rail at Aycliffe are shown in Figure 7. The stress values taken in isolation, are considered to be quite small, i.e, -70MPa average and 38MPa, and well below the yield of rail steel. However, the compressive stresses in the rail head (under each axle) are additive to the compressive stresses caused by the wheel-rail contact and therefore should be included in any detailed assessment. Similarly, tensile stresses are at their maximum at the bogie centres, i.e., in between the axles, and these will interact with both residual stresses and the lane stress. Additionally, the tensile stresses are considered to facilitate crack growth once the crack has reached a critical length.

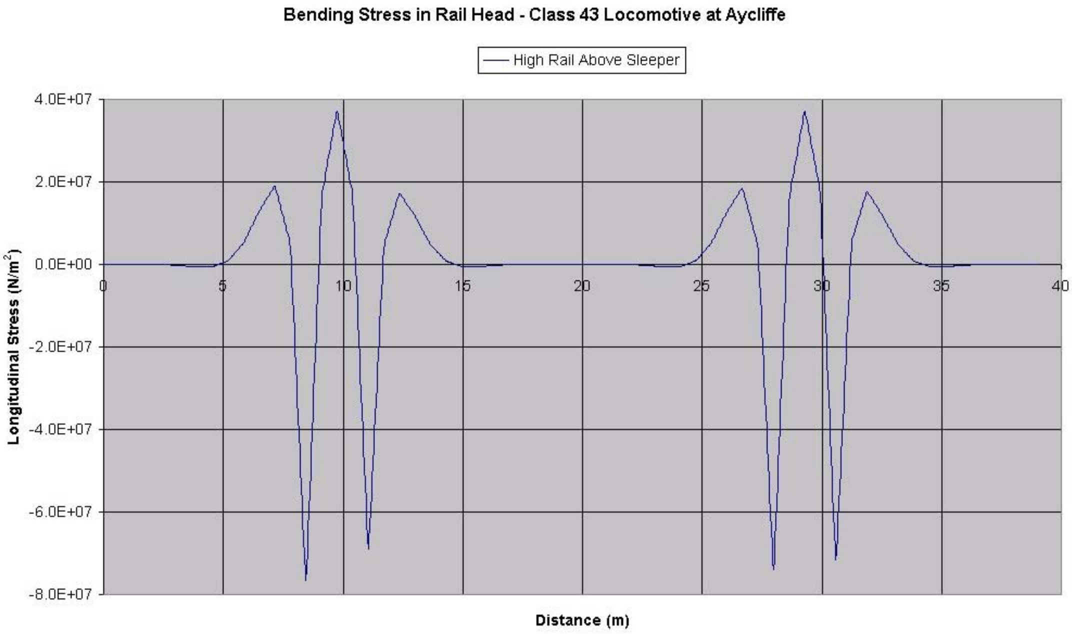

Figure 7 Rail Head Bending Stresses for Class 43 Locomotive at Aycliffe

Rail displacement predictions have also been calculated for individual vehicles and sites. Figure 8 (overleaf) shows displacements for the Class 91, Class 43, and Class 158 vehicles at Aycliffe. Maximum displacement for the Class 91 locomotive is between 2.3 to 2.4mm. The displacement of the Class 43 locomotive varies between 1.8 to 1.95mm and the Class 158 DMU produces an average displacement of 1.6mm.

