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On integrated wheel and track damage prediction using vehicle-track dynamic simulations

Carlos Casanueva*, Roger Enblom, Sebastian Stichel, Mats Berg

Rail Vehicles Unit, KTH Royal Institute of Technology, Stockholm, Sweden.

* corresponding author carlosc@kth.se

Abstract:

The renewal costs for wheels and rails are a substantial part of the costs for rolling stock operators and infrastructure managers all over the world. The causes for reprofiling or grinding are, in most cases, related to the following: (1) wheel or rail profiles with unacceptable wear, (2) appearance of rolling contact fatigue cracks in the surface, and (3) wheel flats caused by locking wheels during braking. The first two causes are related to the dynamic behavior of the vehicle-track system, and can be predicted using multibody simulations. However, there are several limitations that restrain the usefulness of these prediction techniques, such as simulation time constraints, necessary simplifications, and lack of experimental data that lead to educated assumptions. In this paper, we take the end-user perspective in order to show whether the latest developments in wheel-rail damage prediction can be integrated in a simplified framework, and subsequently used by the different stakeholders for an improved management of the different assets involved in the operation of rail vehicles.

Keywords: Rail vehicle dynamics, RCF, wear, wheel-rail damage, MBS, dynamic simulations, operation.

1 Introduction

Rail vehicle operation is a business with relatively low benefit margins, mainly due to the high competition with other means of transport and within rail operation, but also because of the high costs. In railway systems, repair and maintenance actions account for a high proportion of the costs, due to wheel and rail maintenance actions such as wheel or rail reprofiling because of improper profile, cyclic wear such as out-of-round wheels or rail corrugation, or inadmissible surface defects.

Wheel and rail damage depends on several aspects, mainly i) the dynamic behaviour of the train-track system, and ii) the operational conditions. Due to the shared system ownership in most European networks where the track and the vehicles are managed by different organisations, there is only so much a vehicle operator can do in order to decrease the wheel maintenance costs; while the same can be said for the infrastructure manager, that has influence mainly on track aspects.

There are further issues from the point of view of a third player in the railway business, the vehicle manufacturers. The capital costs of rail vehicles for a vehicle operator are high, and in most cases, improving the vehicle designs with new technologies that will reduce wheel and track damage increases the initial cost of the vehicle. However, the long term benefits of improved behaviour as e.g. reduced maintenance costs are shared between vehicle and track owners, and are in general difficult to demonstrate; and thus vehicle operators tend to prefer cheaper existing solutions rather than more expensive novel solutions with improved performance.

Infrastructure managers in some European countries have introduced differentiated track access charges, so that the fee for using the track for vehicle operators depends on how track-friendly the actual vehicle is [1]. However, the differentiation is often small and the charges are limited to marginal costs of track damages, thus the incentive is not that big for operators to use friendlier vehicles.

In order to incentivise life-cycle system cost reductions by investing in innovative running gear, the EU Project Roll2Rail [2] is developing a Universal Cost Model (UCM) that is accepted by major stakeholders [3]. This UCM will quantify running gear performance and its impact on the economics of railway systems. But in order to have a significant impact on novel rail vehicle trends, wheel and rail damage prediction has to be generic and robust enough, i.e. not system dependent, so that it can be applied to innovative vehicle concepts providing realistic results.

Rail vehicle dynamics simulation is nowadays mature enough so that it can be used for vehicle certification [4], [5]. However, wear and tear prediction is a topic with no agreed unique methodology, and involves several interfacing areas such as tribology, solid mechanics, and vehicle dynamics. Research works tend to focus on different aspects of these areas, but only a few of them account for the interaction between them (usually limited to uniform wear and Rolling Contact Fatigue –RCF–), and few discuss the complexities of analysing different length scales in a single damage simulation.

For more than a decade, KTH Railway Group has carried out a constant effort regarding wheel and rail damage prediction in these different interfacing areas, including the development of end-user applications. The latest period has been focused on modelling the coupling between interacting damage effects such as uniform wear and RCF, also including demonstration in real scenarios. Now a further need has been identified, namely the coupling of every scale and damage mode in a single framework, in such a way that the end user has knowledge and control over all the modelling properties and limitations.

Eventually, a vehicle operator shall be able to reduce vehicle maintenance and improve fleet availability by acting on design or operational parameters, and an infrastructure manager should be able to analyse fleet performance in problematic track sections and apply maintenance actions or modify access fees accordingly. In order to do that, the availability of the necessary input data need to be addressed, the integration of damage models has to be discussed, and the different scales involved in the simulation of damage studied, so that a robust and scalable methodology can be proposed and implemented.

