International Journal of Railway Technology
Volume 5, Issue 1, Pages 23-52, 2016.
doi:10.4203/ijrt.5.1.2

SAXE-COBURG
PUBLICATIONS

Railway Wheelsets: History, Research and Developments

A. Bracciali
Dipartimento di Ingegneria Industriale
Università di Firenze
Italy

Abstract

The paper describes the history and the architecture of trailing railway wheelsets. Improvements in the design are described as well, showing remaining unsolved criticalities. Scientific literature on the subject is analyzed, highlighting the wide importance that axles still hold. Some relevant accidents resulting from of wheelset failures are described. A novel design of a wheelset studied to improve safety, reduce maintenance, and reduce LCC, is introduced.

Keywords: wheelset, safety, maintenance, life cycle cost, research.

1 Historical introduction

Stephenson's Rocket (Figure 1), built in 1829, is the locomotive that introduced many fundamental innovations and was considered the most advanced locomotive of its day [1]. Focusing on the running gear architecture, the subject of this paper, two different types of wheelset can be identified:

- the locomotive is equipped with wheelsets whose journal seats are located between the wheels, an arrangement known as "inboard bearings";
- the tender is equipped with wheelsets whose journal seats are external to the wheels, an arrangement known as "outboard bearings".

Inboard bearings were commonly used for steam locomotives with external cylinders for more than 150 years, as connecting and coupling rods were located external to the frame. Even the much more recent Sir Nigel Gresley's locomotive LNER Class A4 4468 "Mallard" (1938), holder of the speed record for steam locomotives at 202.58 km/h [2], used this arrangement (Figure 2).

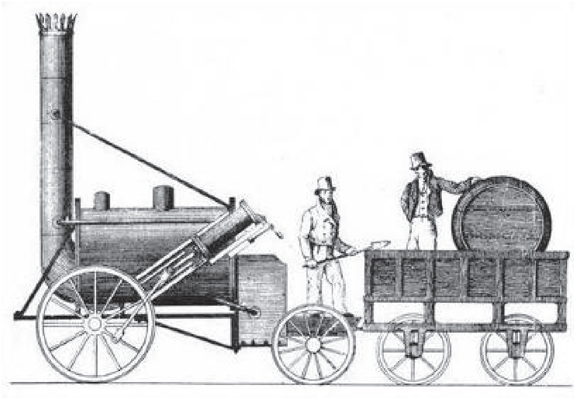

Figure 1: Stephenson's Rocket, built in 1829 for the Rainhill Trials held by the Liverpool & Manchester Railway in 1829 to choose the best design to power the railway [1]. Inboard and outboard bearings are present respectively on the locomotive and on the tender wheelsets

Figure 2: LNER Class A4 4498 "Sir Nigel Gresley", pictured with the celebrated steam locomotive designer. She is a sister of "4468 Mallard", the fastest and one of the most famous steam locomotives of all times [2]

Also, many steam locomotives with internal cylinders, equipped with a crankshaft for the driving axle, had external connecting rods and, therefore, inboard bearings (Figure 3).

As steam locomotives disappeared from normal service, leaving space for electric and diesel locomotives, the inboard bearings solution disappeared from more recent vehicles. Nearly all locomotives are, nowadays, equipped with outboard bearing wheelsets, as well as hauled vehicles of any shape and size. Nevertheless, there is a renewed interest in vehicles with inboard bearings, as described below.

Figure 3: Class 625 locomotive of the FS (Italian State Railways) pictured during a revival train (Bornato, Italy, 15.05.2005). Driving and coupled wheelsets pictured at the Historical Rolling Stock depot in Pistoia, Italy. Journal seats and crankpins for driving rods are clearly visible. Both photos by the Author

2 Technical description of modern trailing wheelsets

2.1 Classification

Only trailing wheelsets are considered in this paper, as their architecture is more general and widespread than driving wheelsets, for which the specific transmission arrangement leads to a variety of designs too large to be discussed here.

A simple but effective classification is shown in Figure 4. The two arrangements on the right are typical of low floor vehicles and may include a so-called “axlebridge”, an element that is similar to the “bridge” element normally used in lorries, where it includes the differential gearbox and the semi axles.

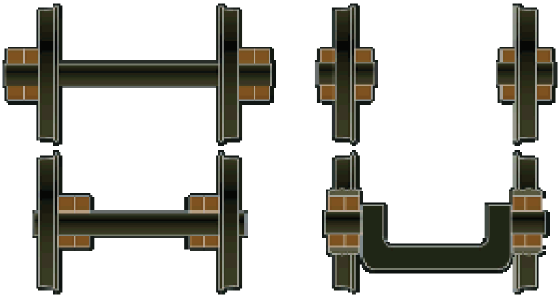

Figure 4: Wheelset classification. Left: outboard bearings arrangement (top) and inboard bearing arrangement (bottom). Right: independent wheel arrangement with bearings on both sides (top) and axlebridge design principle (bottom) (adapted from [3])

2.2 Modern trailing wheelsets technical description

A trailing wheelset (Figure 5) is conventionally intended as the appropriate combination of a rotating axle, two wheels fitted with interference on so-called “wheel seats” machined on the axle, and two external axleboxes, including rolling bearings mounted on “axle journals”.

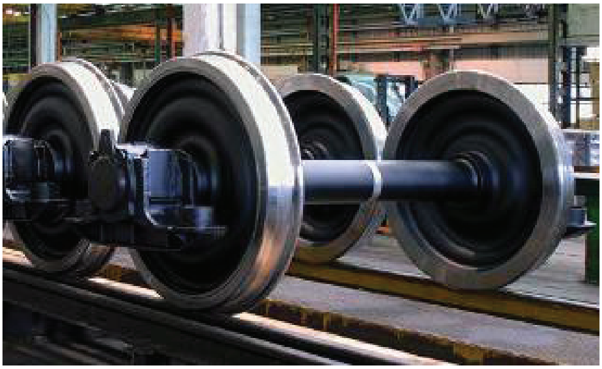

Figure 5: A railway wheelset for freight wagons. Rolling bearings apart, the design is exactly the same as the one used at the beginning of the railway age in the case of tyred wheels (source [4]). Braking is made through traditional tread braking

At the beginning of 20th Century, rolling bearings were also developed for railway applications (Figure 6). Because of the lower resistance to motions and lower maintenance, they soon supplanted sliding bearings. The use of rolling bearing units (“cartridges”) consisting of either two tapered rolling bearings mounted in a back-to-back (“O”), or two cylindrical rolling bearings arranged with a common outer race, is widespread nowadays.

Figure 6: Different types of composite bearings (left: spherical) and compact units (mid: cylindrical rolling, right: tapered rolling) (adapted from [3])

Wheel fitting on the axle, originally obtained by heating the wheels up to around 250 °C (“shrink-fit”), is nowadays almost supplanted by fitting at ambient temperature with hydraulic presses and a proper lubricant (“cold-fit” or “press-fit”).

Passenger cars are normally equipped with brake discs (Figure 7) which possess numerous advantages compared to tread brakes, mainly a higher braking power (more efficient cooling), a lower emitted noise (lower wheel roughness), and the absence of thermal loads induced in the wheels (no thermal power input in the treads).

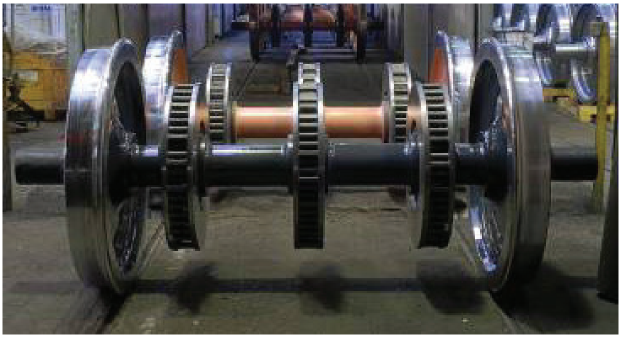

Figure 7: A railway wheelset for a high speed passenger car (source [4]). The use of brake discs started to grow in the ‘60s and is the standard for passenger vehicles nowadays

With regard to wheels, the transition from tyred wheels to monobloc wheels (Figure 8) is almost completed nowadays, mainly for market and maintenance reasons. The development of specific heat treatments allows it to reach compressive stresses in the rim (while the tyre is in tension, in the case of conventional tyred wheels) which are favourable against crack propagation. The development of specific (curved) web geometry enabled the development of so-called “low residual stresses wheels” that can also be used on tread braked freight wagons.

