Re-design of tyred wheels to optimize maintenance

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Abstract

Resources needed to maintain conventional tyred wheels are much bigger than those required by monobloc wheels. A different geometry of the mating surfaces, basically a self-centring dovetail coupling, is proposed. It allows to eliminate the retaining ring resulting in an increase safety. This change is justified by the widespread diffusion of CNC machine tools and Coordinate Measuring Machines (CMM). The adoption of this safer modified geometry leads to a simplified maintenance cycle that is much faster and much cheaper than the conventional one. Historical maintenance procedures are revised in the paper, showing how the new maintenance cycle is easy, and has a low impact on current maintenance plants. The overhaul process looks particularly advantageous on inboard bearings wheelsets installed on inside frame bogies, for which it appears that tyre change can be performed directly on the vehicle during a sort of "pit stop".

Keywords: tyred wheels, maintenance, safety

1 Introduction

Tyred wheels maintenance is complex and expensive. Actually, it is the main reason for the preferring monobloc wheels for any kind of vehicle, although they may have distinct advantages when other considerations are taken into account.

Maintenance cycle for tyred wheels may vary from place to place, but it always include some pre-machining of the raw tyre (boring with the diameter of the wheel centre) and a final machining once the wheelset is assembled. Often, but not always, the wheel centre is machined every time a new tyre is fitted, therefore reducing the useful life of the centre to a finite number of tyres.

In any case, the presence of specific machines for cutting the worn tyre at the end of its useful life and to cut and mount the retaining ring and the need for a heating oven are all elements that make the tyre replacement operation long and expensive.

It is clear that maintenance cycle descends from the workshop practice that was available at the beginning of the railway era. All machine tools were manual as well as all dimensional checks. In that situation, machining a cylindrical surface with a sufficiently small shape and position errors was already a challenging task, and checking the bore size with manual callipers was the only possibility. Today nearly all workshops run CNC machine tools with three or more axes, and dimensional checks are performed on a regular basis with Coordinate Measuring Machines (CMM).

When asking the different operators why they perform different maintenance cycles, the answer has always been "because we have always done so". On the opposite, the revision of the maintenance process that passes through the re-analysis of the design of the tyred wheelset shows considerable potentials to reduce maintenance costs. This innovation must keep safety, generating a better, lower cost and equally safe or safer solution. About this, the authors analysed in two companion papers ([1], [2]) the stresses and strains arising in both the tyre and the wheel centre during fitting and during service, considering that the absence of thermal inputs may lead to substantial mass reduction and simplicity.

2 The regulatory frame

Tyred wheels have been the standard for all railway applications for more than 150 years. Their success was obscured in recent years by the advent of monobloc wheels that have a number of advantages in terms of safety and maintenance.

Typical fields in which the application of monobloc wheels is compulsory are high-speed vehicles, as there are no negative effects of centrifugal forces acting on the tyres and the mass in lower compared to a tyred wheel, and freight vehicles, as tread braking leads to tyre loosening and related problems (see e.g. [2] and [3]).

The first European Technical Specifications for Interoperability were issued in 2002 for high speed [4], and soon after that the supporting EN standards describing only monobloc wheels (see EN 13262 for manufacturing [5] and EN 13979-1 for design [6]) were released. No standardization activities were performed on tyred wheels, that were not of any interest on high speed trains. Nevertheless, tyred wheels were not even reconsidered during the drafting of the so-called "conventional rail" TSIs neither for freight wagons in 2006 [7] nor for locomotives and passenger rolling stock in 2011 [8].

The only reference available today to maintain tyred wheels is available in the EN 15313 standard [9] which, in the informative annex H, states that "requirements for tyred wheels are specified in the following UIC leaflets: UIC 810-1, UIC 810-2,

UIC 810-3, UIC 812-1, UIC 812-4, UIC 812-5 and UIC 813". It can be seen that all these leaflets ([10]÷[16]) were published nearly 30 years ago (the most recent is UIC 810-1 that was re-released in 2003 with minor amendments from the 1981 edition). It is clear that European legislators performed no activities in this field after the creation of the European Union with the Treaty of Maastricht in 1992. Specifically, a design code for tyred wheels is missing.

3 Tyred wheels maintenance

As there was no market development on tyred wheels, no improvements were introduced in their maintenance beyond those arising from the usual machine tools and workshop tooling upgrade. As a result, the sequence of maintenance operations remained unchanged and very similar to the one that was used at the origin of railways.

Let us analyse the common practice and its weaknesses, referring to the well-known components of the tyred wheel (Figure 1) and supposing that the wheel centre has not to be removed from the axle for other reasons.

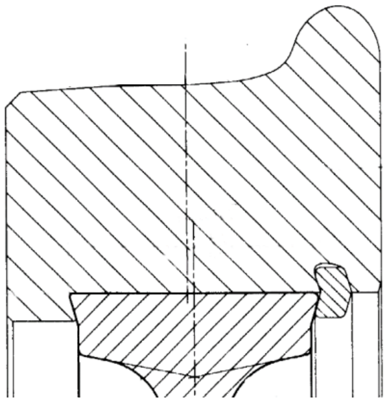


Figure 1. Cross-section of a tyred wheel. The three elements of the wheel, i.e. the wheel centre, the tyre and the retaining ring, are clearly visible.

In the "worst case", the following operations are traditionally performed, starting from the wheelset already removed from the bogie:

1. the wheelset is moved to a "wheelset lathe" where the retaining rings are machined and removed;
2. the wheelset is moved to the tyre cutting station, typically an alternating saw one;
3. the wheelset is moved to the tyre removal station, where the (nearly fully) cut tyres are pulled away from the wheel centre;
4. the wheelset is moved to the "wheelset lathe" where the wheel centres are machined to a new (smaller diameter);
5. new tyres are moved to a vertical lathe and machined to the matching diameter to ensure the right interference;

6. new tyres are moved to the heating station;
7. both hot tyres and the wheelset are moved to the assembly station, where they are assembled with a manual procedure (“upside down”);
8. retaining rings are installed manually;
9. after cooling, the completed wheelset is moved to a “wheelset lathe” where the wheels are reprofiled to the wanted profile and dimensions.

Different operators apply this sequence differently. Although the following analysis in not exhaustive, the authors have found different practices:

- some operators always reprofile the wheel centre, purchase rough tyres and perform the full set of operations;
- some operators reprofile wheel centres and fully machine the tyres before installation, skipping the final machining of the full wheelset;
- some operators remove the tyres by heating and therefore never reprofile wheel centres, purchasing tyres with finished bore that are installed on wheel centres, leaving the final machining of the wheelset as the last operation.

This situation proves that each operator works independently and that in the last decades there has not been any exchange of information among operators using tyred wheels.

There is no need to be top ranking economists to realize that this procedure totally vanishes the advantage of tyred wheels, i.e. the savings related to the replacements of tyres alone instead of the entire wheels. The opposite in fact applies: the maintenance cycle of a monobloc wheel (machining of the bore and press-fit) wins the competition. Unless something is changed, there is no way to revitalize tyred wheels.

3.1 Retaining ring and worn tyre removal

When a tyre has to be changed for whatever reason (large wheel-flats, RCF damages, wear), the first operation is the removal of the retaining ring. It can be performed on a “wheelset lathe” or any parallel lathe large enough to house the entire wheelset. The retaining ring is then machined until its complete removal.

The tyre can then be removed in three ways:

- by cutting the tyre with an oxyacetylene torch;
- by sawing the tyre with an oscillating or rotating saw;
- by heating the tyre until the interference is lost and the tyre is loosened.

All the three methods have advantages and disadvantages:

- torch cutting (Figure 2) requires nearly no tools and is extremely fast, but it is nearly impossible to completely cut the tyre without damaging the wheel centre. This requires to reprofile the wheel centre, thereby reducing its useful life (tyred centres may be designed to have an infinite life). Moreover, as the diameter changes every time, tyre diameter must be adapted to the specific wheel centre;

- sawing (Figure 2 and Figure 3) requires handling, a specific machine tool but cutting can be limited until a resulting thickness of 1 to 2 mm is left. Normally the residual stresses in the tyre are sufficient to break the tyre but this is not always guaranteed. An hydraulic extractor with a three-hands clasp is used, resulting also in this case in a potential wheel centre damage;
- tyre heating (Figure 4) is the only way to remove a tyre without any damage to the wheel centre. This method can be performed in two ways (by gas burners or by induction heating) and allows buying tyres with finished bore. Induction heating, which is not new at all [17], has the great advantage that it has a very low energy consumption and the equipment may be portable. Typical temperature is around 160 °C and typical time is around 10 minutes.

