

Wheel damage prediction for universal cost model applications

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ABSTRACT: In the EU project Roll2Rail, a Universal Cost Model (UCM) is developed, where innovations in running gear can be analysed within a simplified Life Cycle Cost (LCC) framework regarding its impact on energy, noise, vehicle damage and track damage. In this paper, the developed methodology for wheel damage calculation will be described. Besides, it will demonstrate different study cases for a regional train and extrapolate the differential LCC of different infrastructure parameters and vehicle technologies. Both the results and the implementation of the damage calculation methods are discussed, and the benefits of a unified methodology for a wide range of stakeholders are presented.

1 INTRODUCTION

Since early days of railway technology, a key objective has been to develop track friendly vehicles. However, with the separation of track and vehicle ownership, this development was disrupted. The financial impacts of innovative designs of a vehicle may be insufficient to be covered by considering the vehicle alone, since the savings in vehicle maintenance costs may well not exceed the higher capital cost for the vehicle. However, when the total costs of the railway system can be analysed, including the infrastructure, the economic benefits of these innovative technologies becomes more transparent.

Therefore, the running gear part of the European project Roll2Rail WP4 (Roll2Rail 2017) has been set up and aims to develop and establish a Universal Cos Model (UCM). The UCM will incentivise innovation by helping to create a greater awareness of how running gear- performance impacts different cost drivers within the entire railway system. Additionally, the UCM will be useful to help optimise aspects relevant to infrastructure, such as track maintenance. The use of the UCM can facilitate Life cycle Cost (LCC) reduction for the entire railway system by optimising the track friendliness of vehicles and infrastructure maintenance strategies. The main parts of the UCM are: wheel damage, track damage, energy, noise, unavailability and potential hazards. This paper will describe the impact of different vehicle and infrastructure parameters on wheel damage and on the total LCC. The impact of these parameters on track damage are discussed in a separate paper (Casanueva & Dirks et al. 2017).

2 WHEEL DAMAGE PROCEDURE

The damage mechanisms which are included in the UCM for wheel damage are wear and surface initiated rolling contact fatigue (RCF). Multibody system (MBS) simulations were done

with a model of the Swedish regional train Regina running on a line near the Swedish West Coast with a length of approximately 300 km. The maximum speed of the vehicle is 200 km/h.

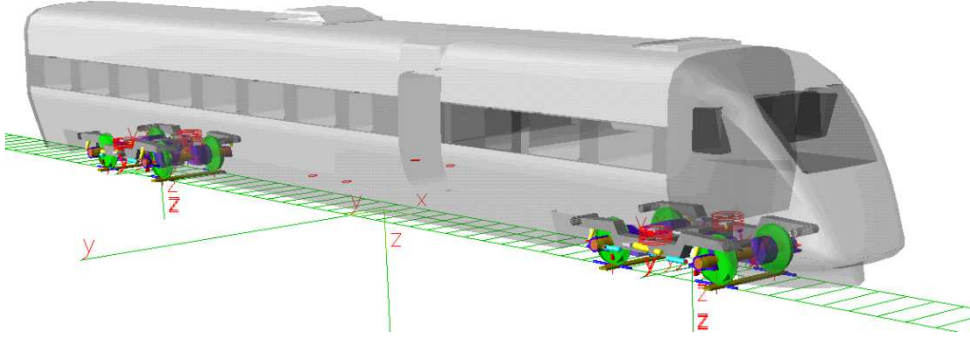


Figure 1. MBS model of the vehicle Regina running on the Swedish West Coast.

About 65% of the line consists of straight track and 35% of curves with a radius $R < 3000$ m. All the railway curves that a wheel would encounter when running on the line need to be represented by a selection of curves. A wheel would, however, also encounter different rail profiles, varying from new to heavily worn, and different contact conditions when for example running through a lubricated curve. The condition of the track (irregularities) can also vary between different sections of the network. For this purpose, a simulation set needs to be defined which reflects the actual rail network. This set of vehicle-track dynamics time simulations contains the different so-called type curves, rail profiles and track irregularities. Therefore, the whole line was divided into different curve radius intervals and for each interval, e.g. 500-600 m, a type curve is defined by calculating the mean radius, length, cant and speed of all curves in that interval. In total 28 type curves have been defined and one straight track section.