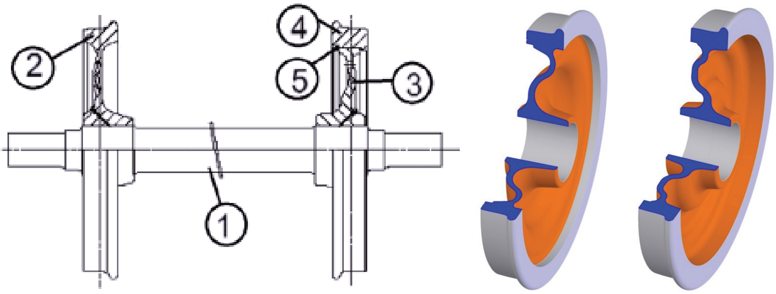

Figure 8: Left: different wheel types pictured on the same wheelset for description only (1: axle, 2: monobloc wheel, 3: wheel centre, 4: tyre, 5: retaining ring) [5]. Right: two different wheel web designs to reduce residual stresses in tread-braked heavy applications (freight wagons) [6]

To reduce fretting corrosion and to improve fatigue resistance, either a surface treatment of mating surfaces (*i.e.* wheel seats and journal seats) with a sprayed molybdenum coating [7] (Figure 9) or cold rolling [8], that leaves a favourable residual compressive stress after plastic deformation, are used.

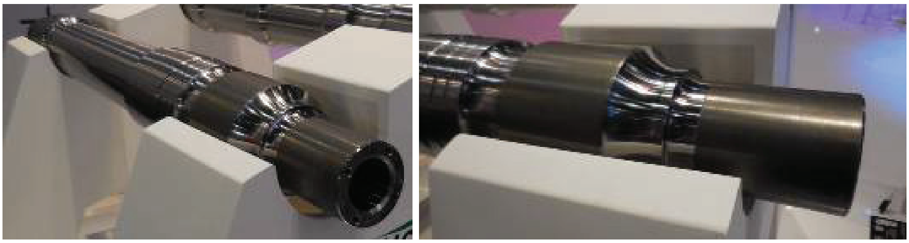

Figure 9: The driving wheelset of the ICx DB train on display at the Lucchini RS stand (Innotrans 2014, Berlin). Opaque grey Molybdenum coated surfaces are visible together with large axle bore (90 mm)

In the last thirty years, a continuously larger number of axles were produced with an axial bore, obtaining so-called “hollow axles”. This solution has not only the advantage of reducing unsprung masses by removing steel, which only slightly contributes to axle strength, but has the very interesting feature of giving access for ultrasonic probes to perform a non-intrusive NDT of the wheel seats (“boretest”), an area that on solid axles can only be inspected with angled UT probes after removing paint from the axle body (Figure 10).

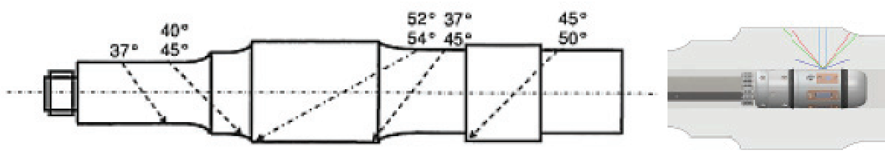

Figure 10: Conventional NDT oblique scanning check on solid axles by means of angled UT probes (left) and complete check of the axle from the bore by using a specific rotating UT probe (right). Sources: VPI04 (left), www.casoni.it (right)

Other wheelset developments worth mentioning are the many attempts to reduce rolling noise ([9], [10]), one of which is shown in Figure 11. Resistance against ballast impacts is obtained by treating the axles with coatings made of high thickness paints (Figure 12). In both these applications, the ability to inspect must be guaranteed; for example, thick protective coatings are possible only if hollow axles are used.

The most important differences between old and modern wheelsets can then be summarized as follows:

- use of rolling bearings;
- use of tread braking almost confined to freight wagons;
- improvement of fretting behaviour of seats by coating;
- improvement of fatigue behaviour on free surfaces by cold rolling;
- lighter design thanks to the adoption of hollow axle;
- better ability to inspect by UT with "boretest";
- reduction of emitted rolling noise;
- axle protection from ballast impacts.

Figure 11: Application of damping treatment on the wheel web of a high-speed train wheelset in order to reduce wheel vibrations and therefore emitted noise (*Syope* treatment, Lucchini RS, [4])

Figure 12: Application of anti-ballast shock protection layer on the axle (*Lursak* treatment, Lucchini RS [4], [11])

2.3 Modern wheelsets with inboard bearings

Vehicles which have wheelsets with inboard bearings are particularly common in the UK because of their reduced track access charges as a result of their higher track friendliness. A short market analysis which reports on the most recent rolling stock using inboard bearings, is shown in [13]. Outside the UK, probably the most interesting application is the Deutsche Bahn ICx trainset. Some pictures of this train and some inboard bearings bogies are shown in Figure 13 and in Figure 14.

Figure 13: The new ICx trainset for German Railways DB. Left: a trailing bogie (*FlexxECO* made by Bombardier Transportation) and a motor bogie (made by Siemens AG) on two adjacent cars. Right: the driving trailer car equipped with *FlexxECO* bogie

Figure 14: Detail of the trailing bogie Bombardier *FlexxECO* for ICx (left) and Siemens Desiro City Thameslink (right) (Innotrans 2014, Berlin)

Wheelsets with inboard bearings (Figure 15) are favourable from the axle stress point of view, as lateral forces reduce the bending moment on the axle (Figure 16). The European standardization of the inboard bearings wheelset is in progress within CEN/TC256/WG11 at the moment, while a British Standards already exists [15]. Siemens and Bombardier applied the European Railway Agency and received a response (ERA-ADV-2012-2) from the European Commission/DG MOVE to accept their proposal.

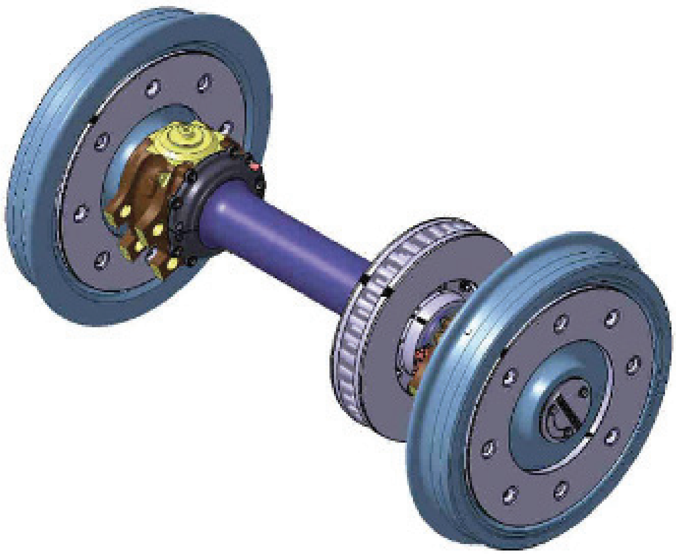

Figure 15: The inboard bearings wheelset that equips the *FlexxECO* bogie [14]

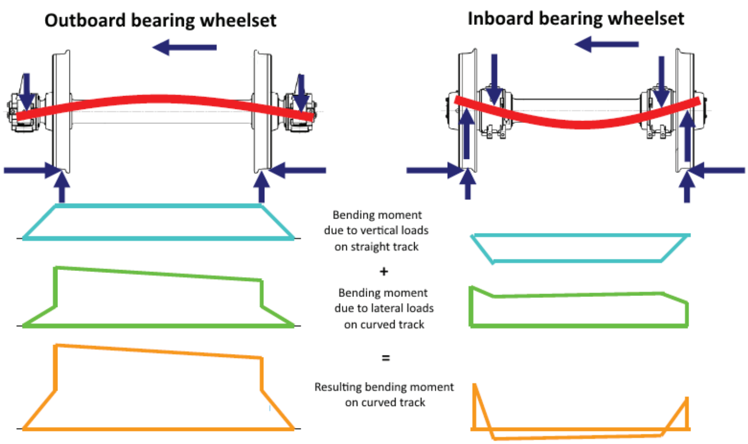

Figure 16: Bending moments on axles with outboard and inboard bearings (adapted from [14])

2.4 Independently rotating wheel (IRW) arrangements

A further architecture worth mentioning here is the one that is typical of vehicles with a low floor, *e.g*. many trams, where the need to eliminate the axle and to use wheels of small diameter leads to special arrangements. In this case, the wheels house the bearings and are “disconnected”, generating the so-called Independently Rotating Wheels solution, or IRW for short (Figure 17).