Figure 2. Cutting a worn tyre with an oxyacetylene torch (left, FS Foligno workshop, *circa* 1997) and with an alternating saw (right, Foligno Trenitalia workshop, 2017)

Figure 3. Remaining uncut tyre (left) and hydraulic extractor (right, both pictures Trenitalia workshop, 2017)

Figure 4. Tyre removal by burner heating on a steam locomotive (left, [18]) and by induction heating with a portable equipment (right, [19])

Heat tyre removal is particularly attractive as it allows to indefinitely reusing the wheel centre. As a consequence of the absence of any damage, new tyres can be purchased with finished bore, ready for installation.

3.2 Wheel centre machining

Theoretically speaking wheel centre surfaces should be reprofiled only after the tyre disassembly resulted in scratches or other types of damage on them. In practice, the maintenance cycle often includes this operation even when damages are not visible (Figure 5). As a sort of "black magic", operators often invoke "plasticization" o "distortion" of the mating surfaces that need a rectification. While this maybe rarely the case for the first application, this can be totally avoided following the recommendations described in [1].

Figure 5. Reprofiling of a wheel centre on a CNC wheelset lathe (Trenord wheelset shop, 2018).

3.3 New tyre bore machining to match the wheel centre

Tyres are normally supplied as rough rolled steel rings [10] and need to be machined on *all surfaces* although in different times during the assembly of the wheelset.

The bore to be shrink-fitted on the wheel centre has always been cylindrical, mainly for the intrinsic difficulties to obtain different profiles without hydraulic copy lathes that were introduced in 1938 by Georg Fischer [20] and before the first lathe equipped with Computer Numerical Control (CNC) was introduced by Arma Corporation in 1952 [21] (although its use became widespread in the 1970s).

To see how tyre machining and control could easily evolve today, Figure 6 shows a vertical lathe common in all railway workshops in the last century. Automation was limited to constant speed feeding derived by the single motor that equipped the lathe. In the same figure a modern CNC lathe is shown. It is clear that CNC allows to turn any revolution shape, and that with *countouring* techniques (see e.g. [22]) even non-revolution shapes can be obtained by using an additional milling head installed on the lathe. The transition from old to modern machine tools needed several decades, especially in the railway sector that is, as well known, extremely conservative. It can be said, as a conclusive remark, that *nearly all lathes installed when the UIC leaflets were released were traditional, while today they were nearly all substituted by CNC lathes*.