2 Vehicle-track modelling and simulation

Wheel and rail damage prediction relies heavily on the dynamic models that represent the vehicle-track system, and thus a short description of the different available models and their coupling to damage is necessary.

2.1 Passenger vehicles and locomotives

When designing new passenger vehicles or locomotives it is today standard for the manufacturers to build up detailed multibody simulation models of the vehicle. These models include the most interesting non-linearities with regard to suspension, kinematics, and mechanics of the wheel-rail contact. For passenger coaches and multiple units the most important flexible modes of the carbody are also accounted for, usually from FE-models of the carbody structure.

For locomotives, acceleration and braking are also important contributors their dynamic behaviour. For instance, electrodynamic braking is very common nowadays, because it allows saving energy and sparing the mechanical braking components. Acceleration and braking is also used to keep the speed of a loco-hauled train constant in uphill or downhill grades, increasing creepage in the wheel-rail contact. In simulations, traction and braking effects are usually accounted for by including the running resistance of the whole trainset (D_t), which includes Mechanical resistance (D_m), Aerodynamic resistance (D_a), Curve resistance (D_c), and Gradient resistance (D_g) for the whole train. The resistance can be positive or negative depending on D_g . In order to keep the speed constant, a PID controller in the simulation model keeps the operational speed by acting on the gearbox torque, which affects creepages in both wheels.

As an example related to wheel and rail damage, the energy dissipation per rolling distance for the outer and inner wheel of the leading axle of a locomotive on the iron ore line in Northern Sweden is shown in Figure 1 [6]. As can be seen, the energy dissipation with traction increases on the inner wheel but decreases on the outer wheel.

Figure 1: Calculated energy dissipation per rolling distance of the leading wheelset, (a) outer wheel and (b) inner wheel; with and without tractive forces ($R=547$ m) [6]

2.2 Freight vehicles

The main difference regarding vehicle modelling between passenger and freight vehicles is that the suspension in most freight wagons relies on friction damping. Friction elements are cheap, need little maintenance and are usually load dependent. This means that the level of friction forces –and thus, the dissipated energy– changes with the axle load, an important feature in freight vehicles as between the axle load of an empty respectively a fully loaded wagon there can be a factor of five.

There are characteristic challenges on freight vehicle modelling. Since manufacturers do not build vehicle models themselves, it is hard to find all input parameters the model needs. Another aspect is that suspension elements are usually strongly non-linear and non-smooth [7], making it very difficult to build up simulation models that provide good results compared to measurements. Further, the characteristics of these suspension elements can vary during operation due to wear or environmental effects like surface contamination [8]. Eventually, the variation in the dynamic behaviour between when correctly modelling all frictional suspension elements is extremely high [9].

Since the axle loads of freight wagons usually are high, the primary reason for simulations is often the investigation of wheel or track wear and RCF in curves, and dynamic stability in tangent track. A thorough review on freight vehicle modelling can be found in [10].

2.3 Infrastructure

For the study of vehicle dynamics and wheel-rail damage, relatively simple models of the track are available in multibody simulation tools [11]. Usually, a moving equivalent mass track model is used, which represents the sleeper and a part of the track oscillating under the wheelset, including stiffness and damping in the vertical and lateral directions. The critical issue is to find the correct values for all these parameters.

This simple track model is adequate for simulating vehicle/track interaction and vehicle dynamics for frequencies up to about 20 Hz, but is not suited to study other effects such as forces in individual track components, effects of wheel flats [12], local variations in track support, broken rail [13], rail corrugation, etc.

3 Damage

3.1 Uniform wear and RCF

Wear is the progressive loss of material when there is a relative motion between two surfaces in contact. It is a tribological phenomenon that depends on the material properties, contact surface geometry and topography, load, lubrication, or relative displacements and speeds. There are many terms describing different wear phenomena, but the most common in wheel–rail contact are the following:

- Adhesive wear, or dry sliding wear, caused by shear between two contacting surfaces.

- Abrasive wear, caused by rough surfaces sliding on each other, or hard particles trapped between two surfaces.
- Erosive wear, caused by relative motion of contact surfaces while a fluid containing solid particles is present between the surfaces.
- Corrosive wear, or oxidative wear, caused by formation of oxides on surfaces due to reactions with the environment.