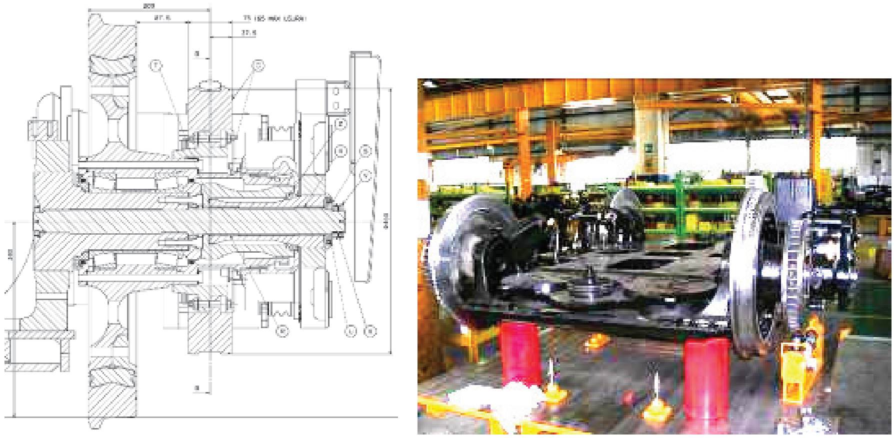

Figure 17: Typical arrangement of a low-floor tram (FIAT CitiWay for ATAC Rome series 9100). An elastic wheel with tapered rolling bearings mounted on an axlebridge can be seen in the section on the left. The bogie is shown on the right. Brake discs are external to keep the floor low

Solutions in which IRW are connected through transmission elements are common in low-floor vehicle motor bogies (see an example in Figure 18). This arrangement is limited to low-speed low-axleload vehicles running in tight curves (the transmission is often equipped with differential gearboxes and/or clutches) and is used only on motor bogies that, as already stated, are not further addressed in this article.

Figure 18: Driving axle of the AnsaldoBreda Sirio vehicle. The shaft connecting the two wheels is in the foreground [4]

IRW potentially avoid undesired hunting motions at high speed and improve curving behaviour. This solution was, therefore, thoroughly investigated in the second half of the last century.

As shown in [12] and in [13], the practical absence of hunting was confirmed. Nevertheless, the intrinsic attitude of the bogies equipped with IRW was to run skewed, *i.e.* with one or more wheel flanges in continuous contact with the rail gauge corner, was extremely pronounced. Any attempt to put ordinary railway rolling stock with IRW into service was abandoned more than 30 years ago. The use of bogies equipped with IRW is, therefore, confined to urban vehicles.

2.5 Independently rotating guided wheels (IRGW) arrangement

A special layout for IRW is the one adopted and patented by the Spanish company Talgo. It produces train sets with IRW mounted on short axles supported by two bearings each (top right in Figure 4, Figure 19). The rigid frame that houses the IRW is guided by rods connected to the carbody of the adjacent vehicles in order to keep the "virtual axle" radial regardless of the actual curve radius. The Talgo arrangement (known as rodal) is often named as Independently Rotating Guided Wheels to highlight the concept that the wheels, although independent, cannot assume an arbitrary position but are guided by the aforementioned rods.

This arrangement has several advantages, *e.g.* the intrinsic absence of hunting bogie motion and lower track forces (longitudinal forces are eliminated). As a result of the height of secondary suspensions, the vehicle is naturally (passively) tilting. Drawbacks are the shorter length of the carbodies (supported in practice each by one wheelset) and the incompatibility of these trainsets with other existing rolling stock.

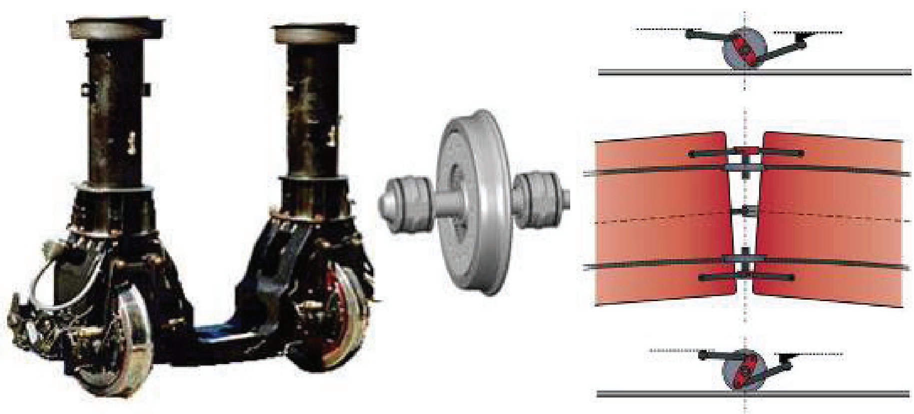

Figure 19: Talgo rodal arrangement where IRW are mounted on a rigid frame (left) and details of the short axle (centre). Linkage mechanism that steers IRW (right). A low-floor passageway between adjacent cars is possible

2.6 Conclusions on existing railway wheelsets

It can be concluded that:

- modern trailing wheelsets, although "improved" or "refined" in many aspects, still keep the same architecture of the wheelset as was conceived at the beginning of the railway era;
- wheelsets with inboard bearings will likely be more widespread in the future;
- IRW had no practical use for conventional railways (vehicles with bogies) as the absence of the torsional link between the wheels is beneficial on running dynamics but absolutely negative on wheel flange wear;
- in "heavy" railways only the Talgo vehicles adopt IRW, but with a specific concept that is totally different from the conventional railway practice;
- the use of IRW is limited to trams or the like, where low-floor is mandatory and the wear is limited as a result of low speed and low axleloads.

3 Review of R&D literature on wheelsets

3.1 Choice of the source of data

Papers on wheelsets are published in many scientific journals and it is almost impossible to trace them all. The European approach to collaborative research, which has passed through several instruments, such as *e.g.* the "Framework Research Programmes" in the past, and is now with the "Horizon 2020" programme [16], deeply involved many academic institutions (universities, research centres) in the development of the railway system.

A fundamental distinction should be made between the different goals for publications as seen by academics and the industry:

- both need to report on the outcomes of their research, according to a "dissemination plan" which is evaluated by the European Union during the project approval procedure;
- academics often publish intermediate or "more complex" results in high "impact factor" journals [17] in order to increase their bibliometric position, mainly useful for public selections to achieve higher positions in the academic hierarchy (*e.g.* the status of "Professor");
- the industry is seldom interested in the results published in journals of high academic reputation which look abstruse and completely extraneous to business;
- the preferred way to share knowledge within the technical community is still the formula of International or World Congresses, where specialists can submit their papers and contributions, often without a "peer-review" process as, in any

case, the quality of a contribution is immediately recognized during the congress by the specialists;

- the industrial communications and development reports often have a large impact on practical applications. They hardly ever find room in high reputation journals which are very likely to reject them or, in the most optimistic case, mark them as "case studies", often with contempt.

The railway industry is represented in Europe by UNIFE, the association of the European railway supply industry. Within UNIFE, the European Railway Wheelsets Association (ERWA) "... aims at promoting usage benefits, life cycle cost improvement and standardisation of railway wheels and wheelsets ..." [18]. ERWA was funded during the 13th Wheelset Congress, held in Rome in 2001.

The International Wheelset Congress (IWC) was founded by the now Lucchini RS in 1963. The first congress took place in Bergamo, Italy, in that year. Since then, with only two exceptions, it was held every third year. As "the oldest railway technical conference in the world" [19], it seemed worthwhile analyzing the papers presented there. The scope of the congress was, at the beginning, only industrial, although, nowadays, it attracts papers written in collaboration with universities. The next IWC will be held in Chengdu, China, on 7-10 November 2016 [20].

