WHEEL-RAIL CONTACT: WEAR EFFECTS ON VEHICLE DYNAMIC BEHAVIOUR

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SUMMARY
The influence of the wear of both rails and wheels on the dynamic behaviour of a railway vehicle is described through various examples taken both from experimental results and numerical simulations. A state of the art of wear modelling of both wheels and rails is also presented.

Keywords: wheel regular wear, wheel poligonalysation, rail corrugation, railway vehicle stability, curve negotiation

1 INTRODUCTION
Wheel and rail surface modifications due to wear have a very important impact on some critical issues of railway engineering. Although the effects of wear in railway systems are well known since more than one century, and a large amount of experimental and numerical research work has been already carried out, some major topics still require further investigation.

This is probably due to the fact that a thorough comprehension of wear phenomena occurring at wheel/rail interface requires a multi-disciplinary approach, where competencies ranging from contact mechanics to rail vehicle dynamics and train-track interaction are needed, together with a strong competency on material behaviour. This kind of approach has been perhaps lacking in the past, and there is the need to form suitable research teams where all the above mentioned fields are covered.

Among the open questions in the field, there is a strong need for a deeper comprehension of the causes of some wear effects, typical of railroad systems, like rail corrugation [16] or wheel poligonalysation [22], in order to find appropriate treatments to mitigate these phenomena. Moreover, reliable models of wear phenomena are needed, in order to optimise the strategies for maintenance planning, to improve the design techniques of both rolling stock and track systems, and to allow the reduction of total life cycle costs. Any significant improvement in these fields is likely to have a very high economic impact, and to enhance the competitiveness of railways with respect to other transportation systems.

Concerning rolling stock design issues, the change of the transversal wheel/rail profile (often referred to as “regular wear”) is responsible for a decrease in vehicle stability at high speed and affects curving performances as will be described in section 2. Therefore, a reduction of wear rate or an optimisation of re-profiling strategies could lead to an increase of commercial speeds.

Moreover, the progression of wear on rail and wheel surfaces is strictly connected with surface or sub-surface damage phenomena due to rolling contact fatigue. These topics are strictly related to both safety and total life cycle costs.

On the other side, the formation of irregular wear patterns on wheel and rail surfaces (sometimes called “irregular wear”) like wheel out-of-roundness and rail corrugation, negatively affects the ride comfort of train passengers and is responsible for the emission of noise and ground-borne vibrations from the railway line towards the surrounding environment, thereby affecting the environmental friendliness of railway transportation systems. It is worth recalling that, especially in Europe, environmental issues are of main relevance in the recent developments of innovative transportation systems, and play a major role towards the development of sustainable growth plans.

2 EFFECTS OF REGULAR WEAR ON VEHICLE DYNAMIC BEHAVIOUR
As a consequence of wear, wheel and rail transversal profiles undergo a continuous change of shape with time. As will be summarised in this section, these changes have a significant impact on the behaviour of the railroad system, so that when the shape of the profiles becomes too far from the original one, maintenance operations are performed in order to restore the original shape. In the case of the wheel profiles, this means that the wheels are re-profiled, which is a rather costly maintenance operation. On the other side, if the worn rail profile is too far apart from the new one (see figure 2.), there is no way to restore the original shape other than replacing the rails with new ones. Jamison [12] reports that the yearly costs for rail replacement in North America in the early 1980s was around $600 ML.

The typical features of wear occurring on a railway wheel used for Intercity or high speed service is shown in figure 1., where the original ORE S1002 (dashed line) profile is compared to a worn profile measured after approximately 300,000 km of service, a value which falls within the typical range of mileage after which the wheel is re-profiled.

It is clear that wear mainly occurs in two regions of the profiles: on the tread and on the flange.
Wear on the flange mainly occurs during curve negotiation, and is caused by the fact that, at least for the leading wheelset of each bogie (see section 2.2), a displacement of the wheel relative to the rail in lateral direction takes place and a contact between wheel and rail appears on the flange. In this contact patch, high longitudinal creepages are generally present, due to the big variation of rolling radius (that is the distance between the point of contact on the surface of the wheel and the wheel axle). Obviously, the flange thickness cannot decrease too much in order to meet safety requirements. Moreover, as will be described in the following, the variation of the wheel profile in the flange region may lead the wheelset to be more prone to flange climb (derailment) phenomena.

Wear on the thread changes the originally convex profile into a concave one, thereby leading to a conformal contact with the railhead when the vehicle is running in tangent track. This change in the local shape of the contacting surfaces has several consequences: first of all the contact patch becomes wider in the lateral direction, and therefore the values of normal contact pressure are generally smaller than for a new wheel profile. From the point of view of vehicle dynamics, the worn wheelset is more prone to undergo hunting motion, which is a well known instability phenomenon taking place in railway vehicles running at high speed. This topic will be covered in section 2.1.

As to the effects of rail profile changes, figure 2 shows the comparison between the original UIC 60 rail profile and a hugely worn wheel profile. In this case, a huge modification of the profile occurs on the inner side of the rail. This is typical for rails placed in curved sections, and the mechanisms leading to this kind of rail wear are the same as described above for flange wear on the wheelsets. Rail wear can be particularly severe when the curved track is negotiated by vehicles equipped with independent wheels. This happens because, contrary to the behaviour of conventional rigid wheelsets, independent wheels do not have a natural self-aligning behaviour, and therefore the effect of centrifugal forces acting on the vehicle in curve must be fully balanced by the flanging contact between wheels and rails.

In the following subsections, the effects of wear on vehicle stability and curving performances are discussed in more detail, based on the use of a numerical model of train dynamics and train-track interaction [4], [7].

### 2.1 Vehicle Stability

As far as stability is concerned, the main difference between new and worn profiles is that the latter show a much higher “equivalent conicity”, i.e. the variation of rolling radius (due to the non-cylindrical shape of the wheel), produced by a lateral relative wheel-rail displacement is greater for worn profiles. It can be shown, also by means of elementary models [6], that wheel conicity is responsible for the appearance of the so called “hunting motion” of the wheelset, i.e. a combined lateral and yaw vibration occurring at high speed due to the combined action of longitudinal and lateral creep forces on the wheels. Above a certain speed, the hunting motion becomes unstable and results in a limit cycle that is dangerous for ride safety and may induce permanent deformations along the line. The higher the conicity of the profiles, the lower will be the critical speed of the vehicle.

In this section, the effect of wheel profiles on vehicle stability is studied by means of a numerical model of train dynamics and train-track interaction. To this end, two different couples of wheel and rail profiles are used, respectively referred to as new and worn profiles. The new profiles are the theoretical ORE S1002 for the wheels and UIC 60 for the rails (inclination 1:20), widely adopted by European railway administrations. The worn wheel profiles were measured on a Pendolino vehicle a short time before re-profiling (one of the two wheel profiles is shown in figure 1.), while the worn rail profiles were measured on the “Direttissima” Italian high-speed line between Florence and Rome. Track irregularity is assumed as prescribed by ORE B176 document, and no wheel out-of-roundness irregularity is considered. Figure 3. allows to compare the results of the simulation for the two different profiles. The lateral component of wheel – rail contact force acting on the right wheel is shown: in the case of worn profiles, the presence of a limit cycle with frequency around 7 Hz producing high values of lateral force can be easily recognised. On the other side, with new profiles, only a
small dynamic value of lateral force occurs, due to the random forcing effect introduced by rail irregularity.

![Graph](image1.png)

**Figure 3.** Lateral contact force on the right wheel for new (up) and worn (down) profiles at 240 km/h on a straight track.

### 2.2 Curving Performance

Due to the stiffness of the primary suspensions connecting the wheelsets to the bogie, the leading wheelset has a negative angle of attack, thus producing transversal creep forces on both wheels pointing outwards the curve. In order to guarantee the equilibrium of the wheelset in lateral direction, a huge flange force is required, and therefore flanging contact takes place. As a consequence of flanging, the rolling radius of the outer wheel increases, inducing a high value of longitudinal creep force on the outer wheel pointing forwards. If the wheelset is not subjected to braking or traction couples, a longitudinal force with the same value and opposite direction is induced on the inner wheel in order to keep the rotational wheelset equilibrium. The increase in the rolling radius of the outer wheel leads to a yaw movement of the rigid wheelset. Since the angle of attack of the trailing wheelset is positive, its lateral creep forces point inward the curve, and therefore no flanging is required unless the curve is negotiated at a high value of cant deficiency. Figure 4. shows the contact forces acting on the four wheels of a bogie at steady state curving, obtained from numerical simulations.

![Diagram](image2.png)

**Figure 4.** Schematisation of the contact forces during steady state curving for a railway bogie.

It should be noted that the ripage force on the leading wheelset (sum of the lateral forces on right and left wheel) is smaller than that of the trailing one. This is because the couple generated by the longitudinal forces on the leading wheelset applies a yaw moment that is counter-acted by a difference of the ripage forces on the two wheelsets [21]. This effect is much more pronounced for worn wheel/rail profiles rather than for new ones. Figure 5. shows the ripage forces on the trailing bogie axles for new and worn wheel and rail profiles at different radius keeping the non-compensated lateral acceleration equal to $2 \text{ m/s}^2$.

![Graph](image3.png)

**Figure 5.** Ripage forces on the trailing bogie axles for new and worn wheel/rail profiles. Lat. acc.: $2 \text{ m/s}^2$.

### 3 EFFECTS OF IRREGULAR WEAR ON VEHICLE DYNAMIC BEHAVIOUR

As anticipated in the introduction, rail corrugation as well as wheel poligonalisation generate noise and reduce ride comfort. Moreover, due to the increased dynamic effects on both the track and the railway vehicle suspensions, irregular wear reduces the life of track and vehicle components. It is therefore of great importance to investigate the causes for the different mechanisms of formation of irregular wear and to develop strategies to reduce and possibly avoid this kind of wear. Figure 6. shows a picture of track corrugation taken in Milan underground.

![Image](image4.png)

**Figure 6.** Rail corrugation.

The wavelength of rail corrugation can vary from 3 to 15 cm depending on track and wheelset characteristics.
3.1 Ride Comfort

Irregular wear is generally characterised by short and medium wavelength irregularities on both the wheels and the rails. Therefore, at high speed, the excitation introduced by these irregularities is characterised by high frequencies that are almost completely filtered out by primary and secondary suspensions of the railway vehicle. This means that, usually, irregular wear of rails and wheels doesn't affect ride comfort. However, in those cases in which the lateral dynamics of a railway vehicle is relevant due to hunting instability, wear produces a significant gauge variation with wavelengths equal to $8 \div 12$ m. These lateral track irregularities produced by wear are seen also by vehicles that do not show any hunting instability and therefore that should not have any significant lateral dynamics. In these cases the gauge variations are transmitted to the railway vehicle carbody that starts to vibrate affecting ride comfort.

3.2 Structural Vibrations and Noise Emission

Irregular wear is also the main responsible for structural vibrations induced in nearby buildings due to train transit and noise emission. Vibrations and noise are particularly critical for tracks lying in populated areas. Obviously, for a fixed value of train speed, the greater the irregularities on wheels and rails, the higher will be the emission of the structural vibrations and noise induced by a railway vehicle transit.

In the figure shown below, experimental data relative to structural vibrations in a building near an urban underground railway line are shown. The measured acceleration clearly shows the influence of rail corrugation on structural vibrations: with big irregularities on the rails, the RMS value nearly becomes greater than the maximum value accepted by the current standards (ISO 2631). Railway authorities are therefore obliged to grind the rails to suppress corrugation. Also at higher frequencies the effects of irregular wear can be felt. In this case the vibrations are transmitted by the air and not by the ground. At high frequencies rail corrugation causes an increment in noise emission equal to $10 \div 15$ dB inside the building.

![Figure 7. Building acceleration due to train with small (up) and big (down) rail corrugation.](image)

4 ROLLING CONTACT FATIGUE PHENOMENA

A wide variety of damage and degradation phenomena are summed up in the term "wear". These phenomena are known to occur at wheel – rail interface, and many of them are particularly important for high speed vehicles, where the increase of operating speed leads to increased dynamic loads on the wheels.

A brief description of the damage phenomena occurring in rolling contact is given below:

- abrasion;
- nucleation of micro-cracks in a thin layer below the surface of the wheel, which may propagate inside the wheel;
- propagation of cracks due to the presence of small defects like inclusions or deep shelling whose presence in the material is due to the technological processes used in wheel manufacturing;
- shelling or spalling defect can occur on the rolling surface in shakedown);
- structural duced by repeated cycles of elasto-plastic deformation of the outer layer of the wheel (elastic or plastic modifications produced by local overheating of the rolling surface, which may lead to the formation of martensitic structures.

All these phenomena cause an increase in maintenance and total life cycle costs and, in the most severe conditions, may lead to wheel failures, thereby seriously affecting vehicle’s running safety. Abrasion and crack growth are in competition: if abrasion is faster than crack growth, no critical failures due to crack propagation will be observed. If, on the contrary, surface treatments are used to increase the hardness of the contacting surfaces and therefore to reduce the abrasion rate, critical failures may occur [17]. For these reasons, the study of damage phenomena in rails and wheels is strictly connected to the study of abrasive wear. In order to be able to separate the effects on wear of the different mechanisms considered, accurate experimental tests should be carried out. Laboratory tests on surface wear...
of rolling bodies are generally performed using cylindrical roller rigs. These tests are often performed under creepages much higher than those occurring in wheel rail contact and the cylindrical shape of the rollers is not adequate to reproduce a three-dimensional stress distribution at the contact. This explains why the results of these tests may be quite far from the real phenomena taking place in wheel – rail rolling contact fatigue, the rates of wear and crack propagation being different with respect to the conditions to be studied. A different approach is represented by tests performed on barrel-shaped rollers, where a three-dimensional stress condition holds, provided that the values of creepages is accurately controlled and kept in the range below 1 %. A more refined but rather demanding way to deal with these problems is represented by a roller test rig where a complete wheelset rolls over two rail – profiled rings [5]. In this case lateral, vertical and longitudinal actuators are used in order to apply to the wheelset some realistic time histories of lateral and vertical loads combined to a yaw motion. Unfortunately, few full-scale experimental tests at known loading conditions have been carried out on rails and wheels. Therefore, at present, no separation of the different phenomena on wear could be made.

5 STATE OF THE ART OF WEAR MODELS

In order to be able to predict wheel and rail wear, a dynamic model of the train – track interaction and a wear model should be coupled. Regular wear is mostly associated to the slow railway vehicle dynamics due to curve negotiation and lateral motion of the wheelset on a straight track. Irregular wear instead is associated to the fast train – track interaction dynamics that is usually linearized around regime conditions. Therefore, the range of frequency of the dynamic models to be coupled with the wear model is different depending on the fact that either regular or irregular wear is studied.