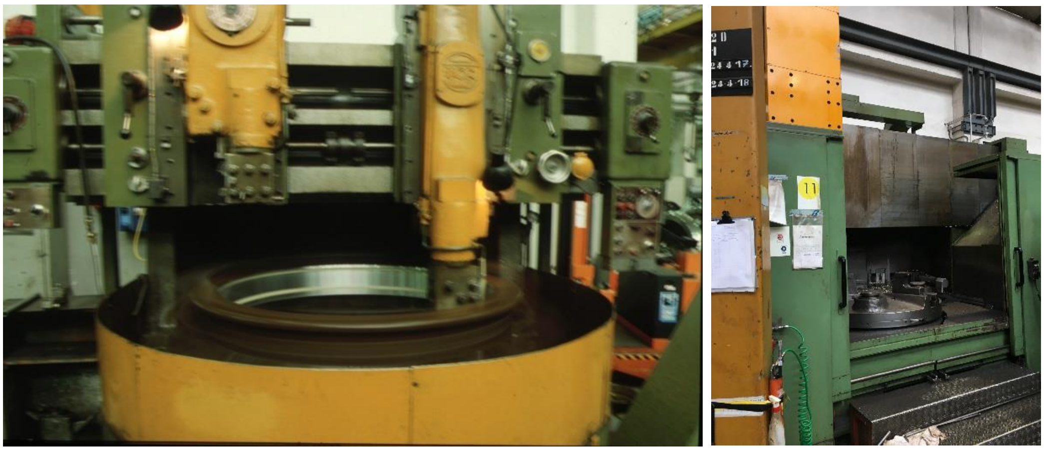


Figure 6. Machining the bore of a tyre on a conventional vertical lathe (left, FS Foligno workshop, *circa* 1997) and on a modern CNC vertical lathe (right, Trenitalia Foligno workshop, 2017)

3.4 Dimensional check techniques

Measuring dimensions changed over the years as well. While thirty years ago the common practice was to measure tyres by using exclusively large bore gauges that can only be used on cilyndrical bores, Co-ordinate Measuring Machines (CMM) allow to do the same check on any arbitrarily complex geometry with a much greater accuracy and automation (Figure 7).

Figure 7. Dimensional check of a tyre with a bore gauge and with a Hegenscheidt profile projector (top, FS Firenze Porta al Prato workshop, *circa* 1997); check of a ring with a Coordinate Measuring Machine (bottom)

Contactless measurements, based on laser-camera technologies, are today accurate enough to replace conventional tools on both fully automated measuring stations and on routine checks of tyre wear (Figure 8). It can be concluded that *modern dimensional control techniques go well beyond the needs of railway tyre application*.

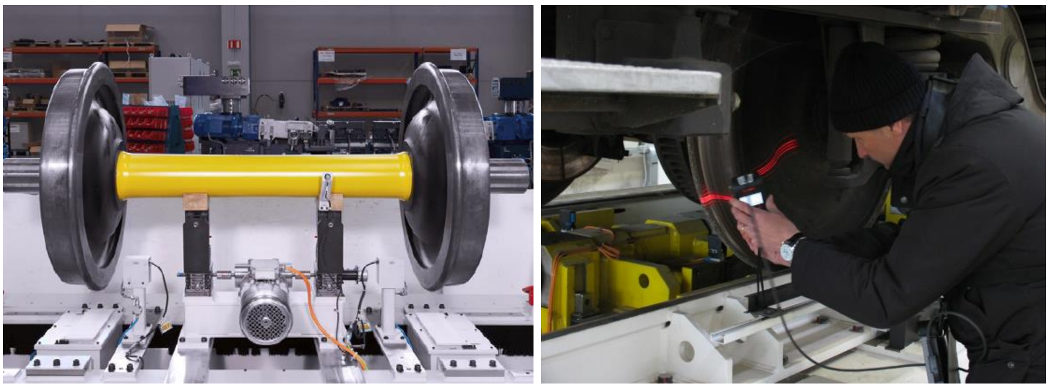


Figure 8. Contactless dimensional check of wheel profiles with a specific testing station (left, www.danobatgroup.com) and with a portable equipment (right, www.nextsense-worldwide.com)

3.5 Tyre heating and mounting

As it will be shown later in greater detail, tyres need to be heated to allow shrink fitting on the wheel centre. Conventional heating was originally performed by using combustion heating ovens, which provided a moderately carburizing environment with the related problems. More recently, the use of electric ovens became widespread, although their use is today limited almost only to monobloc wheels heating for shrink fitting on the axle (Figure 9).

Considering the shape and the size of a tyre, induction heating systems are very attractive and they were adopted since many decades ago (Figure 9). Heating time is in the order of 15-20 minutes with minimum energy losses.

Figure 9. Electrical oven wheel heating system (left) and tyre induction heating system (right, www.primaeng.it)

Mounting is traditionally performed with the so-called “upside down” configuration. The hot tyre rests on the floor and the wheel centre, already mounted on the axle, is dropped down until the abutment on the tyre is firmly engaged. Then the retaining ring is installed and pressed, and the wheelset is stored to allow a complete cooling by calm air.

Figure 10. The wheelset is lowered on the hot tyre (left), the retaining ring is bent and cut at the right length (centre), and the ring fitting machine is ready to finish the job.