To restrict the field of the analysis, but considering, in any case, that the railway sector is rather conservative and that developments need normally over ten years to become widely spread and adopted, the proceedings of the last five editions were reviewed:

- 13th IWC, Rome, Italy, 17-21 September 2001;
- 14th IWC, Orlando, FL, USA, 17-21 October 2004;
- 15th IWC, Prague, Czech Republic, 23-27 September 2007;
- 16th IWC, Cape Town, South Africa, 14-19 March 2010;
- 17th IWC, Kiev, Ukraine, 22-27 September 2013.

Considering the 3 year interval between conferences, it may be said that this analysis covers the last 15 years of industrial development in the wheelset field.

3.2 Analysis of papers presented at IWC 2001-2013

Papers given at 13th-17th IWC were categorized according to their title. Where the attribution was not straightforward, *e.g.* with papers such as "Assessment of Crack Initiation and Propagation from Press Fits of Railway Axles" that could possibly fit into two or more categories, the full papers were analysed and a final decision was taken. As with any decision process, if repeated by other people, it could lead to slightly different results. It is, nevertheless, believed that the results would substantially be the same.

The results of this analysis are shown in Table 1. The following conclusions can be drawn:

	Conference number	IWC 13	IWC 14	IWC 15	IWC 16	IWC 17		All editions		Group 1	Group 2
	Total # of papers	72	67	66	48	37	%	290	%		
Code	Description										
FAT	Fatigue and fracture	6	10	11	5	11	30%	43	15%		
NDT	NDT	6	10	10	8	1	3%	35	12%		
M	Materials	5	6	5	3	5	14%	24	8%		
LC	Life & Cost	8	2	2	5	5	14%	22	8%		
P/M	Production / Manufacturing	7	2	7	2	1	3%	19	7%		
D	Design	2	6	3	4	1	3%	16	6%	221	76%
N	Noise	2	3	4	4	1	3%	14	5%		
RCF	RCF	2	5	3	3	0	0%	13	4%		
L	Loads	3	3	4	1	2	5%	13	4%		
FIT	Press-fit	0	2	4	3	2	5%	11	4%		
BEA	Bearings	3	4	2	2	0	0%	11	4%		
R	Residual stresses	2	1	4	0	2	5%	9	3%		
B	Braking	3	2	1	2	0	0%	8	3%		
DYN	Dynamics	7	1	0	0	0	0%	8	3%		
W	Wear	1	4	0	1	0	0%	6	2%		
TFAT	Thermal Fatigue	1	0	0	2	2	5%	5	2%		
WF	Wheel flats	2	1	2	0	0	0%	5	2%	59	20%
MON	Monitoring	3	1	0	0	1	3%	5	2%		
C	Corrosion	0	1	2	0	1	3%	4	1%		
PROF	Wheel profile	2	1	0	1	0	0%	4	1%		
S	Return from service	0	0	0	1	1	3%	2	1%		
ADH	Adhesion	1	0	1	0	0	0%	2	1%		
DISC	Brake discs	0	1	0	0	0	0%	1	0%		
O	Other	6	1	1	1	1	3%	10	3%	10	3%
(A)	Papers about axles	3	7	16	10	12	32%	48	17%		

Table 1: Analysis of the papers given at 13th-17th IWC, sorted in decreasing order of percentage for all editions

- the number of presented papers is decreasing. This may reflect a tendency because of the state of the world economy after the 2008 crisis (66 papers in 2007 and only 48 in 2010, with a minimum of 37 in 2013);
- fatigue/fracture and NDT are the only two topics which are consistently the preferred subjects for R&D with a total number over 10%. Materials, life & cost and Production/Manufacturing are over 7%, identifying how economic indicators are important in industry papers;
- at the last conference the papers on fatigue/fracture were 30% of the total;
- some categories tend to fade away. It should not be forgotten that other scientific (International Workshop on Railway Noise – IWRN, Contact Mechanics and Wear of Rail/Wheel Systems – CM, International Association of Vehicle System Dynamics – IAVSD) and railway (World Congress on Railway Research – WCRR, International Conference on Railway Technology – ICRT, EuroBrake) conferences may look more attractive to some authors who may decide to publish the results of their activities elsewhere;

- categorized papers were (arbitrarily) grouped in those with more and those with less than 4% of total papers presented. Group 1 (≥ 4%) counts 76% of the total number of papers, Group 2 (< 4%) counts 20% of the total number of papers;
- a limited number of papers (10, around 3% of the total) that do not fit in any category (such as papers on rails or on track conditions analysis) are considered only for completeness;
- the last line of the table separately indicates how many papers are focused on axles. It can be observed that the axle is by far the most important component of the wheelset, attracting 17% of the total number of papers given to the 5 considered conferences, and even 32% of the last edition. This may also be as a consequence of the serious accidents resulting from axle failures that will be analysed later.

4 Risks associated with the current wheelset design

4.1 Introduction

Railway wheelsets are safety critical components. As long as the wheelset cannot be duplicated and, therefore, a fail-safe strategy cannot be adopted, safety can be obtained only through a severe and rigorous inspection plan with the use of many non-destructive testing technologies, such as Visual Testing (VT), Magnetic particles Testing (MT), and Ultrasonic Testing (UT).

It should be remembered that the concept of "zero risk" is intrinsically impossible in any mechanical system, *i.e.* the probability of failure, intended as the mathematical function that describes the possibility of it happening, can never be zeroed. That's why "risk management" is so fundamental for all railway components, specifically for axles.

Although the useful life of some axles may be rather long (the case of 30-year old axles is not sporadic), wheels and bearings may fail in service and need regular checks as well. It should be said that none of the components of a wheelset is less important than the others. A failure in the axle, in one of the wheels or in one of the bearings, leads almost inevitably to a derailment.

Axles are historically the weakest component of the wheelset. The Meudon accident on 8 May 1842, known also as "the Versailles accident", was as a result of a broken axle and led to the researches performed by August Wöhler which are still the basis of the knowledge of materials fatigue (Figure 20). Stresses reverse every half cycle ("rotating bending") and this makes the axle a component prone to failure in service. This is why regulations impose that maximum stresses are limited and that materials with well known crack propagation rules are used.

Despite almost two hundred years of development, statistics say that broken axles still represent a quite common event. A very interesting report of the ESIS/TC24 [22] indicates as 78 the number of broken axles in 2006, 103 in 2007, and 104 in

2008. More recent statistics can be found in the 2014 biennial report of ERA on railway safety [23], where the precursors to accident are shown in Figure 21.

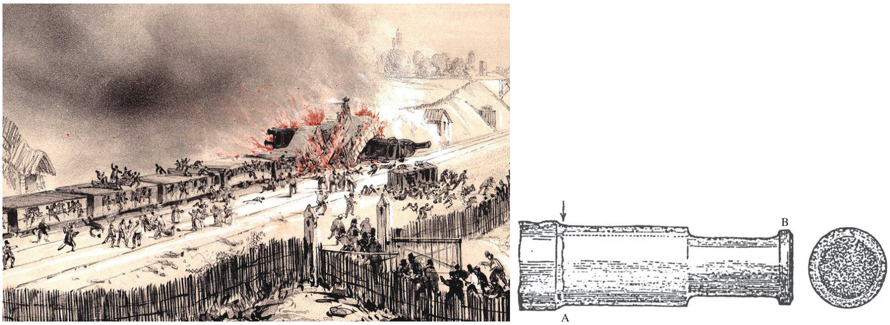

Figure 20: The Meudon accident (left) and the sketch of a broken axle (right) [21]

Table 8	Number of precursors to accidents																												
Precursors to accidents	Year	AT	BE	BG	CT	CZ	DE	DK	EE	EL	ES	FI	FR	HR	HU	IE	IT	LT	LU	LV	NL	NO	PL	PT	RO	SE	SI	SK	UK	All	EU-27
Broken Axles	2010	0	0	1	0	2	4	9	0	1	0	0	2		1	0	5	0	0	0	0	5	23	0	0	4	0	0	0	57	52
	2011	1	0	2	0	3	3	14	0	2	0	0	0		0	0	1	0	0	0	0	1	3	0	0	4	0	0	0	34	33
	2012	1	0	27	0	0	0	7	0	0	0	1	0		1	0	20	0	0	0	0	2	3	0	0	1	0	1	0	64	62

Figure 21: Broken axle precursors to accidents in the EU in the 2010-2012 period (excerpt adapted from [23])

4.2 Some accidents involving axles

Two accidents in 2008 and 2009 were particularly severe in terms of consequences, either potential or, unfortunately, real.