Wear regimes are typically determined in laboratory tests, in order to create relationships between contact parameters and removed volume [14].

Rolling contact fatigue (RCF) is caused by cyclic stress variations leading to fatigue of wheel or rail materials. They generally result in the initiation of surface, sub-surface and deep-surface cracks, and eventually material pitting and spalling, even transverse fissures in the worst-case scenario. Similar to wear regimes, relationships can be found between contact parameters and crack initiation likelihood [15].

From a tribological perspective, some types of wear and RCF have elemental processes in common [16]. From a practical one, RCF creates cracks that grow, while wear removes material, making cracks shorter – or even remove them all. The perfect balance between crack removal and profile evolution is commonly known as Magic Wear Rate: big enough to remove cracks, but small enough so that profile evolution is not an issue [17].

Wear and RCF calculation has been blended within dynamic simulation context since the RSSB model [18], and in some later works more precise modelling techniques are demonstrated [6], [19], [20].

A good overview of the different damage calculation techniques and their industrial implementation for wheel surface deterioration is given in [21]. The main conclusion is that the developed end-user applications only deal with a basic follow-up of certain parameters under specific operating conditions, and that it is not possible to use them as a tool in the vehicle design phase. For instance, fatigue assessment is so far only a risk indication. Even though, the article firmly states that these tools are useful for the industry and should be further developed. The ICRI on RCF and Wear of Rail/Wheel systems (International Collaborative Research Initiative) in wheel and rail damage has acted in the last years as a catalyser in order to fill the knowledge gaps in these topics, as for instance the effect of lubrication in the different wear regimes, or the completion of wear maps with extended experimental data.

3.2 Non-uniform wear

Non-uniform wheel and rail wear is considered the one that has a frequency content, which for wheel wear needs to have wavelengths shorter than the actual perimeter. Its modelling is usually more complex than uniform damage.

3.2.1 Periodic wear

Wheel polygonalisation or rail corrugation are a similar type of damage mode that generates a wavy shape on the damaged surface [22], [23]. They need both an initiation mechanism, where a discontinuity is generated in the wheel or rail surface, and a propagation mechanism where a resonance in the system

accumulates the damage in the same position during several cycles, generating a wave-like damage pattern. Its prediction is usually out of the scope of the simulations that vehicle operators and track managers perform, and the solutions tend to be increasing maintenance frequency in order to avoid the propagation phase. Advanced research allows for its simulation and prediction see e.g. [24], with a mathematical and computational complexity level that might not be suitable for end-user applications.

3.2.2 Damage in switches and crossings

One of the most critical elements regarding safety and maintenance costs in railway networks is switches and crossings, which introduce discontinuities in the wheel-rail contact that generate high-frequency dynamic interactions. Damage in switches is not straightforward to model, as several works have demonstrated [25]–[28]. Several authors choose to analyse it with finite element models, which does not allow for a system modelling approach or oversimplifies damage modes [29], [30].

The latest works still try to focus on the dynamic modelling of the vehicle-turnout system, and use the RCF and Energy Dissipation indicators as pointers for damage in the switch [31], or model the distribution of wear with Archard throughout the crossing nose [32]. Although not validated with experimental results, the techniques seem promising.

Commonly disregarded, wheel damage caused by running through switches can also be significant. The damage generated in this case, though, can be considered as uniform damage when looking from the whole system perspective [33].

3.2.3 Wheel flats

Wheel flats are ground off areas of the wheel tread with the shape of a flat, oval surface, caused when wheelsets are locked while the vehicle is running, which is usually related to an unintended brake performance [34]. Wheel locking also dissipates big amounts of frictional energy, and with high enough temperature, the material could experience phase transformations [35]. Martensitic areas are much more brittle than the rest of the wheel, and eventually crack under regular operation, creating small cracked holes. Most maintenance workshops do not differentiate it from RCF shelling.

A wheel flat, being a sudden reduction in the wheel radius, causes impact loads on the rail. With continued operation, flats can increase in length (not in depth) [36] and generate out-of-round wheels [37]. Considering all this information, flat generation is a damage mode not related to vehicle dynamics, and thus, it is not deemed necessary to include it in an integrated damage calculation model. It is however worth to describe it, being an important trigger for other damage modes such as periodic wear or cracks.