3.6 Final machining of the wheelset

Once the tyre has completely cooled down, the external profile (contacting with the rail) and both the sides can be machined on a "wheelset lathe". With this operation it is possible to respect all the dimensions and tolerances of the EN 13260 standard [23] (obviously applied to a tyred wheelset).

4 Machining and tyre mounting considerations

4.1 Machining tolerances

UIC 812-4 [14] defines the tyre-wheel centre interference as $i = X\ D_C/1000$, where D_C is the diameter of the wheel centre and the factor X ranges normally between 1.3÷1.8 to "make allowance for influences, such as wheel centre design and stiffness", while for large diameter wheels it can be brought down to 1.1. Some operators restrict the field for their specific wheels, leading to 1.2÷1.4 as in the case of [24].

With the aim of defining a general and unified approach to machining useful to purchase fully finished parts, it can be shown that a t7/S8 coupling according to ISO 286-1 [25] satisfies these requirements. It should be said that modern vertical lathes can perform turning down to class IT6, and in exceptional cases down to submicron accuracy [26]. If wheel centres are fitted on the wheel seats on the axle after machining, both wheel centre and tyre machining can be performed on the same machine with the same accuracy.

As a worked example, let us consider the case of a wheel centre with a nominal size of D_C=800 mm. According to [24], this leads to minimum and maximum interferences of respectively i_{min}= 0.96 mm and i_{max}= 1.12 mm. With ISO standard [25], the dimensions and tolerances become 800 t7/S8 --- shaft 800.640÷800.560 / bore 799.620÷799.495 --- i_{min}= 0.94 mm and i_{max}= 1.145 mm.

As the minimum tolerance class is IT7, any current machine tools can bore the tyre *regardless of the dimension of the wheel centre*, obviously provided that the wheel centre keeps its dimension over time (i.e. it is not damaged by tyre removal process).

4.2 Heating and mounting considerations

Heat shrinkage of the tyre needed for mounting described in UIC 812-4 [14] is quite vague, saying that "the tyre must be heated, preferably, to between 200 °C to 250 °C, but not above 300 °C". This is typical of former UIC codes, that left the member railways the freedom to decide the actual application conditions.

Some operators (see e.g. [24]) restrict the field of heating to 200-220 °C. In the worst case of a room temperature of T_{room}=40 °C, a heating temperature of 200 °C, the maximum interference of i_{max}= 1.12 mm and using α=12*10^{-6} °C^{-1} as the thermal expansion coefficient of steel (constant as the temperature range is limited), the initial interference is recovered when the (uniform) tyre temperature reaches $\Delta T=i/\alpha D$= 117 °C, i.e. a final temperature of T_{fin}= T_{room}+ΔT=117+40=157 °C. When the tyre is further heated up to 200 °C, the play becomes p=(200-157)*12e^{-6}*800=0.416 mm with a radial clearance of 0.208 mm. *According to the code of maintenance [24], this play is enough to lower the wheelset "upside down" on the resting hot tyre*.

With the standardized coupling 800 t7/S8 with i_{max}= 1.145 mm, the loosening temperature becomes T_{room} +ΔT= T_{room} +$i/\alpha D$= 40 + 119= 159 °C. The play at 200 °C becomes p=(200-159)*12e^{-6}*800= 0.391 mm. Heating up to the maximum of 300 °C, the play becomes p=(300-159)*12e^{-6}*800= 1.351 mm, with a radial clearance of 0.676 mm, more than twice than that strictly needed to mount the tyre. This extra-clearance allows to design the mating surfaces with a different geometry

5 New tyre geometry "designed for maintenance"

5.1 Dovetail coupling and mounting procedures

One of the disturbing elements of the tyred wheels maintenance procedure is the retaining ring. Its role is to prevent that the tyre may "slip" laterally under the action of outward forces (that may happen e.g. on switches). This is necessary as safety against lateral movement is demanded only to friction, and in other couplings, such as wheel-axle fitting, it may generate big troubles (see e.g. [27]).

