Common Safety Analysis of the AIR Wheelset

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Abstract:

The paper describes the process and the results of a Common Safety Assessment (CSA) applied to a highly-innovative wheelset design with apparently independently rotating (AIR) wheels. All the components of the AIR Wheelset, which has been designed to improve maintenance and to remove the risk associated with axle failures, are evaluated in order to investigate their failure modes, the associated hazards, risk levels and possible mitigations. The results are critically compared with the conventional wheelset architecture, showing that the AIR Wheelset is superior from all points of view.

Keywords: AIR Wheelset, Common Safety Methods, Risk analysis, Innovative Wheelset.

1. INTRODUCTION

Safety of wheelsets remains a central issue in modern railways. The progresses in non-destructive testing (NDT) and in maintenance organization and procedures help minimizing the risk associated to the harder operation profiles and the scarcity of resources.

Nevertheless, axle failures remain a spectre for railway engineers, due to their sudden growth and their catastrophic consequences. As only off-line non-destructive testing are possible today, the risk may be mitigated with a proper definition of the inspection interval but it cannot be completely eliminated.

As an attempt to drastically eliminate all the risks associated to the use of axles, a novel wheelset design was developed and patented. Although the concept was described in a number of references, all mentioned in this paper, the central issue of safety was not addressed yet. The goal of this paper is to evaluate safety of this novel design showing its advantages with respect to conventional wheelsets.

2. THE AIR WHEELSET

2.1. General concept

The AIR Wheelset was conceived with the twofold goal of reducing the risks associated to rotating bending fatigue of axles and to make maintenance easier.

The idea was first presented in 2015 [1], after having filed on 22.06.2015 the application for a patent that was eventually released on 16.01.2019 [2]. It consists of a wheelset made of a non-rotating bridge on which two wheels rotating on roller bearings are mounted, similarly to the well-known principle of the Independently Rotating Wheels (IRW) architecture.

In order to avoid the "erratic" dynamics of IRW wheelsets, that prevents their use in conventional vehicles limiting their application to low-floor trams, a torsional link connecting the two wheels, restoring the correct behavior of a rigid wheelset, is used. Furthermore, different solutions for a torque limiting device were developed, giving the AIRW (Apparently Independently Rotating Wheelset) previously unreachable and outstanding performances in terms of negotiation of sharp curves and track friendliness.

Academics can get more information on running dynamics of AIR Wheelset in [3]; contact mechanics advantages are discussed in [4]; the design of the specific bearings arrangement is described in [5]; torque limiter validation on a mixed line is described in [6].

Railway engineers can get information about maintenance in [7]; integration on existing vehicles is covered in [8]; wheelset specialists can get a comparison of different wheelset innovative design in paper [9], given at the previous edition of this series of Conferences.

In the following paragraphs a short description of the main components is made with reference to Fig. 1. The description is limited to the target of this research, i.e. the correct allocation of risks and hazards linked to the adoption of the AIR Wheelset.

2.2. Advantages on running dynamics

Running in straight track or in mild curves, no differences with a conventional wheelset in terms of dynamic behaviour are expected using the AIR Wheelset, meaning that contact forces, ride characteristics and wear are absolutely comparable with the conventional design.

The "centring effect", necessary for the proper guidance and totally absent in IRW arrangements, is fully kept in the AIR Wheelset until the set torque limit is reached. Then, longitudinal forces are higher than those needed to restore the centred position in tangent track. Wheelset offset is therefore completely avoided.

Instability problems, caused by the progressive increase of the equivalent conicity γ_e, are reduced as the most important cause of wear of the running table (i.e. longitudinal force in mild and sharp curves) is greatly reduced, leading to longer reprofiling intervals. The AIR Wheelset still possesses the steering ability of conventional wheelsets, but it is limited by the torque limiter to an "equivalent coefficient of friction" of around μ=0.35. This avoids rail damages in dry season or in metros where it is not uncommon to observe $\mu \cong 0.6$.

2.3. Advantages on reliability

The AIR Wheelset has just a few components more than a conventional wheelsets. Their design leads to lower stresses and longer life. Bearings are oversized, leading to less failures in service. This means that the AIR Wheelset is

possibly more reliable than a conventional wheelset, where large defects can often be checked only after a major failure happened.

2.4. Advantages on availability

Continuous monitoring, easily achievable on the AIR Wheelset, implies that the fleet is always under strict control. Failure mode of bearings is progressive, while failure mode of axles is sudden. This means that bearings that tend to overheat will give warnings and will be changed before major accidents happen. As a result this will increase the availability of the fleet.

2.5. Advantages on maintainability

Al serviceable components are grouped in one element that include the wheel, the bearings and the brake discs. Routine checks can be done as usual without any change as well as wheel reprofiling with underfloor lathes is unchanged.

On-condition maintenance is totally different from conventional wheelsets as when a wheelset replacement is needed, only the wheels have to be replaced. Simple tools for wheel removal / mounting can be used in semi-prepared environments. All that is needed is to lift one side of the bogie to gain access to the wheel that has to be changed.

Brake discs can be reprofiled on a conventional lathe by removing the wheel. Wheel replacement requires virtually no intervention on stub axle without any operation on the other components.

Minor adjustments can be done by using simple machine tools (a vertical lathe), even from external suppliers, as tools needed for overhaul can be easily found in any conventional mechanical workshop.

2.6. Advantages on noise and vibration

Less wheel wear means less polygonization and therefore less noise. Similarly, less rail wear means less corrugation, less noise generated and less vibrations introduced in the ground.

A greater wheel damping is offered by the bearings that are in direct contact with the wheel, possibly reducing rolling noise as well as squeal noise.

2.7. