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The characteristics of the selected types of wheel wear and their effect on the rail vehicle – track interaction

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The aim of this paper is to present the selected types of rail wheel wear and their influence on vehicle-track interaction. The first part discusses the wheel-rail interface and presents the essential information about the wear of rail vehicle wheels. Differences in the nature of the wear of rail and tram wheels are pointed out. Then, characteristics of typical forms of wheel wear are presented, together with the description of the mechanisms of their occurrence and the existing technical measures leading to their reduction. In the last part of the text, the impact of the previously described forms of wheel wear on the vehicle-track interaction is discussed.

1. Introduction

Wear is a significant problem in the operation of rail vehicle wheels. While the wear process itself in friction pairs, of which the wheel-rail contact is an example, is inevitable, the attempts made to reduce it or to eliminate its serious forms are the key issues concerning the improvement of the rail transport system operation. Reducing the rate of wheel wear processes or preventing critical defects is possible by identifying the causes of their occurrence and at least minimizing them. This leads to an extension of the service life of the rolling stock and the infrastructure, providing a measurable improvement in the functioning of the rail transport system. For the operators of these systems, this results in benefits connected with improved driving comfort, traffic safety and finally, reduced financial costs. Because of the technical progress made in the construction of rail vehicles, higher dynamic loads are acting on the vehicles and the track. For this reason, limiting wheel wear is undoubtedly an important engineering challenge that determines the correct operation of the rolling stock and the infrastructure.

The process of wheel wear in rail vehicles is a function of many factors such as the dynamics of the rail vehicle or the mechanics of the wheel-rail contact, creating a research problem of many origins. Therefore, the division of types of wheel wear is not always unequivocal, whereas, in the present study, wheel wear types were divided into three basic groups: wheel wear occurring in the transverse direction of the wheel rolling surface, resulting in a change of wheel profile (its evolution), deviations of the rolling circle shape from the ideal wheel (out-of-roundness defects) and rolling contact fatigue wear by shelling and spalling. Wheel wear, which is the subject of this study, has a negative impact in the vast majority of cases, both on vehicle dynamics and on the technical condition of rolling stock and infrastructure. Due to its consequences, which affect the functioning of the rail transport system, it is important to distinguish between these types of wear, to understand the mechanisms of these defects, and to develop technical measures to prevent intensified wear of rolling stock and infrastructure.

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2. The wear of rail vehicle wheels

The wheel-rail interface is an important area because it affects the dynamic behavior of the vehicle, the emission of sound, vibrations, and finally the wear. This means that the level of wheel wear both influences and is influenced by the phenomena occurring at the wheel-rail interface. Assuming that the radius of the wheel and the curvature of the rail head are constant at the point of contact, the contact patch has an elliptical shape and has an area not exceeding 1 cm^2. For this reason, large values of the contact stresses occur at the wheel-rail interface, often as high as 1500 MPa.

Three main types of contact can occur between wheel and rail. Wheel-rail contact at a single point (area) provides relatively better vehicle dynamic characteristics than other types of contact, such as self-steering ability and reduction of rolling resistance between wheel and rail. Due to the small contact area, high values of the contact stresses occur and create conditions for escalate wheel and rail wear. Multipoint contact (usually in the form of a two-point contact) takes place when apart from the nominal contact point, there are additional contact areas, e.g. between the flange root and the rail gauge corner, for instance in case of curving. Multipoint contact is undesirable because the contact points are located on non-identical rolling radii of the wheel, which causes different rolling speeds. This results in creepages, which intensify wheel and rail wear and lead to increased noise emission [10]. Conformal contact appears when the wheel or rail is worn so that their contact patch is spread over a large area due to the similarity of their geometries. It limits the wear of the wheel and rail, however, it worsens the dynamic properties of the vehicle, such as lowering the critical speed or increasing the frequency of hunting motion.