The output from the MBS simulations for all the 28 curves and straight track were used as input for the wear and RCF models. The output from these wheel damage models are wear depth and crack depth/length and are the Key Performance Indicators (KPIs) which trigger wheel maintenance actions, like wheel re-profiling. The total track length for each type curve has been used for weighting the wheel damage (wear and RCF). For example, there are relatively many curves with a radius between 1500-1700 m on the line, which means that the simulation results from these curves will be weighted more.

The ‘simple’ method has been chosen for the wear calculations of the wheel, which means that no wheel profile updating takes place.

Since the location of the wear can differ throughout the life of a wheel between re-profiling, both new and worn wheel/rail profiles have been taken into account in the MBS simulations. Different probabilities have been assumed for the occurrence of worn/new wheel and rail profiles. The occurrence probability of new wheels and rails are 10% and of worn rails and wheels is 90%.

2.1 Wheel wear

For calculating the wear in this study, Archard's wear model was used (Jendel 2002) where the wear volume V_{wear} [m³] is a function of the normal force F_n [N], the sliding distance s [m], the hardness H [N/m²] and the wear coefficient k [-]:

$$V_{\text{wear}} = k \frac{F_n \cdot s}{H}. \quad (1)$$

The wear coefficient is a function of the sliding velocity and the contact pressure and can be presented in a wear chart containing four different regions (Jendel 2002). Based on previous wear studies with the same type of vehicle but running on a different network, the wear coefficients in the wear chart have been adjusted (lowered). Furthermore, in case of track-side lubrication in the small radius curves, the wear coefficient compensation factor of 1/11 has been applied.

The wear damage from each simulation has been weighted according to the distribution of curves on the network. Since the simple method has been used to calculate the total amount of wear, the wear distribution has been adjusted. In reality when there is wear at a certain position on the wheel/rail, the contact position moves away from this location after a while (since there can't be any contact inside a hole). Since in this study, the simulations have been done only once (no profile updating) and the total damage for a certain running distance has been accumulated, the position of the wear damage is quite local. Therefore, the total amount of accumulated wear has been distributed parabolically over the tread area and flange area of the wheel, like it would be in reality.

2.2 Wheel RCF

For calculating the RCF damage in this study, a stress index (SI) model has been used (Dirks et al. 2016; Ekberg et al. 2014). This model only takes into account the shear stresses in the wheel-rail contact which exceed the yield limit in shear k_y , according to:

$$SI = \sqrt{\tau_{zx}(x, y)^2 + \tau_{zy}(x, y)^2} - k_y, \quad (2)$$

where $\tau_{zx}(x, y)$ and $\tau_{zy}(x, y)$ are the shear stresses in each element of the contact. The SI was used to determine the stress magnitude σ_a in the fatigue model:

$$c_p = \sum_{i=1}^N \frac{1}{\alpha(\sigma_a)^{\beta}}, \quad (3)$$

where c_p is the predicted crack length or depth [mm], i is the wheel revolution, N is the number of load cycles and α and β are material parameters.

By combining the results of the RCF model and the wear model, the actual size of the crack, as it would appear on the wheel, can be calculated.

2.3 Wheel maintenance

To estimate the costs for wheel maintenance/renewal, the KPIs from the models (wear and crack depth) need to be translated in maintenance actions. The European standard (EN15313 2010) has been followed in order to determine the re-profiling frequency due to wheel wear. The standard defines limits for flange thickness, flange height and the flange inclination (q_r) as a function of the wheel diameter. The wheel defect manual from RailCorp NSW (ESR 0330 2013) has been used to determine the re-profiling frequency due to wheel RCF.

The wheel maintenance/renewal costs for a whole fleet in a certain period of time can now be calculated by using the calculated KPIs, the wheel maintenance standards and the following parameters: number of vehicles in a fleet, running distance of a vehicle per year, number of wheels per vehicle, difference between maximum and minimum wheel diameter, reduction in wheel diameter due to re-profiling, cost for re-profiling per bogie and the costs for renewal of the wheels per bogie.

3 STUDY CASES

Several study cases were proposed in order to assess the usability of the UCM and are shown in Table 1. These study cases allow the assessment of the UCM within different scenarios and were selected in order to demonstrate its usefulness for different stakeholders. It should be noted that the models are not calibrated for this specific application. This means that the results won't be accurate and can only be used to show the relative impact of a certain parameter.

This paper will show the wheel damage sustained by different configurations in both the vehicle and the track components. From the vehicle side, the impact of a passive steering bogies will be assessed versus conventional bogies (study case RA). These steering bogies will have a more radial position in curves due to the cant deficiency, resulting in reduced sliding in the wheel-rail contact, and therefore also reduced damage to both wheels and rails. The UCM will

exemplify if bogies with improved steering capabilities substantially decrease RCF and wear for non-high speed lines.