The proposed solution removes the need of the retaining ring as the cylindrical coupling is replaced by a "positive" coupling and *not to friction*. This solution, named *dovetail coupling*, has several distinct advantages:

- it is self-centring, as during tyre cooling the surfaces tend to align correctly in a natural way;

- there is no possibility of lateral tyre movement due to loosening, as the coupling is generated in a “positive” way, i.e. *surfaces interact not through friction but on abutments*;
- it allows to simplify machining operation and, what’s more, maintenance procedures are dramatically cut.

An example of the design of such dovetail coupling is shown in the case of a wheel centre with a typical diameter d=800 mm and a typical diameter width of w=90 mm, using the aforementioned 800 t7/S8 tolerances and considering a wheel centre of the maximum size of d_{max}=800.640 mm and a tyre with the minimum size of D_{min} =799.945 mm (800 t7/S8).

A small conicity can be applied resulting in maximum diameter of d_{ext}=801.440 mm. This leads to a play of p=0.551 mm when the tyre is heated up to 300 mm ($D_{300°C}$=801.991 mm). The radial clearance of 0.276 mm is sufficient for mounting (Figure 11).

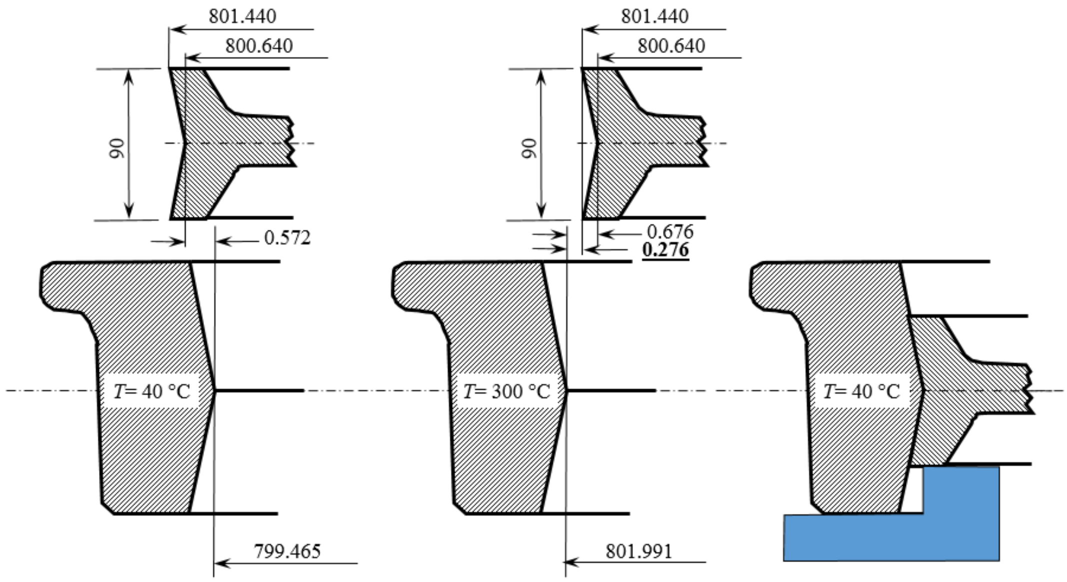
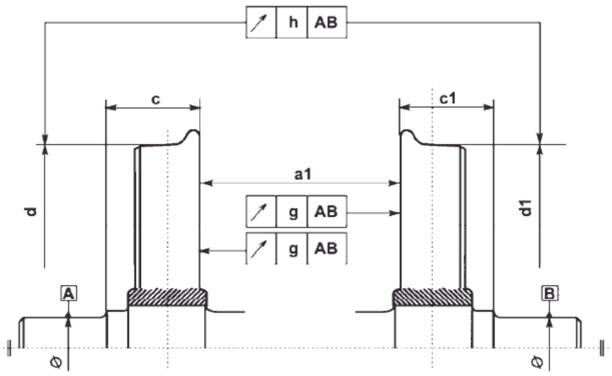


Figure 11. Relative position of coaxial wheel centre and tyre with 800 t7/S8 coupling in cold (right) and hot (centre) conditions. A sufficient radial play for mounting of 0.276 mm is obtained even with the maximum radial interference of 0.572 mm. Right: simple tool to guarantee the respect of geometrical tolerances after fitting.