The characteristic of wheel-rail interaction create the conditions for wear mechanisms, of which three basic ones can be listed [2]:

1. Rolling Contact Fatigue (RCF) – this type of wear mechanism can be characterized as fatigue wear caused by cyclic contact stresses of variable values at the wheel-rail interface. It can occur on or underneath the wheel running surface and has the character of spalling or shelling wear [7].
2. Adhesive wear – it is related to the roughness of the wheel and the rail. The roughness vertices of the wheel and rail surfaces stick together and, due to the relative velocity, they are plastically deformed or sheared.
3. Abrasive wear – it is caused by a third party between the wheel and the rail or by the wheel and rail surfaces rubbing against each other resulting in subsequent localized material loss. In the wheel-rail system, abrasive wear is very often created by grains of sand used to increase friction between the wheel and the rail (distributed by sandbox) and metallic wear products which are emitted from the brake system.

There are also fundamental differences between wheel wear of tram vehicles and wheel wear of rail vehicles. The most important of them are those which are the outcome of the differences in the construction of those vehicles. The narrower flange width of tram wheels causes more frequent contact with the side of the rail head, whereas the smaller diameter of the wheel results in a smaller contact area and thus higher stress in that area. It also affects in an increased number of rolling cycles. In addition, the presence of small radius curves in tram tracks (the minimum radius of a curve in the tram network is 18 m) gives a rise in a more intense and more frequent generation of creepages between the tram wheel and the rail.

3. The evolution of the wheel profile

As a result of wheel-rail contact accompanied by normal or tangential forces, abrasive and adhesive wear of the wheel profile and the rail occur. For this reason, the original (nominal) contour of the wheel rolling profile is lost. A comparison of the nominal and worn PST profiles is presented in Fig. 1.

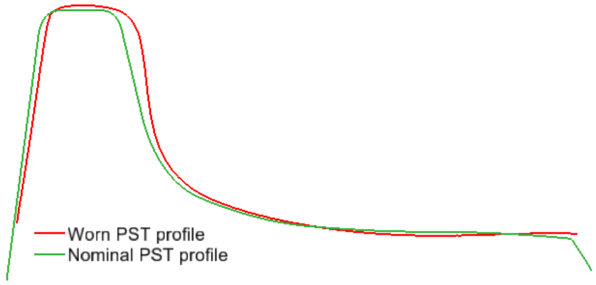

Fig. 1. The comparison of nominal and worn PST wheel profiles

The most important and the most frequent changes in the wheel profile are those related to the flange, namely reduction of its inclination, as well as changes in the width and geometry of the flange root. Additionally, the height of the flange increases as an outcome of the wear of the rolling surface [1]. In tram vehicles, a decrease in the flange width of leading wheelsets is observed, whereas in the case of trailing wheelsets its increase is a frequent phenomenon because of the smaller values of acting forces. Another important phenomenon that originated from the evolution of the wheel profile is hollow wear, which is caused by uneven material wear in the central area of the rolling surface [9]. This gives rise to the increase of the value of the equivalent conicity, which describes the ratio of the difference of the inner and outer wheel radii related to the lateral displacement of the wheelset. As the wheel wears (and thus its conformality increases), the value of this parameter rises due to non-uniform wheel wear, resulting in a difference in length of the rolling radii on the inner and outer wheels.

The change in the shape of the rolling profile is inevitable, but there are technical measures to minimize it. The most important is to ensure that the shape of the rolling profile is optimal with regard to the intensity of wear, so as to eliminate as far as possible creepages or to reduce impact loads and the values of the contact stresses at the wheel-rail interface. Another technical measure is the flange or rail lubrication, which is used for counteracting abrasive and adhesive wear. Rail or wheel lubrication is very often used on tight curves to reduce creepages intensity (and consequently squealing noise). A routine method of restoring the original rolling contour of a wheel is reprofiling, which is applied at specified intervals. The amount of reprofiling is limited by the material range allocated for it. For example, the nominal wheel diameter of the Tramino S105p tram is 610 mm and the minimum is 520 mm.

4. OOR defects

4.1. Polygonisation

Polygonisation of wheels is manifested by deviations of radius length occurring on the circumference of the wheel, which can be described as the loss of round shape by the wheel and its transformation into a polygon. This form of wear is seen in every segment of rail vehicles and, of all the OOR-type defects, it is considered to be the one that most adversely affects vehicle-track interaction [8, 12]. Figure 2 shows typical forms of polygonisation – eccentricity, ovality, and trigonality. Under operational conditions, several different forms of polygonisation may coexist [6].