The first accident happened on 9 July 2008 at the central station in Köln, Germany, and affected a driving axle of an ICE3 trainset (Figure 22).

Figure 22: Broken axle of the IC518 ICE3 train in the Köln main station, 9.7.2008. Left: the broken driving axle seen from the internal side. Right: investigators looking at the derailed train [24]

Luckily the train derailed as a result of the broken axle when it was running on the switches at very low speed and, therefore, there were no major consequences. A very interesting failure analysis is reported in [24], which states: "...immediate measures: substantial reduction of UT-inspection interval (EBA 10.7.2008: UT of all axles made of 34CrNiMo6 60.000 km instead of 300.000 km), currently: 30.000 km" and: "all ICE3 driving axles will be changed".

A less fortunate case is the axle failure which was responsible for one of the most tragic railway disasters which happened in Europe in the last decade. The freight train 50325 Trecate-Gricignano, composed of a locomotive and 14 tanks carrying LPG, derailed in the Viareggio station, Italy, on 29.6.2009 (Figure 23 and Figure 24).

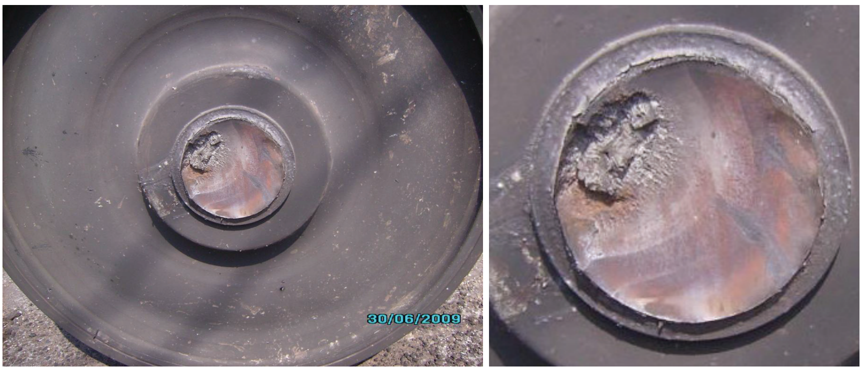

Figure 23: Broken axle that caused the Viareggio accident (left) close-up of the fractured section (right)

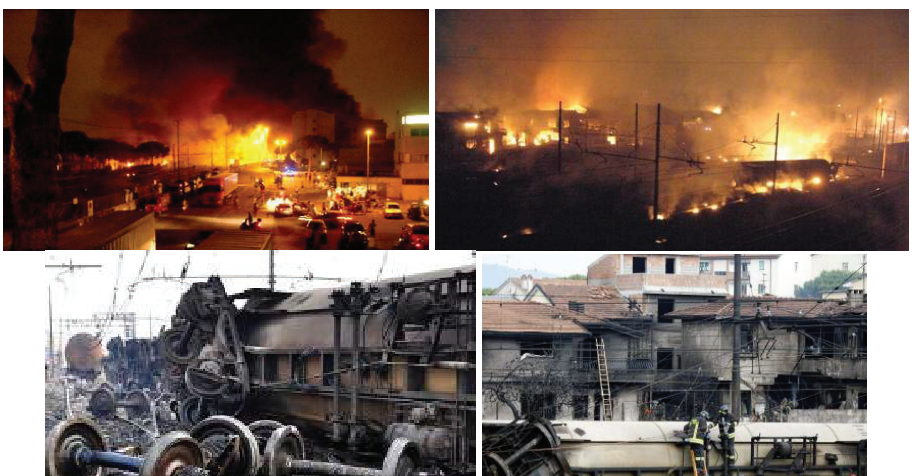

Figure 24: Some snapshots of the apocalypse which struck the peaceful town of Viareggio during the warm summer night of 29 June 2009

The derailment was as a result of the sudden failure of the leading axle of the first wagon. After the derailment, the tank wagon overturned and started leaking LPG which, after a few minutes, caught fire, burning a large area around the railway station and killed 32 people. Many more were injured with severe burns. The criminal trial is still in process to ascertain who was responsible for this accident.

4.3 Modern approaches to axle integrity

Any non-destructive technique has a detection threshold*, i.e.* the minimum size of the defect that can be observed in practice. UT devices used for axle integrity checks are calibrated by using sample defects machined on a specimen made of the same material as the axle to ensure exactly the same ultrasonic characteristics of the steel.

As with any other experimental, non-destructive technique, UT supplies information (known as "indications") with a non eliminable degree of uncertainty. This means that the so-called Probability of Detection (PoD) depends on many factors (see [25] for an extensive explanation about PoD derivation, applications and limitations). An interesting paper about the application of the PoD approach to railway axles can be found in [26].

Although deterioration progresses continuously, no on-board monitoring techniques are currently available to check in real-time the propagation of axle cracks. They can only be inspected at predetermined intervals by using the previously mentioned equipment. In case a crack of the size below the detectability threshold is present at a certain inspection, the interval should ensure that this crack does not propagate, breaking the axle before the following inspection (Figure 25). As seen, the consequences of a misconducted NDT testing, or an underestimated crack propagation law, can be tragic.

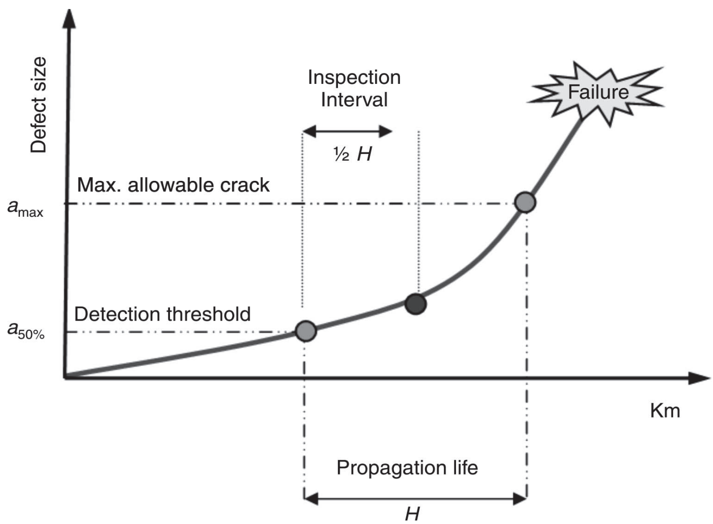

Figure 25: Crack propagation curve and inspection interval definition [27]

Axle fatigue fracture is always brittle and sudden, despite the fact that the steels for axles have a rather limited ultimate tensile stress and a high ductility. The analysis of fractured surfaces shows that this is the one typical for shafts subjected to rotational bending under low nominal stresses and mild stress concentrations (Figure 26). Failures normally happen in transition zones. That's why the design of fillets and abutments is somewhat critical in axle design. It is interesting to observe that from failure analysis it appears that torsion does not play an important role in fatigue, even in driving axles.

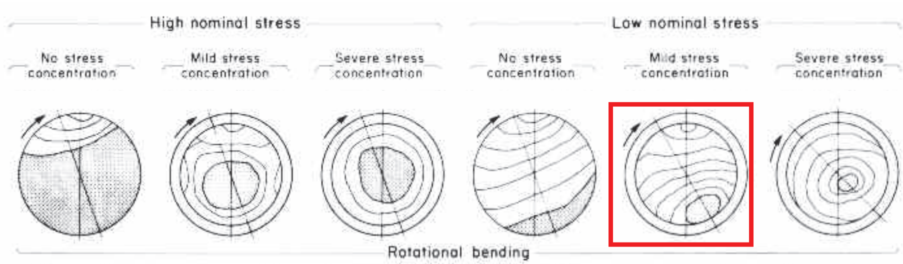

Figure 26: Schematic of marks on surfaces of smooth and notched shafts under various loading conditions [28]

5 Wheelset maintenance

Maintenance is a topic which is completely missing in the list of research and development categories mentioned in Section 3. It is obvious that although the argument is particularly important in times of crisis, it is of low interest to the community of researchers, although from industry.