Table 1. Study Cases for the 'Conventional Line' analysis.

	Running Gear Modifications	Infrastructure Modifications
Study Case A	Effect of passive steering on track damage (wear, RCF), wheel damage (wear, RCF), damage in S&C and energy	Effect of track quality (irregularities) on track (vertical settlement, wear, RCF) and wheel damage (wear)
Study Case B	Effect of vehicle characteristics (wheel load, unsprung mass) on track damage (squats, vertical settlement) and energy consumption	Influence of substructure condition on track damage (vertical settlement and squats)
Study Case C		Effect of track-side lubrication on track damage and wheel damage (wear and RCF)
Study Case D		The effect of track layout on track damage and wheel damage (wear and RCF)

From the infrastructure side, the effect of track quality (IA), track-side lubrication (IC) and track layout (ID) on wheel damage will be assessed.

For the baseline calculations, the running gear has passive steering in curves and the curves with a radius $R < 900$ m have track-side lubrication. The LCC results of the baseline study and all study cases are shown in Figure 2 and will be discussed below.

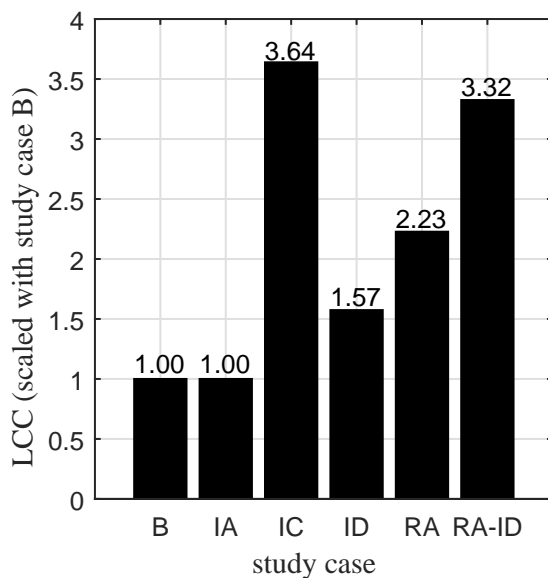


Figure 2. Life cycle cost for the different study cases and scaled with the baseline study case (B).

3.1 The effect of track quality

In order to see the effect of track quality on wheel damage (IA), the track irregularities (vertical, lateral and rotational direction) in all MBS simulations have been changed. The results show that the wear on the tread of the wheel has increased compared to the baseline calculations. The results even show that the worse track quality has a slightly positive influence on wheel RCF damage, since the wear rate on the tread of the wheel has increased. However, the flange wear is still the dominant factor for wheel re-profiling, which means that there is no difference in LCC between the two study cases.

3.2 The effect of track-side lubrication

For study case IC, no track-side lubrication in the small radius curves ($R < 800$ m) was implemented. Thus, the wear coefficient compensation factor has not been applied. The results in Figure 2 show that the costs increase by a factor of 3.64 due to more flange wear. The running distance before re-profiling of the wheel has decreased to 190 000 km. When including the costs for lubrication devices (investment and maintenance), the cost savings are about a factor 15 of the costs. Thus, the decrease in the wheel LCC alone will already cover the extra costs of the lubrication devices. When also including the decrease in LCC of the rail (wear and RCF), the cost savings would be even more (Casanueva & Dirks et al. 2017).

3.3 The effect of curve radius (track layout)

For study case 1D, the effect of curve radius will be studied by changing the curve radius distribution on the line. There are three times more small radius curves ($R \leq 10000$ m) and the straight track section has been decreased from 65.6% to 49.8%. It can be concluded from Figure 2 that the LCC have increased by a factor 1.57 for study case 1D compared to the LCC of the baseline study due to more wear on the flange and tread. The RCF damage has also increased for this study case. Although the re-profiling of the wheel is still controlled by wear, the RCF damage becomes almost critical. This effect is illustrated in Figure 3, where the wear depth and crack depth development is plotted. Since wear can influence crack growth (more wear, less RCF), the ‘crack depth’ in Figure 3 is the estimated crack depth by the model and the ‘real crack depth’ is the actual crack depth where the effect of wear is included. Where the real crack depth for the baseline study was only 0.8 mm after running 300 thousand kilometers, the real crack depth is 2.1 mm for study case ID. This study case illustrates that depending on the line/network, the vehicle, contact conditions etc., that either the wear is dominating the wheel maintenance or the RCF damage.

