Optimisation of Wheelset Maintenance using Whole System Cost Modelling

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Abstract — The maintenance and renewal activities of wheelsets account for a large proportion of the whole-life costs for railway rolling stock. These activities are influenced by a large number of factors including depot constraints, wheel surface damage (i.e. rolling contact fatigue, wear and flats) \(^1\), fleet availability and vehicle design (e.g. wheel diameter limits between bogies and axles). If these factors are not managed efficiently it can have significant implications on a vehicle’s service provision, track damage, environmental and whole life costs. Therefore the development of an effective wheelset management tool will support the optimisation of maintenance and renewal regimes, thereby increasing wheelset life and reducing costs.

Previous versions of the Vehicle Track Interaction Strategic Model (VTISM) linked vehicle-track characteristics (e.g. vehicle type, traffic levels, degradation rates, geometry) and maintenance regimes to outputs such as rail life, replacement and maintenance costs. The Stage 2 development of VTISM, which is part of the RSSB-managed rail industry research programme funded by the Department for Transport, has enhanced the rolling stock modelling capabilities of the tool through the development of the Wheelset Management Model (WMM). This model aims to assist in the strategic planning of wheelset maintenance and renewal activities and thereby allowing users to examine the benefits and cost impact of a range of different scenarios to optimise wheelset management strategies. These enhancements go some way to determining the whole life costs of the complete system (vehicle and track).

This paper describes the capabilities of the WMM and illustrates how the model can be used to optimise a fleet’s maintenance strategy through the application of a realistic industry case study. The implications of different wheelset maintenance regimes (e.g. regular interval vs. condition-based tyre turning) on wheelset life and costs were examined. Finally, the paper presents how the tools can be used to investigate whole-system costs and demonstrate the impact of wheelset maintenance on track costs.

Keywords — asset management, rolling stock, wheel/rail damage, whole system costs

I. INTRODUCTION

The Stage 2 development of the Vehicle Track Interaction Strategic Model (VTISM) has enhanced the rolling stock modelling capabilities of the software through the development of the Wheelset Management Model (WMM), Wheelset Strategic Planning Application (W-SPA) and the Wheel Profile Damage Model (WPDM). The aim of these new tools is to allow the user to optimise wheelset management strategies by evaluating the associated with wheelset renewal, maintenance and inspection. Combining these enhancements with the existing VTISM tools, help to determine the impact of system changes on both wheelset and track asset management costs and provide a means for optimising whole system costs.

This paper describes the capabilities, benefits, limitations and assumptions of the new wheelset management tools through the application of a realistic industry case study. Using a number of simulations were conducted to predict the whole life costs associated with wheelset inspection, maintenance and renewals for a typical DMU fleet. The influence of changes to maintenance strategy (e.g. changing from an interval- to condition-based turning regime), lubrication and vehicle primary yaw stiffness on the predicted costs were investigated. The outputs from the wheelset whole life cost analysis, in terms of wear rates and changes to the profile shape, were used to support the analysis of track costs using the existing VTISM tools (Whole Life Rail Model (WLRM), Track Geometry Pre-Processor and Track Strategic Planning Application (T-SPA)) on a typical section of track. The variation in costs associated with rail rolling contact fatigue (RCF) and wear damage for the different wheelset maintenance strategies is demonstrated.

II. VTISM AND WHEELSET MANAGEMENT MODEL

VTISM is a strategic modelling tool which links asset data with a number of deterioration models to predict the whole life costs for the vehicle-track system. It enables the user to understanding the cost implications of changes to the vehicle-track system (such as vehicle type and service levels, track maintenance regimes and design) and thus facilitates the optimisation of design and maintenance regimes.

VTISM is managed by RSSB on behalf of the Vehicle/Track System Interface Committee (V/T SIC) and is jointly owned by RSSB and Network Rail. The Stage 1 development of VTISM resulted in a model which focused on the damage, degradation and whole life costs for the track side of the interface \(^2\). The track cost model utilises vehicle dynamic models to predict wheel/rail forces for use in the WLRM to predict rail RCF and wear damage for a specified section of track \(^3\), while empirical models predict the degradation of track geometry and ballast condition. These are combined with the track and vehicle characteristics, along with historic information on the performance of the asset, within T-SPA to predict the impact of the different options for track renewal, maintenance and traffic levels on the future condition and performance of the track over a specified time period. Figure 1 illustrates the VTISM methodology process, which has been applied to recent
vehicle procurement processes and the assessment of vehicle track access charging.