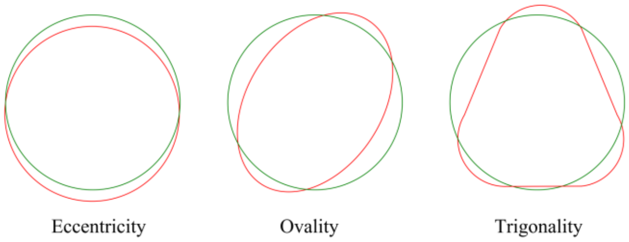

Fig. 2. The typical forms of polygonisation

The effect of wheel polygonisation is the induction of impact loads at the wheel-rail interface, which has a negative effect on the dynamics of the rail vehicle and increases the wear of vehicle and track components. Although the mechanisms of polygonisation are very complex and depend on many variables, based on the information presented in the literature, the following causes of polygonisation can be listed [8, 12]:

- impact loads on the wheelset (unsprung mass),
- resonant frequencies acting on the wheel, which may originate e.g. from track or vehicle excitations,
- stick-slip phenomena between wheel and rail,
- the elasticity of the wheelset and track,
- the action of pad brakes,
- wheel flats,
- dimensional and shape inaccuracies of the support rollers of the lathe,
- stress formation during reprofiling of a wheel by a rotary lathe,
- instability of the wheelset.

As a way of preventing polygonisation, more frequent wheel reprofiling is suggested, which would remove non-heterogenic microstructure from the surface and thus inhibit the initiation of this type of wear. Another method to reduce this type of wear is to minimise the unsprung mass of the wheelset. This is achieved by reducing the mass of the axle, e.g. by hollowing it out, while disc shapes optimised for this purpose are used to reduce the mass of the wheel. Another way to reduce polygonisation can be to check the dimensional and shape accuracy of the support rollers of sub-track lathes more frequently [11].

4.2. Wheel flat

According to [15], a wheel flat can be defined as a local abrasion occurring on the wheel rolling surface, causing the loss of its original contour (Fig. 3). Wheel flat occurs as a result of sliding between the wheel and the rail, which is most often generated by wheel locking during braking due to poor technical conditions of the brake or improperly selected braking force. Other factors that contribute to wheel-rail slip are third-party bodies between the wheel and the rail (e.g. leaves, snow) or contamination of the rail surface. Fig. 4 shows a wheel flat on the wheel running surface.

Fig. 3. Wheel flat [16]

The formation of the wheel flat is related to abrasive wear and a martensitic transformation of the wheel rolling surface material. In this case, the mechanism of the wheel flat formation can be described in the following points [6]:

1. The occurrence of full slip between the wheel and the rail which is caused by an inappropriate braking process.
2. Local temperature rise at the wheel-rail interface because of the frictional energy dissipation.
3. Rapid cooling of the wheel running surface due to rotation of the wheel and conduction of heat into the wheel.
4. Generation of residual stresses and the formation of brittle and hard martensite on the wheel running surface.
5. Development of a flat spot as a consequence of cyclic contact stresses leading to abrasion of the martensitic layer.

After the formation of the martensitic layer and the resulting wheel flat, stresses due to rolling loads build up deep into the material. It is reported that, in an extreme case, a wheel flat 40–60 mm long and 1 mm deep can evolve into an area up to 500 mm long and 5 mm deep [6].

Avoiding sudden braking, removing the martensitic layer from the rolling surface or regular detection of wheel impact loads are proposed as effective ways to prevent the initiation of wheel flat. It is worth noting that due to the specific nature of tram lines, frequent and often sudden braking takes place. On this account, tram vehicle wheels are strongly exposed to the formation of wheel flat [9]. Importantly, the contact of the brake pad with the wheel rolling surface, as in the case of a pad brake, reduces the formation of the wheel flat by cyclic abrasion of the surface layer of the rolling surface. As a result, the wheel regains its round shape.

4.3. Scaled wheels

The scaled wheels phenomenon can be defined as sticking of the fragments of material to the wheel rolling surface. The first mechanism of its formation mentioned in the literature is related to sliding between the wheel and the rail, due to the complete wheel blocking during sudden braking [4]. In such a case, by the increase in the wheel temperature, the material becomes more plastic and is detached from one region of the rolling surface. After that, it sticks to another fragment of this surface. The result is an area with adhered material (Fig. 4).