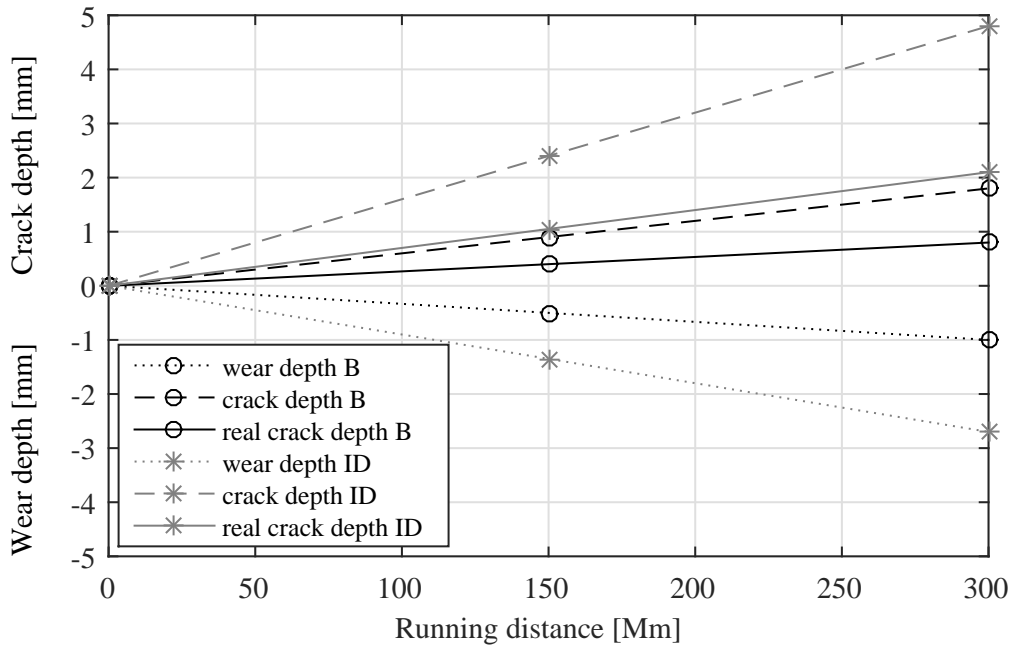


Figure 3. Wear depth and crack depth against running distance for baseline case study B and study case 1D.

3.4 The effect of passive steering bogies

For study case RA, the MBS simulations were done with a vehicle without passive steering bogies to see the effect on the LCC. The side effect of passive steering bogies is that they are more sensitive to instability when running with higher speed. To be able to resist this instabil-

ity, the vehicles have more yaw damping. These extra investment and maintenance costs have been included in the LCC calculations. The results in Figure 2 show that the LCC have increased with a factor 2.23 for the vehicle without passive steering. It can therefore be concluded that the cost savings are a factor 1.23 ($2.23-1$) of the LCC of the baseline study for the steering bogies. In case the vehicles are running on the network with more curves (1D), the cost savings for the passive steering vehicle are even more; $3.32-1.57=1.75$ of the LCC of case B. This study case demonstrates how the UCM can be used to choose a vehicle for a specific network/line.

3.5 Track damage

For some situations, the cost savings due to certain innovations of the running gear might not be sufficient to cover the extra investment costs. For example, when a network/line mainly contains straight track. However, when including also the LCC savings of the track due to this innovation, the overall costs might be lower after all. To confirm this, the LCC savings of the track (wear and RCF) due to passive steering vehicles are a factor 2.9 of the savings of the vehicles (Casanueva & Dirks et al. 2017). It can therefore be concluded that there is more to gain in LCC on the track side than on the vehicle side.

4 CONCLUSIONS

The study in this paper describes the methodology of the Universal Cost Model (UCM) for wheel Life Cycle Cost (LCC) calculations. This paper also demonstrates the application of the UCM for different study cases. It can be concluded that the UCM is a good tool to show the impact of different vehicle and track parameters on the LCC of the vehicle. Since the UCM includes the LCC of both vehicle and track, the economic benefits of innovative technologies become more transparent. In case extra investment and maintenance cost of innovative running gear won't be covered by the vehicle alone, these costs will probably be covered when including the LCC of the track. Especially since the results in this study show that there is probably more to gain in LCC on the track side than on the vehicle side. Although the results in this paper are not completely accurate, since the models were not calibrated for these specific applications, it does give a good indication of what the relative impact can be.

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