The aim of VTISM is to provide a system based approach for assessing the vehicle-track interface, whereby the impact of changes to one side of the interface on the other can be evaluated. Taking into account the achievements of the Stage 1 development, the need to strengthen the wheelset modelling capabilities of the tool to provide further understanding of how variations in wheelset management strategies affect wheelset costs was taken forward enabling track damage and whole system costs (vehicle-track) to be assessed. This was delivered as part of the Stage 2 development of VTISM incorporating the WPDM and WMM. This is illustrated by the green dashed boxes in Figure 1. These were completed by Serco and the University of Huddersfield. These software tools \cite{4, 5} are described as:

- **Wheelset Management Model (WMM)** – The WMM allows users to set up and edit current fleet and wheelset asset data and evaluate wheelset costs for varying maintenance and operating strategies. The WMM incorporates the Wheelset Strategic Planning Application (W-SPA) which was developed with similar functionality to the T-SPA tool. W-SPA tracks the wheelset condition (i.e. diameter, wheel tread wear and damage levels) over time and compares the condition to pre-defined limiting values (railway group or company standards), triggering a maintenance or renewal activity. The costs associated with inspection, maintenance and renewal are then determined and compared in WMM.

- **Wheel Profile Damage Model (WPDM)** – The WPDM was developed to predict deterioration rates of the wheel tread in terms of wear and RCF, when this information is not available from fleet observations. The WPDM can be used as a stand-alone model and generates a result file which can be input into WMM. This is particularly beneficial for the development and introduction of new fleets and the cascade of existing fleets.

### III. WHEELSET WHOLE LIFE COSTS

This section illustrates the methodology for assessing wheelset whole life costs within the WMM using a worked example.

#### A. Methodology

Using the fleet characteristics detailed below, a base case analysis was setup and run in both WPDM and WMM/W-SPA to predict wheelset inspection, maintenance and renewal volumes/costs for the chosen fleet. This base case was selected to represent the current vehicle configuration and associated maintenance and renewal policies. The wheel damage rates predictions were compared with the observed damage rates on the chosen fleet. The results from the base case analysis were compared to fleet data using data such as wheel lathe turning records to determine the accuracy of the model results. A number of alternate cases were assessed to investigate the influence of selected parameters on the predicted wheelset and track whole life costs. These cases included:

- Influence of changes to wheelset maintenance strategy (i.e. changing from an interval- to a condition-based turning regime) and determination of the optimal wheel turning interval.
- Impact of changes to vehicle primary yaw stiffness and lubrication strategy.

The predicted wheelset and track inspection, maintenance and renewal costs for each of the alternative cases were compared to the results from the base case analysis.

#### B. Fleet Characteristics and Duty Cycle

The fleet of DMUs used within the analysis consist of three vehicles with one powered and one trailer bogie per vehicle. Observations of wheel damage from the fleet have shown that the leading trailer axle, at each end of the train, accumulates damage more quickly than intermediate trailers and different damage rates were also observed on powered and trailer axles \cite{1}. Therefore three wheelset types were defined in the WMM: motor (M), internal trailer (T) and leading trailer (L). This allows different damage rates and maintenance criteria to be applied to each of the different wheelset types within WMM/W-SPA. The location of each type of wheelset is summarised in Figure 2.

To accurately predict the damage rates (wear and RCF) for use in WMM it is important to represent the duty cycle of the vehicle, in terms of the routes which the vehicle operates and how frequently it operates on each of these routes. Detailed data was acquired to describe where the vehicles have travelled, together with other useful parameters such as speed and traction/braking performance. This data was extracted from the data-recording systems on the vehicles and was analysed to determine a typical service diagram for a 17-month period which was used in the WPDM analysis \cite{1}.