Usually, during the scaled wheels formation, the plasticised wheel material is mixed with contaminants from the track or the brake system. The mechanism involves both a wheel flat and a scaled wheel generation – respectively a wheel flat is formed on the wheel, which releases material to the rail, and a scaled wheel is formed on the wheel, to which the material adheres.

Fig. 4. Scaled wheels [17]

The second mechanism of scaled wheels creation is connected with wheels that interact with pad brakes [6]. The essence of this type of wear is the loss of the original wheel outline due to metal filings from the brake system pressing into the material of the rolling surface. During braking, when a brake pad contacts with the tread, hot spots occur. Their plasticity leads to the sticking of small particles coming out of brake pads.

Important ways to prevent this type of wear are to avoid sudden wheel-rail slippage by, among other things, suitable braking processes and to limit the formation of material particles which are emitted from the braking system. It can be achieved by replacing classic cast-iron brake pads with composite brake pads [6].

5. RCF wear

5.1. Shelling

Wheel wear by shelling is manifested by the loss of a piece of material of the wheel tread [3]. Two basic types of this form of wear can be distinguished, which differ in the formation mechanism – shelling caused by fatigue of the rolling surface material and shelling generated by a slip between the wheel and the rail [14]. This type of wear is illustrated in Fig. 5.

Fig. 5. Shelling wear [18]

Shelling, caused by material fatigue, occurs as an outcome of plastic deformation originated from the cyclic contact stresses at the wheel-rail contact. When the yield point of the material is exceeded, fatigue cracks appear. Because of the continuous contact stresses, the cracks grow and merge with each other, resulting in either a cumulative crack or shelling of the wheel rolling surface material [5, 14].

Shelling originated from wheel sliding, unlike spalling wear, is generated by heating the entire surface layer of the wheel rolling surface above 300°C for an extended period of time. Due to the prolonged thermal effect, the surface layer of the tread is weakened and more susceptible to thermal cracks. The presence of contaminants such as sand or water between the wheel and the rail can promote the propagation of cracks deep into the cross-section of the surface layer [7].

In order to limit shelling wear, it is proposed to exploit conformal wheel and rail profiles, more frequent reprofiling, or to use steel with fewer impurities as a wheel construction material [3].

5.2. Spalling

The essence of spalling wear is the loss of material particles from the component. Spalling wear on the wheel rolling surface is shown in Fig. 6. The specific feature of spalling wear and the main difference from shelling wear is the martensitic transformation, which occurs on the wheel rolling surface [13]. In the case of rail vehicle wheels, the mechanism of spalling wear formation can be presented in the following two stages:

1. A local temperature rise in the surface layer of the wheel rolling surface due to the dissipation of frictional energy and, as a consequence, the formation of martensite.
2. Spalling of shallow martensite scales as an outcome of cyclic contact of the rolling wheel with the rail.

Fig. 6. Spalling wear [19]

It is pointed out that the spalling phenomenon, especially in the case of tram vehicle wheels, does not lead to abrupt wear of wheel rolling surfaces due to its surface character, because as a result of the frequent wheelset reprofiling, it is possible to inhibit this type of wear [7]. Apart from reprofiling, a way to eliminate the spalling phenomenon is to control the technical condition of the brake in order to prevent wheel blocking during braking [3].

6. The influence of wheel wear on vehicle-track interaction

The wheel-rail interface is an area in which occur phenomena that determine the exploitation of the vehicle and the infrastructure. For this reason, any form of wheel or rail wear will cause a change in the nature of the interaction between those two elements. This change may not always be negative, for example, the wheel-rail conformation, because, unlike single point contact, the contact stresses between wheel and rail have lower values. However, in most cases, wheel wear has a negative effect on both the vehicle and the infrastructure. Table 1 summarises the types of wheel wear and their impact on the track and the vehicle.