4 Multi-scale modelling

The main problem when simulating wheel-rail damage mechanisms is the broad range of time and length scales involved in the whole process. However, as long

as the damage trigger is the quasistatic or dynamic behaviour of the system, they can all be coupled to the simulation of the multibody system.

Typical wheel damage is developed after several thousand kilometres of running a vehicle, but dynamic simulations of vehicles typically cover lengths of hundreds of metres. Local displacements in the multibody simulations are around centimetres, while wheel-rail contact mechanics is one scale lower, i.e. millimetres. Tribological aspects of the wear are even smaller, tens of micrometres. And if one should calculate airborne particle emissions, especially the ones that can become a health issue, it gets even lower.

Figure 2: length scales involved in wheel and rail damage calculations.

The coupling in the medium range is solved for typical simulation applications. Commercial MBS softwares do account for track geometry, including irregularities, by using a Eulerian reference frame for the train that allows accounting for large angles, while the multibody dynamics are solved with local linear reference systems that consider small angles. The wheel-rail contact coupling is usually taken into account using fairly complex contact models, typically Hertzian contact for the normal problem and FASTSIM for the tangential problem.

In order to couple the medium MBS scales with the smaller contact mechanics scales, more complex and detailed contact models exist and are implemented in some of the commercial softwares. They usually have slightly longer calculation times, but an improved precision when calculating contact conditions that differ from a basic Hertzian case. The final objective is to have fast contact calculation models that are precise enough regarding tribological parameters –patch size and shape, pressure and shear stress distribution, creepage and sliding– so that the coupling between the medium scales and the tribology scales is suitable, efficient and accurate. In this context, the latest developments at KTH have succeeded in a wheel-rail contact model, named ANALYN for the normal contact problem and FaStrip for the tangential problem [38], that is only about six times slower than Hertzian contact and FASTSIM while the precision of damage related variables is extremely close to the original CONTACT algorithm, which is the method considered as reference (Figure 3).

Figure 3: Shear stress in the wheel-rail contact patch for three different methods [38].

Scales between the contact patch and tribological phenomena are usually coupled via engineering models. There are also contact mechanics models that account for very precise modelling of the wheel-rail contact, but these are so computationally heavy that co-simulation with MBS software is extremely time-consuming. An extensive review of these models can be found in [39].

The microscopic scales that account for particle emission are not usually coupled to the rest of the length scales, and there is actually no development work on this topic, as the tribology of non-exhaust emissions is still an area based on on-track and laboratory measurements. However, the same way wear and tear tribology is coupled to contact mechanics via engineering models, there is a similar opportunity in this topic. Creating Particle Emission Maps for different realistic wheel-rail contact conditions would allow, from an end-user perspective, to adapt operation of rail vehicles in order to minimise harmful particle emissions.

Scales longer than the MBS ones are coupled in different ways for different damage modes. In order to calculate the change in profiles due to wear, vehicle dynamics and track length are coupled by modifying profiles a significant amount between the so-called wear steps, where the different dynamic simulations use the same wheel and rail geometry. In each wear step, which can account for several tens of km, wear for wheels is evaluated in every wheel turn in each simulation, accumulating all contributions. For rail wear, material removal is calculated for every vehicle passage instead, and accumulated afterwards. Then, the worn profiles are updated with the predicted wear, but smoothing of the final profiles is still needed in order to ensure an adequate mathematical processing of the wheel and rail geometries in subsequent steps.

This methodology ensures the robustness of the wheel profile update throughout long distances, but wear is not computed throughout the rest of the wheel perimeter. This can have significant influence if the wavelength of the track geometry is lower than the wheel perimeter. In these cases high frequency vehicle-track modelling and non-uniform wear calculation is needed, and the evaluation of damage should be carried out with a wavelength lower than that of the wheel cycles. The best example of non-uniform damage inducing component is switches and crossings, where wear and tear evaluation needs to account for rail profile that varies significantly in one wheel turn [33]. In fact, this means that for non-uniform wear the coupling with large distances should be carefully accounted for when including them in an integrated calculation model.

A similar coupling exists between the dynamic simulations and RCF crack initiation prediction. Rolling contact fatigue cracks are generated after several thousand kilometres, while actual engineering methods are not capable of determining the mileage where the surface crack will appear, but a qualitative likeliness of crack appearance [15]. The research question of railway wheel life prediction is being tackled in different works [19], [40] by combining the shakedown RCF estimation and lab tests, Archard wear calculation, dynamic simulations and Palmgren–Miner rule for damage accumulation. Preliminary results are very promising. For instance, Figure 4 shows that crack growth in rails can be accurately estimated when an initial calibration is carried out [20].