#### C. WPDM Analysis
In order to track the life of each wheelset type the WMM needs to know how the attributes of the wheel (i.e. diameter, profile shape and tread damage) deteriorate over time. For existing fleets this information can be obtained from fleet observation data (such as wheel lathe data, flange height and thickness data). In some cases, for example the introduction of a new fleet or the cascading of a fleet, this information is not available. To facilitate this problem, the WPDM was developed to predict the rate of wear, conicity change and RCF for each wheelset type of a vehicle fleet. It uses a description of a fleet’s route diagram to characterise the duty cycle of the vehicle in terms of curve radius, cant deficiency and traction/braking performance. Using this duty cycle a large number of vehicle dynamics simulations are conducted to calculate the wheel/rail forces and predict the formation of wear and RCF damage on the wheelset. Due to the higher primary yaw stiffness and traction/braking forces marginally greater rates are predicted from the WPDM than an Archard (wear) and Tγ (RCF) damage models. The damage rates (i.e. mm/mile) predicted by the WPDM are saved in a comma delimited file and imported into the WMM. Further details of these damage models can be found in [6] and [10]. Figure 3 illustrates the predicted flange height (a) and thickness (b) for both the motor and trailer wheelset. Due to the higher primary yaw stiffness and traction/braking forces marginally greater rates of tread and flange wear are predicted on the motor wheelset.

![Prediction of flange height and thickness](image)

**Fig 3. Predicted flange height (a) and thickness (b) for base case analysis**

**D. WMM Analysis**

To conduct the WMM analysis, the characteristics of the fleet are defined. This includes: engineering standards and limits (e.g. flange height and thickness limits), asset inventory information (i.e. number of trains, vehicles and wheelsets of each type) and the initial condition of each asset (i.e. historical inspection data, wheel diameter, last bogie overhaul, flange height/thickness). The inspection and maintenance intervals for the fleet were also defined:

- Bogie overhaul interval
- Wheelset turning interval – 140,000 miles
- Visual inspection, flat depth and profile measurements – 20,000 miles
- Ultrasonic testing – 100,000 miles

An inspection, maintenance and replacement strategy for the fleet was set-up in W-SPA. This includes a list of programmes which describe the actions undertaken to meet the operational requirements of the fleet and the criteria for each of these actions. Table 1 below includes a summary of the replacement, maintenance and inspection strategies:

<table>
<thead>
<tr>
<th>Wheelset Replacement</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bogie Overhaul</td>
<td>Mileage since last bogie overhaul is greater than bogie overhaul interval</td>
</tr>
<tr>
<td>Wheelset Replacement</td>
<td>Wheel diameter is less than the minimum diameter for running, or the wheelset requires turning for damage and the wheel diameter is less than the minimum diameter for turning, or the wheelset requires turning for damage and wheel diameter after turning would be less than the minimum diameter for running</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wheel Turning (only applied if wheel diameter is greater than the minimum diameter for turning)</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning on Max</td>
<td>Maximum flats indicator is greater than zero</td>
</tr>
<tr>
<td>Flats Height</td>
<td>Flange height is less than the maximum permitted flange thickness</td>
</tr>
<tr>
<td>Turning on Flange</td>
<td>Flange height is greater than the maximum permitted flange height</td>
</tr>
<tr>
<td>Turning on Damage Depth</td>
<td>Damage depth is greater than the permitted damage depth</td>
</tr>
<tr>
<td>Turning on Mileage</td>
<td>Mileage since last turning is greater than the defined turning interval</td>
</tr>
</tbody>
</table>

**TABLE 1: WHEELSET MAINTENANCE STRATEGY**

**Inspection**

Ultrasonic testing: Mileage since last inspection is greater than the...
Case).

- Reduced mileage-based turning interval – turning interval reduced to 100,000 miles to represent a ‘little and often’ turning regime (Case 1).
- Condition-based turning regime – turning triggered by the condition of the wheelset only (Case 2).
- Lubrication strategy – coefficient of friction at the flange contact was reduced from $\mu=0.3$ to $\mu=0.1$, for all curve radii, to simulate vehicle-based lubrication. An additional activity and cost was added to the maintenance strategy for the inspection and maintenance of the lubrication system. This case includes modified wear and RCF damage rates for all wheelset types (Case 3).
- Modified primary yaw stiffness – primary yaw stiffness of the trailer bogie was increased. This case includes modified wear and RCF damage rates for all wheelset types (Case 4).

Figure 4 compares the volume and cost of wheelset maintenance (turning) for each case. It can be seen that more frequent mileage-based turning (reduced turning interval) increases the volume of wheelsets turned for mileage and reduces the number of wheelsets turned for damage. A condition-based maintenance regime results in an increase in the volume of wheelsets turned for damage and as a consequence turning for parity (to achieve wheelset diameter tolerances within a vehicle/bogie) also increases. The costs for turning show similar trends to the volumes of turning, with the condition-based maintenance costs being slightly lower due to a reduction in the number of turning activities.