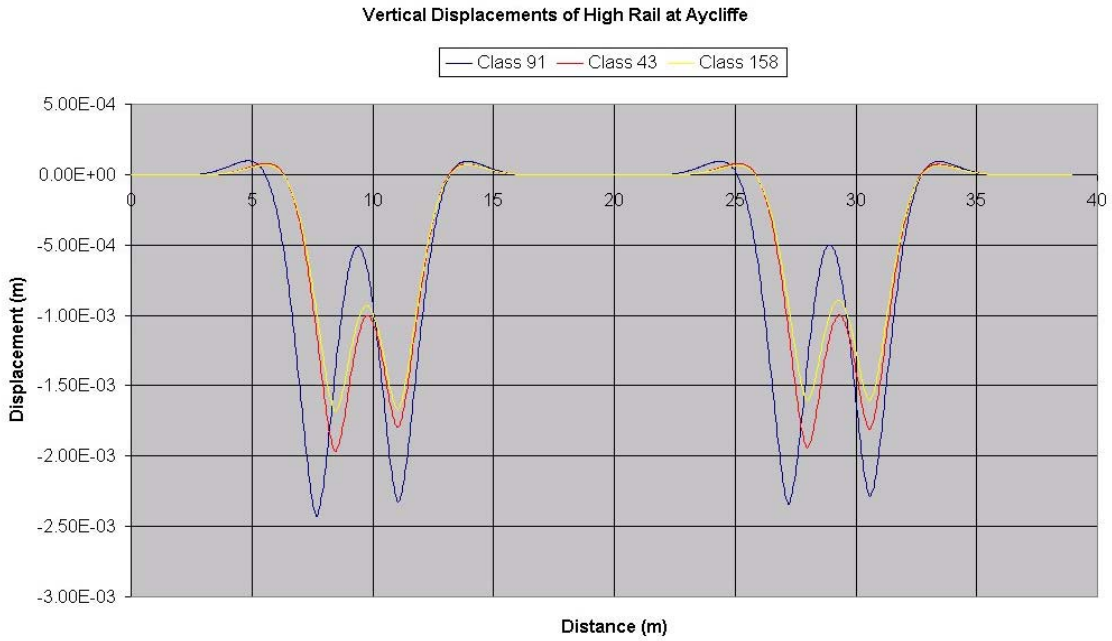

Figure 8 Rail Displacements for 3 Vehicles at Aycliffe

<u>Validation</u>

Validation of the bending stresses predicted by the Global Track Model has been conducted for the Class 43 locomotive at Aycliffe, Wellingborough and Silverton. This was achieved by comparing the predicted values with actual track measurements using strain gauges positioned on the top surface of the rail foot. Both the gauge and field side of the high (Cess) and low (Six foot) rails were measured at locations above and at halfway in between sleepers. A summary of the results from the track measurements and those predicted by the Global Model are shown in Table 2 below. It is shown that the average Global Model predictions compare very well with track measurements although further investigation is required to compare the bending stresses for each wheel. Also, falling weight deflectometer measurements are currently being conducted at selected sites, this information was not available in time for the current work.

SITE	Stress (N/mm^2)							
	C2L	**C4L**	**CG2L**	**CG4L**	**SF2L**	**SF4L**	**SG2L**	**SG4L**
Aycliffe	37.11	57.8	29.3	33.7	29.96		40.8	43.3
Aycliffe	36.97	61.8	33.5	35.5	28.84		38.8	51.5
Aycliffe	43.4	57.9	31.3	34.3	33.51		42.1	45.2
Model (Average)	**46.25**	**54.9**	**36.75**	**40.7**	**43.75**	**44.1**	**33.7**	**35.5**
Wellingborough	39.84	51.77	34.47		32.15	50.07	27.6	48.19
Wellingborough	37.23	43.44	35.16		30.15	48.18	26.5	47.67
Wellingborough	39.63	42.55	35.33		29.88	46.9	25.9	44.83
Model (Average)	**40.1**	**47.7**	**36.9**	**42.0**	**40.98**	**48.7**	**36.3**	**40.7**
All values based on Class 43 Locomotive								

- C2L = Cess above sleeper (field side), SF2L = Six foot above sleeper (field side)
- C4L = Cess halfway in between sleeper
- CG2L = Cess (gauge side)

Table 2 Comparisons of Predicted and Measured Rail Foot Bending Stresses

Once the FWD information becomes available it will be compared with the values used in the Global Model, and if necessary further simulations conducted. Displacement measurements using accelerometers were also conducted at track sites although this data was not suitable to effectively validate the predicted displacements. However, the rail bending stress and track stiffness measurements should have provided sufficient information to confirm the validity of the Global Model.