Figure 4: RCF crack growth validation, wheel measurements from a Stockholm commuter train. c_{pe} = predicted crack length, wear excluded; c_{pi} = predicted crack length, wear included; c_m = measured crack length [20]

Figure 5 shows a different example from [40]. There, the predicted RCF damage accumulation for a locomotive after 40 000 km is shown as the number of cycles where a specific profile section has have positive FI_{surf} values (darkest tone 50 000 cycles). The accuracy of this method is very good, as the average running distance of the real locomotives between two consecutive wheel turnings is actually *ca* 40 000 km and, according to bibliography, the number of cycles where fatigue cracks are visible is 50 000 [40].

Figure 5: RCF severity after 40 000 km with 25% ED braking, number of cycles [40].

When considering crack growth, there is also a huge difference between the solid mechanics approach, where finite element models with fine meshes are simulated, which sometimes needs a multi-scale framework on its own [41]. If the whole system has to be accounted for, using detailed simulation models becomes a burden instead of an advantage. As for uniform wear, the balance relies on simulating as accurately as possible only the variables that are actually needed for damage prediction.

5 Integrated simulation needs

From a research perspective, most of the models have demonstrated capabilities to predict wheel and rail damage correctly. From an end-user perspective, though, there are issues beyond the accuracy of the model itself. For instance, the different input parameters needed for a correct system modelling come from different stakeholders, and might need pre-processing for a correct implementation.

5.1 Input parameters

In this paper a big emphasis has been put on the precision of the different model inputs regarding damage calculation, but an important practical question is: how easy is it to obtain these input parameters? And subsequently, how much time does it take to gather all the necessary information?

The cornerstone is always an MBS model, but the specific needs vary depending on where the damage calculation takes part. For wheel damage, one vehicle is sufficient, while the whole network where it operates needs to be modelled. For track damage, only one track section (or switch section) needs to be modelled, but the MBS models of all vehicles running through that specific section need to be simulated. Table 1 and Table 2 account for these two cases respectively, including the stakeholders most likely to own the information: Infrastructure Manager (IM), Maintenance Company (MC), Vehicle Manufacturer (VM), or Train Operator (TO). Examples of basic simulation, low precision, and high precision for each input parameter are listed.

Table 1: Wheel damage calculation input parameters

Parameter	Responsible	High accuracy	Low accuracy	Basic sim.
Track layout	IM	Measured track	Designed track	Generic curves
Track irregularities	IM	Measured track	Stochastic irregularities	Ideal track
Rail profiles	IM, MC	Set of measured profiles	Set of design profiles	Generic profile
Trackside lubrication	IM	Timing and distribution of lubricant, influence on friction and wear	Timing of lubricant, influence on friction	No lubrication
Track parameters	IM	Flexible track model with experimental parameter values	Flexible track model with literature parameter values	No flexible track model
Vehicle model	VM	Validated MBS model	MBS model with design parameters	Generic bogie vehicle model
Wheel profiles	VM, TO, MC	Set of measured profiles	Design profiles	Generic profiles
Onboard lubrication	VM, TO	Timing and distribution of lubricant, influence on friction and wear	Timing of lubricant, influence on friction	No lubrication
Vehicle operation	TO	Measured GPS data on speed, acceleration and braking	Design speed for the network, acceleration and braking to keep the speed	Generic speed, no accel. or braking
Contact interface	TO, IM	Set of measured friction values for specific network and climate	Literature friction values for specific climatic conditions	Generic values
MBS software	SD	Commercial MBS software with high flexibility regarding wheel-rail contact modelling	Commercial MBS software with low flexibility regarding wheel-rail contact modelling	In-house MBS program