It is a common experience that maintenance costs drive more and more railway practices. The typical structure of the maintenance cycle of a wheelset consists of mainly three phases:

1. regular checks in service to look for abnormal profile wear and running table wear and RCF defects, and/or bearings overheating;
2. wheel reprofiling by underfloor lathes in "first level" workshops (typically located in larger depots and spread over a country);
3. shipment of the entire wheelset to a "second level" workshop (either belonging to the Train Operating Company or an external mechanical workshop) for the complete overhaul when wear has reached its maximum level (*i.e.* wheels cannot be further reprofiled), running table defects cannot be rectified (*e.g.* too large wheel flats) or simply because the prescribed interval (time) or life (km) run by the wheelset has reached the limit indicated in the maintenance plan.

Second level workshops handle complete wheelsets disassembling the axleboxes, the bearings, and the wheels from the axle and then performing VT, UT, and MT on the axle. Old wheels are pressed off by cutting or by oil-injection methods, while new wheels are fitted according to one of the aforementioned practices (press- or shrink-fit) and then turned by conventional lathes.

It is evident that this maintenance scheme is well functioning but forces the moving of heavy and bulk wheelsets to specialized workshops where expensive tools and equipment are needed (heating ovens / hydraulic presses, large size lathes).

The total absence of literature in this subject leads us to suppose that there is a sort of "resignation": wheelset maintenance is expensive, time consuming, complex to organize, involves large capital and human resources but "we have done so for almost 200 years" and "there is no other way to do it".

6 The inglorious end of some developments

Engineers always search for better solutions to win the competition on the market. Wheelsets belong to the category of objects that, being hidden to the final customer (the traveller), are interesting only if they bring technical improvements. These improvements may be linked to a number of factors (cost, maintainability, weight, *etc*.). Two cases of technically interesting solutions developed in the past are described in the following.

6.1 High strength axles

Railway axles are historically produced according to UIC standard 811 [29], which originally specified five steel grades (A1=C35, A2=22MnCrV5, A3=C45, A4=25CrMo4, A5=42CrMo4). European standards on axles were later developed by CEN for design (EN 13103 / EN 13104) and for manufacturing (EN 13261) including only A1 and A4 steel grades. The design of axles is based on EA1N for which fatigue limits and safety factors are available, while adjustments are described in order to evaluate the safety factor and permissible stresses for other steel grades (EA4T and EA1T)

Alloying and thermal treatments are common methods to obtain steels with better performances. This allows the design of optimized components. Fiat Ferroviaria (today Alstom Ferroviaria), in the '70s started developing the well-known and successful Pendolino trains family for Italian Railways, proposed to use the high strength alloyed steel 30NiCrMoV12 [30] to design an optimized wheelset, achieving a substantial mass reduction. According to [31], a reduction of more than 20% in the axle mass can be obtained designing an axle with 30NiCrMoV12 instead of A4T, and more than 30% instead of A1N. A comprehensive description of the properties and the advantages offered by this steel is also presented in [31].

On their side, German Railways (DB) made use of 34CrNiMo6 alloyed steel for the driving axles of the ICE3 train (trailing axles are made of A4T). These axles are designed according to "Techn. Spezifikation /Liefervorschrift für Radsätze ICE 3 - 03/97" (see [24]) which refers to the EN standard [32] of steels for quenching and tempering for the definition of the mechanical properties of the steel.

Table 2 summarizes the mechanical properties of the mentioned steel grades.

Steel grade	**Applicable standard**	**Type**	**R_{eH} [MPa]**	**R_m [MPa]**	**A%**
EA1N	EN 13261	0.35 %C	>320	550-650	22%
EA1T	EN 13261	0.35 %C	>350	550-700	24%
EA4T	EN 13261	25CrMoV	>420	650-800	18%
30NiCrMoV12	UNI 6787-71	High-strength Alloyed	>834	932-1079	15%
ICE 3 driving <160 mm	EN 10083-1	34CrNiMo6 Alloyed	>700	900-1100	12%
ICE 3 driving >160 mm	EN 10083-1	34CrNiMo6 Alloyed	>600	800-950	13%

Table 2: Mechanical properties of several steels for railway axles

Unfortunately, the accident described in [24] forced DB, as mentioned above, to change all driving axles of the IC3 for A4T (to the author's knowledge the change is still in progress at the time of writing). Even the new high speed train V300Zefiro (made by Bombardier and AnsaldoBreda, branded "Frecciarossa 1000" by Trenitalia SpA, which entered into service on June 2014) makes use of A1N axles.

Except for spare parts, the two countries, which in the 20th Century led the way to high strength axles, reversed to A1N, A1T, and A4T steel grades. The balance between the worst fracture mechanics properties and the better (lighter) designs, eventually ended in the safer conservative choice.

6.2 Elastic wheels

So-called "elastic wheels" are common in metros, trams, and light rail vehicles because of the uncoupling of the rim and wheel web offered by interposed rubber elements. Several solutions are available on the market, but, in the following, we will only refer to the application used on modern high-speed trains.

Deutsche Bahn applied the concept of elastic wheels, named BA 064, to ICE1 trainsets in the attempt to reduce abnormal vibrations detected when the original monobloc wheels were used. An accident happened to ICE 884 Munich-Hamburg in Eschede, Germany, on 3 June 1998 killing 101 people [33] (Figure 27).

The official investigation was, obviously, rather long. Paper [34] indicates that the tyre split as a result of a fatigue failure that initiated in its internal part. Although all the wheels that were subsequently examined did not show any crack or progressive defect, supporting "the presumption of a rare or singular event which could have initiated the crack", DB immediately retired all the wheels, marking the end of the only conventional railway application of an elastic wheel.

Figure 27: Sketch of the BA 064 wheel (left, from http://www.ndt.net/news/2000/eschedec.htm). An image on the aftermath of the disaster (centre, from http://uncyclopedia.wikia.com/wiki/File:Eschede-1.jpg). Fractured tyre section (right, from http://www.soue.org.uk/souenews/issue6/jenkinlect.html)

7 Shrink fit, press fit or misfit?

As described in Section 2.2, wheels were originally shrink-fitted on axles by heating them up to 250 °C and then letting them cool down in the correct position. This practice is energy consuming and time expensive, so it was slowly abandoned in favour of press-fitting, *i.e.* a cold process where fitting with prescribed interference is obtained by sliding the wheel on the lubricated wheel seat.

The scope of this shaft-hub coupling is quite unusual in machine design, as it is designed to transmit both vertical and lateral loads under high bending stresses and relatively high torques. This is why the design of wheel fitting requires great experience to avoid undesired consequences. Historically, the UIC regulation on wheel fit on axles was extremely detailed and defined tolerances, temperatures (for shrink-fitting), lubricants, and press-fitting curve properties (for press-fitting) ([35], [36]).

In the translation process of UIC regulations to EN standards ([37], [38]), these prescriptive specifications were relaxed, opening the field to new materials and to a different approach to the definition of the press-fitting curve.

Some accidents happened in the last years as a result of a wrong fitting process. In a case, which the author has already discussed [39], the accident that happened on the Brenner line on 6.6.2012 (Figure 28), several wheelsets displaced laterally resulting in the derailment of several wagons of a train carrying scrap steel. In another case (Maccarese, Italy, 10.02.2010), the wheel of a passenger car moved towards the axlebox and the wheelset derailed on a switch (Figure 29). In Verona, quite recently (13.02.2015), a freight wagon derailed in a marshalling yard as both the wheels of a wheelset displaced laterally leading also, in this case, to a too small wheelset gauge (Figure 30).

Figure 28: Displaced wheels from the wheelset on the first wheelset of the wagon (left). Aspect of the surface after wheel displacement revealed no defects or damages typical of wheels pressing off (right) [39]

Figure 29: Displaced wheels towards the axlebox of a passenger car (left). Aspect of the wheel bore after dismounting during the investigations (right) [40]

Figure 30: Both wheels displaced of a freight wagon in Verona (13.02.2015)

A different type of damage is seldom observed during press-fit mounting as a result of conditions that are sometimes hard to discover. Figure 31 shows the consequences of a wrong press-fitting procedure applied on a passenger car axle. In some cases, this damage can be fixed, but in most cases both the axle and the wheel(s) must be scrapped, with evidently high costs.

Figure 31: Consequences of a misfit of a wheel on a wheelseat. The deepest grooves are originated by the wheel removal process (photo by the author, 2013)

Another problem has been quite recently reported in Germany in which abnormal torsional loads led to a relative rotation between the axle and the wheel (Figure 32). Although this inconvenience did not lead to any derailment or any other major consequence, the design process of driving axles is under revision. The typical fitting diameter, originally in the range 190-200 mm also for locomotives, was increased beyond 230 mm (*e.g.* the driving axle of ICx has a seat diameter of 236 mm). When disc brakes are fitted on the axle, their seats are obviously bigger (245 mm in the case of the ICx), leading to axles whose mass approaches 500 kg.