Contact Stress Model

The contact stress model consists of a short length (200mm) of rail head and a segment of wheel rim with both profiles being based on actual 'site measured' data rather than using as-new nominal dimensions. The MiniProf data was used to produce accurate 2D curves of the wheel and rail components that were imported into the ABAQUS finite element software package. The 2D curves are then converted into 3D solid models using the pre-processor ABAQUS/CAE (ABAQUS 2001). Relative positioning of the wheel to the rail, i.e., the contact position, is based on the output from the vehicle dynamics simulation. As well as the detailed geometry of the wheel and rail, the FE program requires specified material properties for both components. The rail material properties are dictated by their composition and specific manufacturing process. For example the rail at the Silverton monitoring site was Mill Heat Treated (MHT) rail grade and the corresponding true stress-true strain data was used in the analysis. The next stage of model development involves dividing each component into a mesh of discrete elements that can then be used in the FE analysis. This inevitably involves some compromise. In order to reflect the complex geometry of the two components a fine mesh is necessary, however, this increases the processing time. Figure 9 shows the FE mesh of the rail wheel assembly used in the analysis. All of the elements used in the model are 8-noded linear solids.

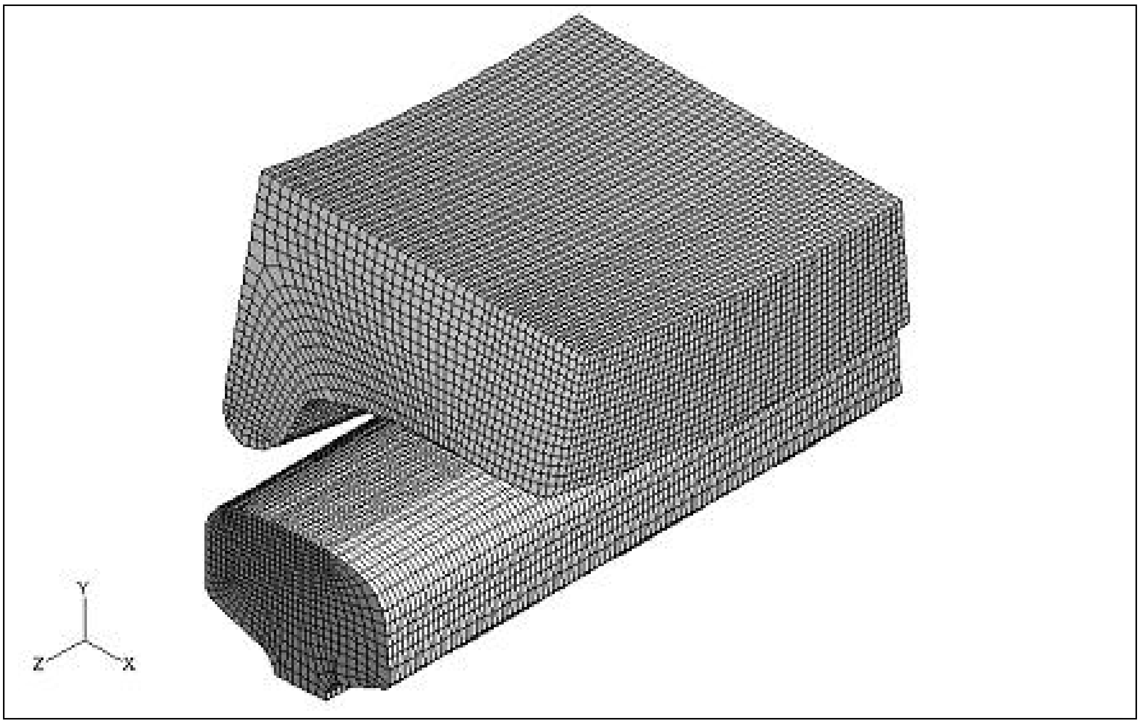

Figure 9 Meshed Wheel and Rail Head Profiles

Finite Element Analysis

For each site a snapshot was taken from the Adams Rail load/time history output. The loads were applied to the wheel vertically and horizontally together with a driving torque. The analysis was conducted as a dynamic analysis using ABAQUS Explicit during which the segment of wheel rim is rolled along the head of the rail under the appropriate loading and torque. The speed of the locomotive was assumed to be constant and a value of 0.45 taken as the coefficient of friction between the two components.