Table 2: track section damage calculation input parameters

Parameter	Responsible	High accuracy	Low accuracy	Basic sim.
Track section	IM	Measured track section, incl. Irregularities.	Designed track section, Stochastic irregularities	Generic curves, ideal track
Rail profiles	IM, MC	Measured profiles	Design profiles	Generic profiles
Trackside lubrication	IM	Timing and distribution of lubricant, influence on friction and wear	Timing of lubricant, influence on friction	No lubrication
Track parameters	IM	Flexible track model with experimental parameter values	Flexible track model with literature parameter values	No flexible track model
Running vehicles	IM	Number of different vehicles with measured axle load and their frequency	Number of different vehicles and their theoretical frequency	Generic set of vehicles with generic frequency
Vehicle models	VM	Validated MBS model, measured wheel profiles, for every vehicle.	Set of MBS models with design parameters	Generic set of models, generic wheel profiles
Onboard lubrication	VM, TO	Timing and distribution of lubricant, influence on friction and wear, for each vehicle	Timing of lubricant, influence on friction values, for each vehicle	No lubrication
Vehicle operation	TO	Measured GPS data on speed, acceleration and braking	Design speed for the network, acceleration and braking to keep the speed	Generic speed, no acceleration or braking
Contact interface	TO, IM	Set of measured friction values for specific section and climate	Literature friction values for specific climatic conditions	Generic values
MBS software	SD	Commercial MBS software with high flexibility regarding wheel-rail contact modelling	Commercial MBS software with low flexibility regarding wheel-rail contact modelling	In-house MBS program

Due to the difficulty of performing the simulation of the entire railway line, the concept of Load Collective is introduced. It consists of a set of simulations that represent the actual track and operational conditions of vehicles, e.g. track design geometry and irregularities, rail profiles, friction conditions, vehicle speed, types and frequency of vehicles, or traction and braking. An extensive example of a load collective for wheel damage calculation that includes most of the input parameters mentioned in Table 1 and Table 2 can be found in [6].

A correct prediction of the damage in the wheel-rail contact is extremely dependant on the quality of the data provided by the stakeholders. For instance, wheel and rail contact position and geometry have a high influence in the uniform wheel wear, so ideally a variety of measured rail profiles should be use for a realistic prediction. When only nominal rail profiles are used, there is a risk that the simulated damage is concentrated into a small section of the wheel.

Track irregularities can also have significant influence on RCF damage [42]. If possible, measured track geometry should be used, but representative stochastic track irregularities can be also chosen, with a higher risk of accuracy loss. It is also important to use irregularity data containing wavelengths covering all relevant frequencies of the investigated vehicle. The accuracy of the damage prediction can be very dependent on the precision of the inputs [33], [43], thus

making the source of the input data, its precision and quality, and pre-processing a critical starting point of the whole process.

A good way to exemplify the complexities of the input parameter selection process is use an actual example. In the following work, wheel wear of a Chinese high-speed train was calculated [44]. First, using measured S1002CN profiles the different parameters of Archard's wear calculation methodology were calibrated. Then a new design of a modified S1002CH wheel profiles is simulated, which is designed for maximizing mileage between reprofiling, and minimizing reprofiling cost. However, the optimization process for these new profiles did not include wheel profile evolution, and thus a new study was proposed for assessing its suitability.

The modelling takes into account all the necessary input parameters with various degrees of precision. Track layout, irregularities and rail profiles were actual Chinese high-speed line parameters provided by the vehicle manufacturer, while track parameters were obtained from literature. A validated vehicle model and wheel profiles were available via the manufacturer, while operational parameters were rather simplified to design speeds, not accounting for traction and braking, for instance. Wheel and rail friction was also assumed from literature, and the used MBS software is Simpack with the default wheel-rail contact model, making it a total of 5 high accuracy and 4 low accuracy inputs. Regarding the difficulty to gather all the data, this case was better than most other studies, as the vehicle manufacturer had high-quality information of the infrastructure side.

Eventually, the predicted worn wheel profiles are in agreement with the measured ones after a running distance of 400,000 km. However, there are some further studies proposed, for instance including braking and acceleration in a refined operational case definition, which affects the wheel wear by changing the creepages, also in straight track. Also, the simulated uneven wear distribution is thought to be caused by how the contact patch was modelled, i.e. the wheel-rail contact position calculation and the Hertzian contact model. Coincidentally, these were two of the inputs introduced with low accuracy.

A third low-accuracy input variable was the friction in the wheel rail contact, and conscious of this weakness, a parametric study was performed in order to check its influence, with interesting conclusions: the model with reduced friction coefficient had substantially more tread wear (Figure 6). This is due to the fact that, with Archard's wear model, contact areas in adhesion do not generate wear, and a reduced friction coefficient created both an increased saturation of the contact patch and slip speeds that surpassed the wear transition, synergistically increasing the removed material.

Figure 6: Radial wear depth for the different cases with $\mu=0.3$ and one case with reduced $\mu=0.2$ [44]

These results clearly exemplify the importance of the input parameter quality during the preparation process, specially the possibility that a single low-quality parameter affects the results of the prediction.