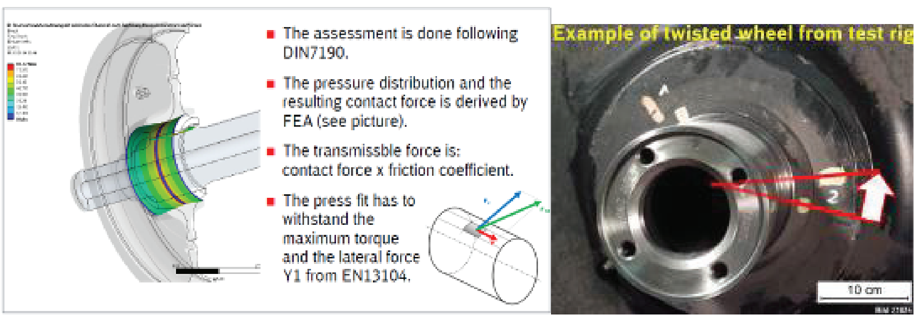

Figure 32: Relative wheel – wheel seat rotation as a result of excessive torsional loads [41].

All these problems descend from the fact that both torque transmission and correct positioning are a combination of the interference and the actual friction coefficient. This is quite different from many mechanical applications where torque is transmitted "positively" (*i.e.* through mating surfaces) and the limit torque is determined by strength considerations rather than by the available friction, which is always uncertain. As a partial remedy, the CEN/TC256/WG11 "Wheelsets" is re-drafting the EN standard on wheelsets [42] "going back" to the original UIC provisions which, for example, allowed only the use of tallow, vegetable oil, vegetable oil + tallow and molybdenum disulphide as lubricant agents during press-fit.

As a (worrying) conclusion on the subject, it should be highlighted that, where known, press-fit diagrams showing pressing force vs. displacement of the mentioned “loose” wheels all fulfilled the requirements of [37] or [38].

8 Axles --- can we do without?

On 17 June 2002 a Lockheed C-130A, N130HP, broke apart in flight while executing a fire retardant delivery near Walker, California. As indicated in the official investigation report [43], the cause was “the in-flight failure of the right wing as a result of fatigue cracking in the centre wing lower skin and underlying structural members. A factor contributing to the accident was “inadequate maintenance procedures to detect fatigue cracking.”. The whole event took about 4 seconds and was captured on video by a passer-by (Figure 33).

Figure 33: Frame taken from the video of a Lockheed C-130A that crashed as a result of a fatigue failure of wings [44].

As long as planes will have wings, accidents like this one may happen, but it is clear that a plane needs wings to fly just as a train needs wheels to travel (unless magnetic levitation is considered, but this is not covered in this paper). So, the main question is: can we imagine a wheelset without rotating axles? And can it be a wheelset whose wheels are not independent, in order not to incur the drawbacks shown in Section 2?

Recently, the author proposed a wheelset arrangement [45] in which wheels equipped with rolling bearings are mounted on stub axles, similar to conventional IRWs and are connected by a torsionally shift shaft and a torque limiter [13] (Figure 34). The design is intended to reduce maintenance as the wheel can be disassembled, overhauled, or replaced with a procedure that is very similar to the one used for lorries, *i.e.* the bogie frame only needs to be lifted and some screws removed to extract the wheel, including the bearings and the brake discs. All serviceable parts are, therefore, accessible together.

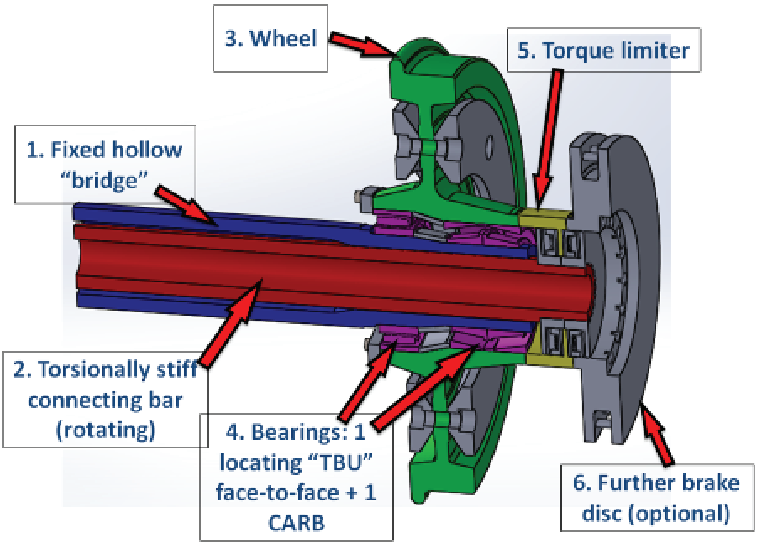

Figure 34: A recently proposed layout with partially independently rotating wheelsets [13]

The design applies only to vehicles with inboard bearings (or, better, inside frame bogies), an architecture that, as already discussed, is gaining favour for the high track friendliness of this type of bogie. A review of the current status of the technology and market of inboard bearings bogie frames is given in [13].

The size of the connecting shaft was known to be critical as the critical speed of the vehicle decreases with the shaft torsional stiffness. Nevertheless, paper [46] shows that the proper running dynamics behaviour in both tangent and curved track can be ensured by a proper design of the connecting shaft and by the proper setting of the maximum torque transmitted by the torque limiter.

Paper [47] describes the impact of the solution on wheel/rail contact forces, showing that there are no major drawbacks with the torque limited arrangement and that, on the contrary, this arrangement may be beneficial in reducing rail damage as a result of too high longitudinal forces which happen in tight curves for high adhesion limits.

Paper [48] describes the assumption and the design of the torque limiter, whose functionalities are central to the success of this new wheelset, while maintenance and LCC issues will be described in paper [49].

Although apparently promising, no conclusions can be drawn at the moment about the real applicability, or on the performance of this novel wheelset arrangement.

9 Conclusions

This review paper has described the current trailing wheelset practice for mainline railway vehicles. It was shown that the modern wheelsets incorporate a certain number of improvements but the original design that dates back to the origin of railways is still holding on for several reasons.

Research and technical publications on wheelsets were discussed, showing a prevalence of papers on axles. Axles, in fact, remain a critical component of wheelsets after almost 200 years from the beginning of the railway era. Failures of different kinds, and criticality in the wheelset assembly, were shown.

The paper ends with a description of a new wheelset which could reduce the risks of failure in service, while reducing maintenance costs significantly.

Acknowledgements

The author acknowledges the help and would like to thank Dr. Stefano Cantini and Dr. Steven Cervello (Lucchini RS), Dr. Rocco Cammarata (ANSF), Mr. Mauro Monti (Polfer), Dr. Mattia Macherelli and Dr. Gianluca Megna (University of Florence), the entire WG11 group of experts.

References

[1] https://en.wikipedia.org/wiki/Stephenson's_Rocket, accessed on 23.08.2015.
[2] https://en.wikipedia.org/wiki/LNER_Class_A4_4468_Mallard, accessed on 23.08.2015.
[3] SKF, “Railway Technical Handbook, Volume 1, Axleboxes, wheelset bearings, sensors, condition monitoring, subsystem and services”, page 30, July 2011. ISBN: 978-91-978966-3-4
[4] www.lucchinirs.it, accessed on 23.08.2015.
[5] CEN - European Committee For Standardization: “FprEN 15313:2015, Railway applications - In-service wheelset operation requirements - In-service and off-vehicle wheelset maintenance”, July 2015.
[6] http://www.bonatrans.cz/en/products/for-freight-transport/bonatrans-stress-optimized-wheels-and-wheelsets, accessed on 01.10.2015.
[7] M. Kašparová, F. Zahálka, Š. Houdková, “Thermally Sprayed Coatings For Railway Applications”, 20th annual conference METAL 2011, Brno, Czech Republic, 18-20 May, 2011.