5.2 Geometric tolerances of assembled wheelsets

Tolerances applied to assembled wheelsets are described in [23] (Figure 12). The values of interest, the radial run-out h and the axial run-out g for standard wheelsets of Category 2 (excluding high-speed applications) are respectively h≤0.5 mm and

g≤0.8 mm. These values can be easily achieved with correct machining and the correct application of the simplified maintenance procedure.



Dimensions in mm

Description	Symbol	Category 2 a	Category 2 b	Category 1
Distance between the internal wheel faces[a]	a_1	$^{+2}_{0}$ [b]		$^{+2}_{0}$ [b]
Difference in distances between the internal face of each wheel and the plane on the journal side defining the corresponding collar bearing surface	$c - c_1$ or $c_1 - c$	≤ 1		≤ 1
Difference in tread circle diameter	$d - d_1$ or $d_1 - d$	≤ 0,5	≤ 0,3	≤ 0,3
Radial run-out in tread circle	h	≤ 0,5	≤ 0,3	≤ 0,3
Axial run-out of the internal wheel face[a]	g	≤ 0,8	≤ 0,5	≤ 0,3

[a] Measurement at 60 mm beneath the top of the flange

[b] The tolerances may be changed for special designs of wheelsets

Figure 12. Tolerances and maximum errors after wheelset mounting (excerpt from [23]).

5.3 Imbalance

In the range of conventional speeds (≤ 200 km/h), the standard EN 13260 [23] prescribes a maximum imbalance of 75 gm for speeds greater than 120 km/h, while no requirements are given at lower speeds.

With the new tyre geometry, the correct balancing can be obtained simply by balancing the axle with the wheel centres fitted on. As the tyres are automatically balanced, being fully-machined parts, no additional balancing is needed after tyre fitting. This saves further time in the maintenance process.

6 Safety analysis of the modified tyre

Common Safety Methods defined by European Union establish the path that must be followed to evaluate the impact on safety of any solution that modifies the railway system according to Regulation 402/2013 [28]. It is interesting in this context because the evaluation of the impact of a generic modification on safety is obviously applicable to wheelsets. One of the authors gave a paper at the IWC 2016 [29] discussing similar topics. The basic concepts are reported here for clarity and then applied to the modified tyred wheels maintenance cycle.

In general, if the proposed modification is considered "not significant" (see Art. 2(2)(b)) on the basis of a set of well defined criteria (see Art. 4(2)(a) to (f)), "keeping adequate documentation to justify the decision shall be sufficient". The assessment has to be performed by the proposer under his responsibility without further evaluations, acting as the owner of a Safety Certificate with an approved Safety Management System.

The authors believe that the correct application of [28] in the present case is straightforward and painless. Removal of safety conditions based on friction (use of mechanical abutments), elimination of tread braking (no tyre loosening possible) and correct machining and mounting procedures are sufficient to implement the modification without any real impact on safety, which results increased by the new geometry.

7 Conclusions and further developments

The authors described in a previous paper the elasto-plastic behaviour of a tyred wheelset reaching the conclusion that fully machined tyres may be installed on finished wheel web respecting the final tolerances of the assembled wheelset. This conclusion would be nevertheless of low advantage if other features of conventional tyred wheelset are not critically reviewed and changed.

Resources needed to maintain tyred wheels are much bigger than those for monobloc wheels. The maintenance cycle of wheelset requires the removal of the worn or damaged wheelset from the vehicle, the shipment to a specialized workshop and a set of operations.

A different geometry of the mating surfaces, i.e. a *dovetail coupling*, is introduced in this paper, discussing current regulations, workshop practices and safety implications. Its adoption may lead to much faster and much cheaper maintenance cycles and to safer operations.

The resulting overhaul process looks particularly advantageous on inboard bearings wheelsets installed on inside frame bogies. For this arrangement, which is gaining nowadays more and more favour, the authors are currently developing a fully automated cycle based on a sort of "pit stop" [30].

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