Results & Outputs

Simulated forces for the Class 43 and Class 91 locomotives at seven different sites were applied to the rail-wheel Contact model. Typical results are the surface contact pressure, surface stress and contact patch size. Additionally, subsurface stress distributions are calculated for both the wheel and rail components, including directional and shear stresses. Von Mises stress distributions on the rail surface for the Aycliffe (Class 91) and Wellingborough (Class43) sites are shown in Figure 10.

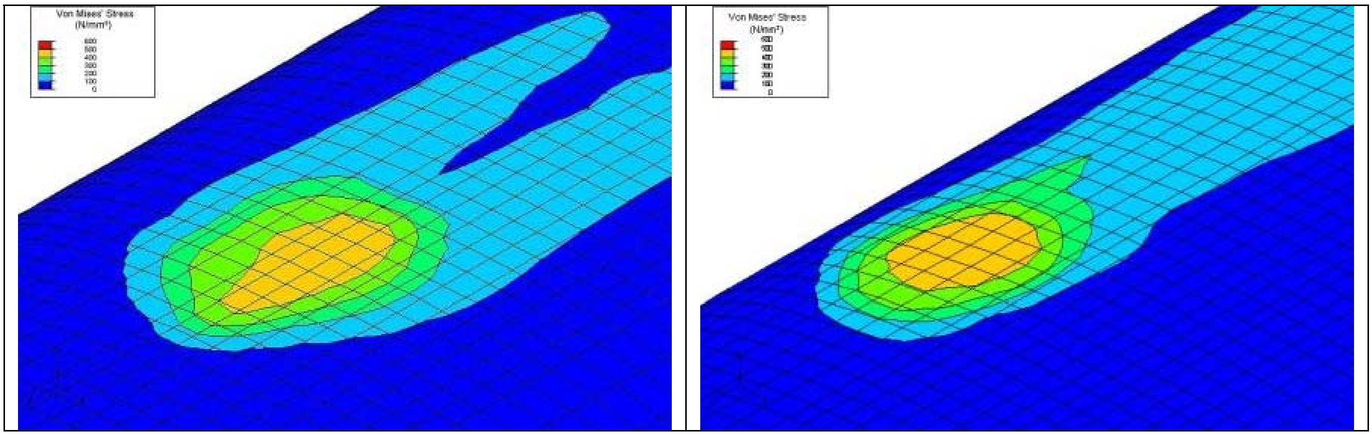

Figure 10 Von Mises Stress Distribution for Aycliffe and Wellingborough Sites

Von Mises stress values are between 500 – 600 N/mm^2. In both cases the von Mises stress exceeds the yield stress of the material, i.e., 400 N/mm^2 for Grade220, and the Figures clearly show the residual trail of permanent deformation. This leads to work hardening of the material, which continues on a gradual basis with every wheel passage. A major benefit of the contact model is the ability to show the stress distribution through the rail head. The von Mises and longitudinal shear stress distributions in the rail head are shown in Figure 11.