5.2 Time consumption of scale coupling

Cross-scale modelling is not an issue by itself; the limiting factor is the time consumption that a multi-scale problem simulation entails. When considering dynamic simulations, time integration for the MBS software, pre-processing time for transforming operational conditions that feed the MBS simulations, and post-processing of contact variables into wheel and rail damage, are all enclosed in the same order of magnitude regarding computing time. One can encounter models which are not optimised for non-linear and non-smooth problems, which is already the case of most freight vehicles and their friction damper suspension models [44] but if needed, integrators can be optimised and models can be simplified for improving computation time [7].

The time consumption increases exponentially if the prediction needs to account for damage evolution; then, there is a need of regularly updating wheel-rail contact pairs in order to include its influence in the dynamic simulations, so there is a higher level time-scale, commonly known as wear step, that accounts for the evolution of the profile [21].

There can still be an even higher-level time frame (Figure 7). When optimization techniques are used for designing a wheel profile with improved behaviour, the mathematical optimisation models need to run several simulations in order to evaluate different target functions, including the ones not related to damage, and steer the intermediate results towards the optimal solution. When using optimisation techniques in the lower-level dynamic simulations –this is, without profile evolution calculations– the total time increase is in the order of magnitude of the profile-evolution techniques [46], [47]. If the choice is to apply optimisation algorithms with a target function that depends on damage evolution, then the time consumption increases dramatically, as the multiple optimization simulations need to be carried out over the wear evolution simulations – which entail several wear steps on their own.

Figure 7: representation of the simulation time-frame hierarchy

In order to deal with optimisation that accounts for profile evolution, attempts of reducing time consumption of different calculation sections have been made. In [48] a *wear ratio* has been proposed that maintains a linear relationship between the calibrated wear depth calculated by Archard, which is time consuming, and the calculated wear number $T\gamma$, which is an output of the time domain simulation, in order to reduce the damage post-processing time as much as possible. Figure 8 represents the *wear ratio* evolution in the wheel profile.

Figure 8: *Wear ratio* (Archard-calculated wear depth/ $T\gamma$) for a specific vehicle and network [48]

With this technique, time consumption for the wear calculation procedure is significantly reduced, but at a high cost on precision: the volume of the removed material has unacceptable error levels, ranging 20% to 50%. The methodology is more accurate for shorter simulation distances, and for a wheel profile optimization process that accounts for the shape of the profile after thousands of kilometres, the wear ratio can give a reasonable estimation that could be used in the target function of the optimisation method.

The importance of the overall computer time usage of the damage calculation methodology rises when several simulations are needed for calibrating the models for a specific user, or for debugging the different codes that form the

damage calculation platform. In this point, fast models have a competitive advantage regarding tests and fine-tuning.

6 Conclusions

Wheel and rail damage prediction using vehicle-track dynamic simulations is rather common, and modern examples of successful prediction have been presented throughout the article. However, from an end-user perspective, simulation of damage can be a resource-consuming task where they don't have the knowledge needed to correctly evaluate its precision or limitations, or available high quality input data from other stakeholders that will allow a precise prediction. In this paper, the gaps and accuracy losses of the different technique have been addressed, in order to allow the end-users a solid and robust framework of knowledge and methods. The objective is not to create a tool, but to state the requirements that such tool would require in a simplified, clear manner, so that rail system stakeholders are empowered to use them.

Special attention is put on the inputs needed for these prediction simulations. Different inputs come from different stakeholders, generating a managerial challenge. End-users should be aware of the difficulty of gathering all the necessary data, and that gathering the information and pre-processing is very time consuming, calendar time-wise. Time consumption of the simulations due to the several scales that arise in these types of studies is also tackled.

After 20 years of damage modelling at KTH, and considering that many of the research gaps are being addressed in the ICRI work groups, the latest effort has been to discuss the integration of damage models, including the different scales and computational time consumption of their coupling, in order to set the path for a clear and simple methodology that end-users can profit on. Simulations have a big potential for wheel and rail damage prediction, but they also entail technical, computing and organizational challenges. Stronger and more open cooperation is needed between the different parties for successfully reaching a good result in a damage prediction project. Research groups all over the world are making substantial advances, but in order to jump the innovation barrier more partners are needed, with a deeper involvement, both in local innovation projects and in global initiatives such as the ICRI.

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