Additional analysis runs were carried out to identify the optimal turning interval for this case study (i.e. interval which provides the least wheelset cost) by modifying the wheelset turning interval defined in W-SPA. Figure 5 shows the total wheelset costs for varying turning intervals. It can be seen that reducing the mileage-based turning interval from the base case value of 140k miles results in an increase in costs. Although slightly less material may be removed on the lathe with a reduced turning interval, wheelsets are turned more frequently and reach minimum wheel diameter earlier, resulting in an increase in wheelset replacement. As the turning interval is increased, wheelsets are allowed to run longer distances and accumulate greater levels of damage. To remove this damage a deeper cut is required during turning resulting in a greater proportion of wheelsets reaching minimum wheel diameter earlier. It can also be seen from Figure 5 that increasing the turning interval to 160k miles (from 140k miles) produces a slight benefit in terms of reducing the whole life costs of wheelset maintenance.

The reduction in damage rates associated with the lubrication reduces the volume of turning undertaken for damage depth, but as a consequence the volume of mileage-based turning increases. Modifying the primary yaw stiffness increases the rate of damage resulting in a larger proportion of wheelsets turned for damage depth and as a consequence turning for parity also increases.

**Fig 4. Wheelset maintenance (a) volumes and (b) cost**

**Fig 5. Total costs for varying turning interval**

The results presented in Figure 5 have also highlighted the interaction between the shape of the worn profile and the accumulated damage depth on the radial material loss during wheel turning. As illustrated in Figure 6 and 7, the results show that at low mileages the radial material loss from the wheel is governed by the amount of material loss required to restore the profile shape, which normally depends on the amount of flange wear.
Generally for this case, flange wear occurs early in the life of the profile and then stabilises, so the depth of cut on the lathe would be needed to restore the wheel profile remains fairly constant with mileage after the initial flange wear. As the mileage increases the level of RCF damage also increases resulting in greater radial material loss to remove damaged material. Therefore there is an optimum interval where the damage has reached the same depth as the cut needed to restore the profile shape. This interaction, along with observations of the variation in wheel turning across a vehicle, will be described in more detail in a future paper.

IV. WHOLE SYSTEM COSTS

Increased intervals between wheel re-profiling may result in a cost benefit to train operators and vehicle maintainers, but an increase in wheel/rail conformality may result in increased levels of wear and/or RCF damage on the track, as illustrated in Figure 8. Therefore to reduce whole system costs (vehicle-track) it is important to optimise both sides of the interface. The inclusion of the WMM and WPDM within VTISM enables it to be used for the analysis of whole-system costs. It is now possible to assess the impact of wheelset management strategies on track costs and the impact of track management strategies on wheelset costs to give a strategic view of the total whole system costs.

To assess the impact of changes to vehicle design and maintenance regime on whole system costs, a VTISM track analysis was carried out to predict maintenance, renewal and inspection costs for a section of track. Representative worn wheel profiles were selected from the wheel wear distributions generated during the WMM analysis and used to calculate wheel/rail forces to predict track wear and RCF damage within the WLRM in VTISM.

The change in flange height and thickness for each wheelset in the fleet for the entire 30-year projection was exported from WMM and used to determine the distribution of wheel wear. Using this information wheel profiles were selected and the proportion of the fleet running with each of the selected worn profiles was determined for use in the VTISM track analysis to scale the damage associated with each wheel profile. Figure 9 shows the cumulative distribution of flange height (a) and thickness (b) for all the simulation cases. This illustrates that reducing the turning interval results in the vehicle being re-profiled more often and therefore a higher proportion of light to moderately worn wheels running on the network. Changing to a condition-based turning regime, results in an increase in the number of worn to heavily worn profiles running on the network. The impact of lubrication on the predicted flange thickness can also be seen in Figure 9. The reduction in the rate of flange wear due to the application of lubrication reduces the proportion of wheelsets operating with smaller flange thicknesses. Different wheel profiles were selected to represent each of the wheel wear states presented in Figure 9. This can impact on the track costs, as new profiles generally have a lower conicity and therefore tend to cause more wear, whereas worn profiles will have a higher conicity tending to increase RCF damage on the track. Therefore the results from the track analysis are a trade-off between wear and RCF due to the different proportions of worn profiles operating on the network.

Track renewals, maintenance and inspection costs were derived using T-SPA over a 30-year projection. The default criteria were used to trigger track renewals and maintenance for all cases. Figure 10 shows the impact of the different wheelset maintenance and variant cases on track damage (wear and RCF only) and wheelset costs, when compared to the base case analysis (i.e. 140k mile turning).