[8] M. Carboni, “MARAXIL Project - Effect of cold-rolling onto axle life prediction”, ESIS TC24 Workshop, Milano, Italy, 30 March, 2012.
[9] D. Thompson, “Railway Noise and Vibration - Mechanism, Modelling and Means of Control”, Elsevier, 2009. ISBN: 978-0-08-045147-3
[10] A. Bracciali, M. Pippert, S. Cervello, “Railway Noise: the Contribution of Wheels, Lucchini RS”, LRS-Techno Series #2, Lucchini RS, 2009.
[11] D. Sala, “LURSAK: The new high performances axle protection”, Predicting real world axle failure and reliability, ESIS TC 24, London, 3-4 March, 2011.
[12] R.V. Dukkipati, S. Narayana Swamy, M.O.M. Osman, “Independently Rotating Wheel Systems for Railway Vehicles: A State of the Art Review”, Vehicle System Dynamics, 21(1), 297-330, 1992.
[13] A. Bracciali, “Apparently Independently Rotating Wheelset - a possible solution for all needs?”, The Stephenson Conference - Research for Railways, Institution of Mechanical Engineers, London, 23-25 April, 2015.
[14] H. Mannsbarth, “Moderne innengelagerte Drehgestelle für den Vollbahnbereich”, Aachen University IFS-Seminar, 9 December, 2014.
[15] British Standards BSI 8535:2011, “Railway applications – Wheelsets and bogies – Powered and non-powered axles with inboard bearings – Design method”, August 2011. ISBN: 978 0 580 68029 8
[16] http://ec.europa.eu/programmes/horizon2020/en/what-horizon-2020, accessed on 25.08.2015.
[17] https://en.wikipedia.org/wiki/Impact_factor, accessed on 25.08.2015.
[18] http://www.unife.org/about-us/committees/33-erwa-steering-committee.html, accessed on 25.08.2015.
[19] https://en.wikipedia.org/wiki/International_Wheelset_Congress, accessed on 25.08.2015.
[20] http://www.iwc2016.com/dct/page/70014, accessed on 25.08.2015.
[21] R A Smith, S Hillmansen, “A brief historical overview of the fatigue of railway axles”, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 1 July, vol. 218, no. 4, 267-277, 2004. doi: 10.1243/0954409043125932
[22] T. Gerlach, F. Murawa, “Railway Axles Fatigue Strength Assessment – where does the journey go – „Quo Vadis“ ?”, ESIS TC 24 Workshop on Fatigue Strength and Fatigue Life of Railway Axles, BAM, Berlin, 11-12 October, 2010.
[23] European Railway Agency, “Railway Safety Performance In The European Union 2014”, downloaded from www.era.europa.eu on 25.08.2015.
[24] C. Klinger, D. Bettge, R. Hacker, T. Heckel, D. Gohlke, D. Klingbell, “Failure analysis on a broken ICE3 railway axle – Interdisciplinary approach”, ESIS TC 24 Workshop on Fatigue Strength and Fatigue Life of Railway Axles, BAM, Berlin, 11-12 October, 2010.
[25] G. A Georgiou, “Research Report 454 - Probability of Detection (PoD) curves. Derivation, applications and limitations”, Jacobi Consulting Limited for Health and Safety Executive, 2006.

[26] M. Carboni, S. Cantini, "A "Model Assisted Probability of Detection" approach for ultrasonic inspection of railway axles", 18th World Conference on Nondestructive Testing, Durban, South Africa, 16-20 April, 2012.
[27] S. Beretta, M. Carboni, S. Cantini, A. Ghidini, "Application of fatigue crack growth algorithms to railway axles and comparison of two steel grades", Proc. Instn Mech. Engrs, Vol. 218, Part F: J. Rail and Rapid Transit, p. 317-326, 2004.
[28] S. Antolovich, A. Saxena, "Fatigue Failures", in ASM Handbook 11, "Failure Analysis and Prevention", 2002.
[29] UIC Leaflet 811-1, "Technical specification for the supply of axles for tractive and trailing stock ", Paris, 1987. Available on www.uic.org
[30] UNI 6787:1971, "Assi fucinati di acciaio speciale legato, bonificati, ad elevate caratteristiche di fatica e di tenacità per sale montate di rotabili ferroviari. Qualità, prescrizioni e prove.", Italian Standardization Body UNI, 1971. Available on http://store.uni.com/magento-1.4.0.1/index.php/uni-6787-1971.html, accessed on 31.08.2015.
[31] G. Mancini, A. Corbizi, F. Lombardo, S. Cervello, "Design of railway axles in compliance with the European Norms: high strength alloyed steels compared to standard steels", Proceedings of the World Congress on Railway Research, Montreal, Canada, 4-8 June, 2006. Available on http://www.railway-research.org/WCRR-Congresses-2001-2008, accessed on 31.08.2015.
[32] EN 10083-1:1996, "Steels for quenching and tempering, General technical delivery conditions", CEN, Bruxelles (withdrawn and substituted by EN 10083-1:2006).
[33] https://en.wikipedia.org/wiki/Eschede_train_disaster, accessed on 01.09.2015.
[34] V. Esslinger, R. Kieselbach, R. Koller, B. Weisse, "The railway accident of Eschede – technical background", Engineering Failure Analysis 11, 515–535, 2004. doi:10.1016/j.engfailanal.2003.11.001
[35] UIC Code 813, "Technical specification for the supply of wheelsets for tractive and trailing stock. Tolerances and assembly", International Union of Railways, Paris, 1989.
[36] UIC Code 813, "Technical specification for the supply of wheelsets for tractive and trailing stock - Tolerances and assembly, International Union of Railways", Paris, 2003.
[37] EN 13260:2003, Railway applications - Wheelsets and bogies - Wheelsets - Products requirements, CEN, Bruxelles, 2003.
[38] EN 13260:2010, Railway applications - Wheelsets and bogies - Wheelsets - Products requirements, CEN, Bruxelles, 2010.
[39] A. Bracciali, M. Monti: "Analysis of the sequence of events after railway accidents", in Proceedings of the Second International Conference on Railway Technology: Research, Development and Maintenance, J. Pombo, (Editor), Civil-Comp Press, Stirlingshire, United Kingdom, paper 156, 2014. doi:10.4203/ccp.104.156
[40] Agenzia Nazionale per la Sicurezza delle Ferrovie (Italian NSA), Rapporto su Maccarese (Rm), 10.02.2010 (restricted access).

[41] S. Friedrich, M. Traupe: Dynamic Torsional Loads on Wheelsets - Recent Findings for the Assessment, European Structural Integrity Society, Technical Committee 24 “Integrity of railway structures”, TC24 MEETING “Axle Durability Analysis and Maintenance”, Politecnico di Milano, Italy, 1-2 October, 2014.

[42] prEN 13260:2015, Railway applications — Wheelsets and bogies — Wheelsets - Product requirements, CEN/TC 256/WG11 internal document N282_13260 REV 2015 04 29 _E_.pdf

[43] National Transportation Safety Board, http://www.ntsb.gov/about/employment/_layouts/ntsb.aviation/brief2.aspx?ev_id=20020621X00954&ntsbno=LAX02GA201&akey=1, accessed on 27.08.2015.

[44] Hercules C130 Strange Crash! – YouTube, https://youtu.be/PK49QALNj-0, accessed on 27.08.2015.

[45] AB Consulting sas di Andrea Bracciali & C., “Railway Wheelset With Partially Independent Wheels”, International patent PCT/IB2015/051855 (13.03.2015), European patent EP15173213.8, 22.06.2015.

[46] A. Bracciali, G. Megna, “Running dynamics of railway vehicles equipped with torsionally flexible axles and partially independently rotating wheels”, 24th IAVSD, Graz, Austria, 17-21 August, 2015.

[47] A. Bracciali, G. Megna: “Contact Mechanics Issues Of A Vehicle Equipped With Partially Independently Rotating Wheelsets”, Contact Mechanics 2015 Conference, 30, Colorado Springs, USA, 8-3 September, 2015.

[48] A. Bracciali, G. Megna, “Validation of the design of the torque limiter of the AIR Wheelset on the Sardinian backbone network”, to be presented at the Third International Conference on Railway Technology, 5-8 April 2015, Cagliari, Italy, Civil-Comp Press, Stirlingshire, UK.

[49] A. Bracciali Andrea, P. Cavicchi, A. Corbizi Fattori, “Maintainability of wheelsets: a novel solution to save time and money”, submitted to 11th World Congress on Railway Research 2016, Milan, Italy, 29, 5-2 June, 2016.