Of the consequences of wheel wear listed in Table 1, three basic changes in the interaction between vehicle and track can be singled out:

1. Impact loads at the wheel-rail interface – a common feature of wheel defects concerning the loss of round shape is the generation of forced periodic vertical vibrations at the wheel-rail interface. In particular, polygonisation of the wheels results in an increased level of vibration emission, both negatively affecting the passengers or loads and also spreading to the environment, e.g. the ground.
2. Increased noise emission – wear and defects in the wheels increase the rolling noise. Rough surfaces and their contact cause oscillations in the vertical direction of the wheel and the resulting noise. Impact noise is a special case of rolling noise, which is not only emitted during normal operation, e.g. when running over rail joints, but also as an outcome of defects in the OOR wheels.
3. Change in vehicle dynamic behavior – the evolution of the wheel rolling profile, e.g. as a result of hollow wear or change in flange root geometry, causes a deterioration of the vehicle dynamic behavior and consequently in an increased level of loads acting on the rails, mainly in the direction transverse to the track axis. An increase in the hunting motion frequency, caused by wear on the wheel rolling surface, leads to longitudinal track irregularities. OOR defects also worsen the dynamic of the vehicle in the track due to the loss of wheel conicity and also increase the susceptibility to derailment through wheel underload. Positive changes in the dynamic behavior of the vehicle are contributed to by, for instance, a reduction in flange width, which reduces the susceptibility to the de-

Table 1. Types of wheel wear and their effect on the track and the vehicle

Wear type		**Impact on the track**	**Impact on the vehicle**
The evolution of wheel profile	Reduction of the inclination of the flange	Contact of the flange with the side of the rail head, increased impact loads	Increased susceptibility to derailment
	Reduction of the width of the flange	Increase in contact stresses values between flange tip and the groove of the crossing (tram vehicles)	Increase of the lateral displacement of the wheelset, reduced susceptibility to derailment
	Change of the geometry of the flange root	Increased impact loads, multipoint contact with the wheel	Increase of the displacement lateral displacement of the wheelset, reduced susceptibility to derailment
	The increase of equivalent conicity value	Increase in impact loads	Reducing the critical speed, increase in the frequency of the hunting motion
OOR defects	Polygonisation	Increased risk of rail and sleeper fracture, creation of vibrations in the track, increased rail roughness	Deterioration of dynamic vehicle behaviour, intensified loading of wheelset axles and bearings, fatigue wear of wheels, bending of wheelset axles, emission of rolling and impact noise, increased susceptibility to derailment
	Wheel flat		
	Scaled wheels		
RCF wear	Shelling	Dynamic overloading which can lead to fracture, increase in rail roughness	Vibration reducing driving comfort, the possibility of wheel breakage
	Spalling	Increase in rail roughness	Vibration reducing driving comfort

derailment, or an increase in wheel-rail conformation, which results in a reduction in the contact stress acting at the wheel-rail interface.

7. Summary

In the article, the characteristics of typical forms of wheel wear and their influence on the interaction between the vehicle and the track were presented. When analysing the origins of the forms of wear of railway vehicle wheels, one can notice a certain relation that the vast majority of defects are caused by the creepages between the wheel and the rail, both those resulting from the processes of braking and kinematic guidance in the track. It confirms the theoretical assumption that, in order to ensure the best possible interaction between the vehicle and the track, the contact between the wheel and the rail should be as rolling as possible. This implies the need for design solutions in the construction of rolling stock that minimize the occurrence of creepages, such as new, optimised rolling profiles or springing characteristics, which enable passing tight curves in positions as close to radial as possible. When considering the design challenges from the infrastructure side to minimise wheel wear, for instance, rail lubrication is suggested. Preventive measures for RCF wear could be more frequent wheel reprofiling, while OOR defects could be limited by reducing impact loads at the wheel-rail contact.

An important conclusion is that wheel and rail wear is strongly related to the nature of the wheel-rail interaction. The wear of this friction pair both determines the quality of wheel-rail contact and is strongly dependent on it. In addition, it should be noted that different forms of wear are dependent on each other – wheel flat may cause polygonisation, while the mechanism of wheel flat generation may be related to scaled wheels formation. An important observation is that not all forms of wheel wear have a negative impact on the vehicle and the track. For example, the evolution of the wheel profile, which manifests itself, among other things, in the reduction of the flange width, reduces the susceptibility to vehicle derailment, while the conformality of the wheel and the rail decreases the contact stresses values at the interface between these two elements.

Nomenclature

OOR	out-of-roundeness
RCF	rolling contact fatigue

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