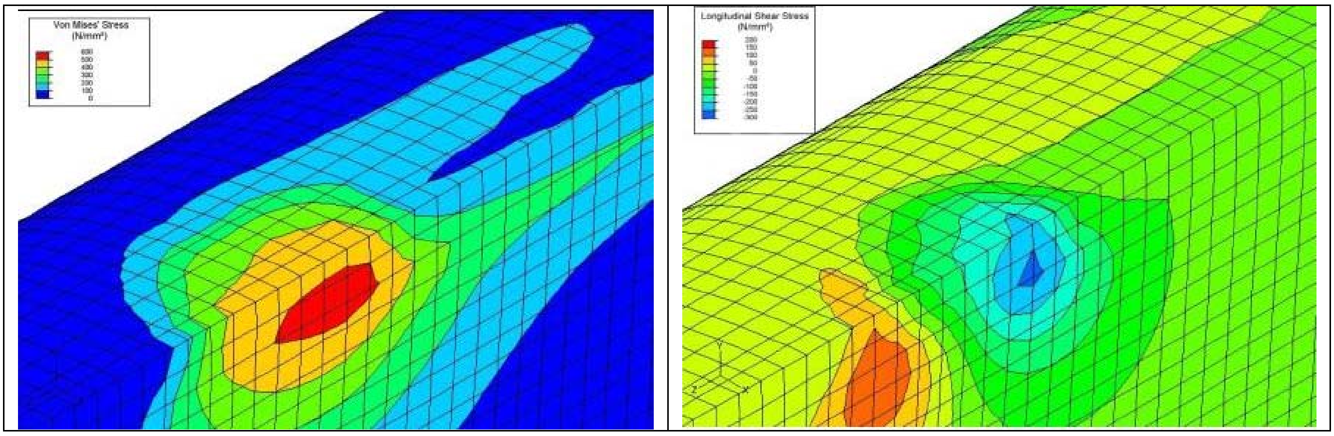

Figure 11 Von Mises and Longitudinal Shear Stress Distribution Through Rail Head

It is interesting to note that the maximum stress values occur approximately 3-4 mm below the rail surface. Maximum shear stress is 172 N/mm^2 and occurs at the front of the contact patch (appears in red in the picture) whilst the minimum value at the rear of the contact patch is –235 N/mm^2 (appears in blue in the picture). This is because the rail material is extended in front of the wheel and compressed behind it, as it is driven. It is believed that these longitudinal shear stresses have a significant influence on the development of RCF and crack propagation.

The same output can also be provided for the wheel component. Figure 12 below shows the stress distribution in the wheel both at the start and end of the analysis. The residual trail of plastic deformation can be clearly seen and this can provide useful information on wheel life.