In the past two different approaches have been followed: on one side the phenomena of wear between two rubbing surfaces has been analysed in a very detailed way for sliding contact. On the other side, a simplified rolling wear model has been coupled with a complex railway vehicle model in order to be able to predict wear. At present, the wear models adopted in the field of railway vehicles assume that the worn material is proportional to the frictional work in the contact area. The coefficient of proportionality between mass loss and frictional work is identified on the basis of experimental data available from on line tests. This means that such wear models do not consider separately abrasion, rolling fatigue and fracture mechanisms. Archard's sliding wear model [2] was the first to be applied in the field of railways even though the principal cause of wear is rolling and not sliding. Fries and Davila [9] proposed four different variants of Archard's wear model in order to predict wheel tread wear for a railway vehicle running on a straight track. The vehicle – track interaction is analysed in the frequency domain. Kalker [15], [19] was mostly concerned about contact mechanics modelling. However, he also proposed a wear prediction model for railway wheels. This model is based on the correlation between the frictional power distribution on the contact area and the mass loss distribution on the same area. Since the procedure is based on a very complex contact model (CONTACT93, [14]), it was only applied to very short straight track simulations. Moreover, vehicle dynamics is not taken into account. The wear prediction tool proposed by Linder et al. [20] uses the multibody code MEDYNA to simulate railway vehicle dynamics. The Kik-Piotrowsky contact model (rigid interpenetration contact model [18] is used to determine the frictional work in the contact area. Zobory [25] developed a wear prediction tool for both wheels and rails. The vehicle – track interaction is simulated through a multibody code, the normal contact problem is solved through a hertzian approach while the tangential contact problem through FASTSIM. The wear estimation procedure developed by Braghin et al. [3] uses a non-linear numerical model of the railway vehicle interacting with the track. The model allows to determine the number and the position of the contact points together with the values of the resulting contact forces and creepages as function of time. For each time step, the distribution of the tractions and of the slippages in the contact area are determined using Kalker's CONTACT93 algorithm. The wear prediction tool also allows to simulate irregular wear of both the wheel and the rail.

At present there are several model for the formation of rail corrugation both in the frequency domain and in the time domain but actually a full understanding of the problem is not yet available. This may be due to the fact that, although common, the problem of railway corrugation presents features that differ from one site to the other. Tassilly and Vincent [23], [24] developed a rail corrugation model in the frequency domain that linearizes the wheelset behaviour around the steady-state condition in full curve. The rail is considered as a beam on a two stage continuous elastic layer while the wheelset is introduced through its frequency response function. According to this model the wavelength depends only on the coupled wheelset – track resonances. The corrugation model proposed by Knothe [10], [11] is also based on a frequency domain approach. In this case, through a representation of corrugation via Fourier series, the variation of track impedance along the sleeper bay can be considered leading to a profile of corrugation modulated in amplitude and wavelength as experimentally observed. The model proposed by Ahlbeck and Daniels [1] is based on a time domain approach allowing to include the non linearities due to the contact forces. The wheelset is modelled as a rigid body, adding one degree of freedom of torsional flexibility while a simple lumped parameter scheme is adopted for the track. The proposed mechanism of corrugation is the stick-slip mechanism due to torsional oscillations of the wheelset excited by the variation of normal loads. The model, based on a time domain approach, proposed by Diana et al. [7], [8] states that the mechanism of corrugation is based on the variation of the track impedance along the sleeper bay.
This variation excites the deformable modes of the wheelset, which fall into the frequency range of track impedance variation. This, in turn, leads to variations of normal contact forces in the same frequency range. In situations where high creepages take place, these dynamic variations of the normal load produce considerable variations of the tangential contact forces that are responsible for corrugation.

6 CONCLUSIONS

Both numerical and experimental results showing the influence of wear on vehicle dynamic behaviour were given. In particular, the main effects of regular and irregular wear were presented and discussed. A brief description of the different phenomena associated to wear and the state of the art of wear modelling has also been presented.

Although the effects of both regular and irregular wear are well known and may be correctly reproduced by a simulation code, at present no fully satisfying explanation of the causes of irregular wear is available. Moreover, the importance of the different phenomena associated to wheel and rail wear, as well as the associated damage mechanisms, should be investigated in the different wear regimes in order to be able to separate abrasive wear from ratchetting effects. This will help to find countermeasures and improve planning strategies for maintenance activities and to develop wheels and rails with longer life.

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8 REFERENCES