It can be seen that increasing the turning interval results in a cost benefit to both vehicle and track, whereas increasing the primary yaw stiffness generates larger costs on both sides.
of the interface. It is interesting to note that both the condition-based turning and lubrication strategy provide a cost benefit for the track whereas a small increase in wheelset costs can be seen. This can be explained by the reduction in rail wear associated with running with a larger proportion of higher conicity wheel profiles (condition-based) and lower coefficient of friction (lubrication). As wheel wear is not a significant driver for wheel turning on the fleet analysed, these savings are less significant in the wheelset costs and are offset by deeper cut depths (condition-based) and extra inspection/maintenance (lubrication system).

V. CONCLUSIONS

The Stage 2 development of VTISM has resulted in the development of new tools for the prediction of whole life costs associated with wheelsets. These tools allow for the strategic modelling of wheelset renewal, maintenance and inspection policies based on the following inputs:

- Wear and RCF deterioration rates as a function of mileage
- Probability of generating flats
- Renewal and maintenance criteria
- Initial fleet conditions
- Budget and depot volume constraints
- Representative or fleet specific unit costs

These new tools are capable of answering key questions relating to wheelset deterioration, renewal and maintenance, as follows:

- Impact of changes to vehicle design, wheel profile and routes operated (e.g. P8 vs. P12 wheel profiles and cascading of vehicles to different routes).
- Impact of changes to wheelset maintenance and renewal criteria on whole system costs (e.g. turning interval, overhaul periodicity).
- Understand the effect of system changes on wheelset maintenance (e.g. lubrication and grinding strategy).

The capabilities of the new wheelset management tools have been demonstrated by predicting the whole life costs for a typical DMU fleet. The characteristics, asset inventory and initial conditions for this fleet were set up in WMM, along with a maintenance strategy in W-SPA. This strategy included programmes for wheelset replacement, bogie overhaul, wheelset turning and inspection. This strategy was run for a number of different scenarios to investigate the influence of changes to maintenance strategy on the predicted costs. The results from this analysis showed:

- More frequent mileage-based turning results in an increase in the volume of mileage-based turning and a reduction in the number of wheelsets turned for damage. A similar amount of material is removed at turning to restore the profile, so wheelsets reach minimum diameter earlier resulting in an increase in costs.
- A condition-based turning regime results in an increase in volume of wheelsets turned for damage (and generally more material removed each time) and as a consequence turning for parity also increases. Direct maintenance costs are slightly lower due to a reduction in the number of turning activities, but these savings are offset by an increase in vehicle out-of-service costs due to the unscheduled nature of condition-based maintenance.
- Increasing primary yaw stiffness increases the rate of damage resulting in a larger volume of wheelsets turned for damage and parity. A greater proportion of wheelsets reach minimum diameter earlier, increasing wheelset replacement costs.

Investigation of the optimal turning interval highlighted the interaction between the shape of the worn profile and the accumulated damage depth on the radial material loss during wheel turning. This suggests that there is an optimum interval where the worst damage has reached the same depth as the cut required to restore the profile shape. Through the use of the WMM this was shown to be approx. 160k miles for the example presented. This revised turning interval is now being implemented on the fleet.

To help understand the impact of wheelset maintenance on track costs, the outputs from the WMM analysis were used to select worn wheel profiles which were representative of the distribution of wheel wear in the fleet. These profiles were used in VTISM to predict RCF and wear damage on the track. The variation in track RCF and wear damage costs was investigated as follows:

- More frequent wheel turning results in a larger proportion of new to moderately worn wheel profiles running on the network. This leads to an increase in wear damage resulting in an overall increase in cost.
- A condition-based maintenance regime results in a larger proportion of moderate to heavily worn wheel profiles running on the network. This leads to a reduction in the level of wear damage, but increases RCF damage. For the route section investigated wear was the dominate cost driver due to the curve distribution and therefore a reduction in cost was predicted.
- Reducing the coefficient of friction through the application of lubrication resulted in a reduction in wear damage and costs on the track.
- Increasing the primary yaw stiffness resulted in an increase in both wear and RCF damage and therefore a significant increase in costs on both sides of the interface.

This study has demonstrated the benefit of using VTISM for carrying out ‘what-if’ analysis aimed at determining the impact of system changes on both vehicle and track costs and the importance of assessing both side of the interface in order to optimise costs.

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