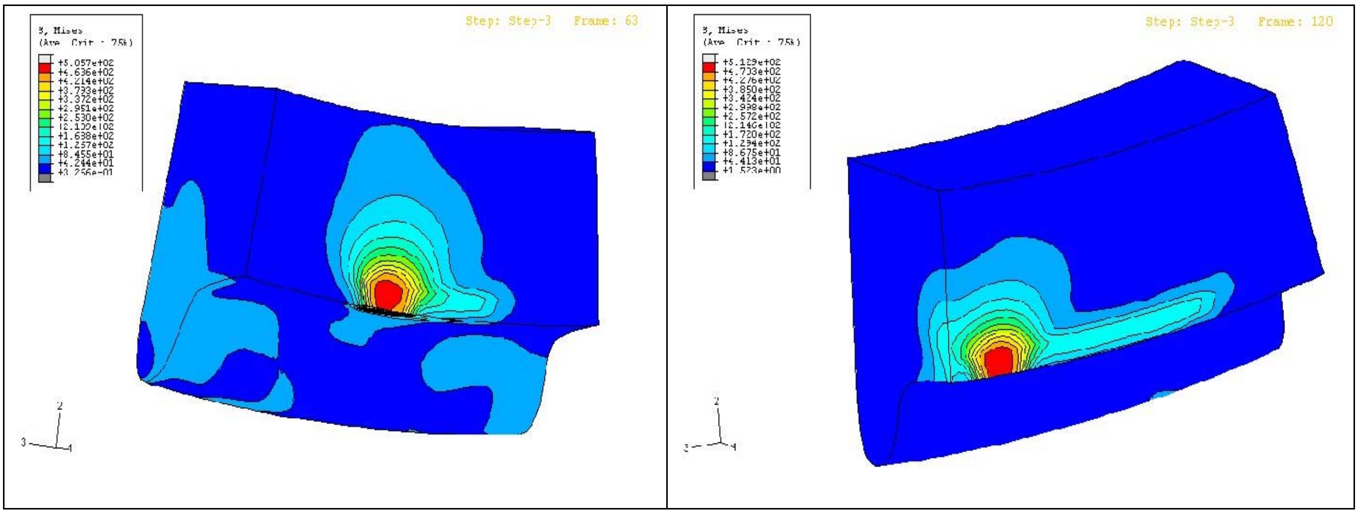

Figure 12 Von Mises Stress Distribution Through Wheel Section

<u>Rail Life Evaluation</u>

The TSM comprises a suite of models that each plays a crucial role in the prediction of in-service conditions. The vehicle dynamics modelling predicts the wheel forces and the contact patch positions, the Global Track model predicts the bending stresses and the Contact model predicts the contact stresses at the rail surface and the stress distribution through the rail head. Sub-surface stress distribution is of primary importance for understanding the development of RCF and crack growth. The Contact model essentially provides a window to visualise the mechanical process occurring during contact and the resulting distribution of stress, both directional and in shear. It is also considered to be a very accurate method for quantifying contact stress compared to other methods and therefore provides a benchmark. The TSM in conjunction with the practical understanding of RCF, through site monitoring, will enable the development of analytical fatigue life models that can be used by the track engineer to support decision making for an optimum rail grinding strategy and rail renewal programme.

CONCLUSIONS

A library of seven ADAMS/Rail vehicle models have been developed and used to predict wheel-rail contact forces and contact patch positions for a number of different sites. The vehicles selected were representative of the wide range of vehicles currently running in the UK and probably account for over 50% of vehicle passages on mainline track. The vehicle models have been validated using strain based TFD equipment and comparisons show that the simulations are producing similar behaviour that matches that of the vehicles on the measurement site. Further investigations are being conducted, however, to assess vehicle model accuracy in more detail. The results have been used as key inputs for the CRT Global Track and Contact models. The Global Track model has predicted the bending stresses when subjected to vehicle forces. In isolation the stresses are considered as relatively small, however, these stresses are considered to play an important role once an RCF crack reaches a critical length. The Global Track model has been validated against on-site measurements with good agreement although further investigation is required to compare the bending stresses for each wheel. The rail-wheel Contact model has predicted surface and subsurface stresses for the Class 43 and Class 91 locomotives at seven different sites. Von Mises stresses are predicted to be significantly above the yield stress of rail Grade 220 and this is shown by the residual trail of plastic deformation. The contact model has the capability of calculating both directional and shear stresses through the rail head and indicates maximum von Mises stresses at approximately 3 - 4mm below the rail surface. Quantifying subsurface stress is particularly important in terms of longitudinal shear stress, which is considered to significantly influence RCF development and crack propagation.

Surface and subsurface stresses can also be calculated for the wheel component and can provide useful information relating to wheel life. The TSM comprises a suite of models that each plays a crucial role in the prediction of in-service conditions. Coupled with the practical understanding of RCF, through site monitoring, the system approach will facilitate the development of accurate fatigue life models to evaluate rail life.

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The Rail Technology Unit

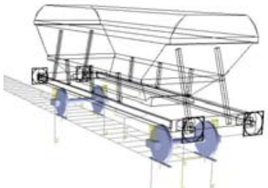
Rail Technology Unit

Manchester Metropolitan University

The **Rail Technology Unit** based at **Manchester Metropolitan University** carries out research and consultancy into the dynamic behaviour of railway vehicles and their interaction with the track.

We use state of the art simulation tools to model the interaction of conventional and novel vehicles with the track and to predict track damage, passenger comfort and derailment. Our simulation models are backed up by validation tests on vehicles and supported by tests on individual components in our test laboratory. We are developing methods to investigate the detailed interaction between the wheel and rail.

January, 2004
Simon Iwnicki
(RTU Manager)



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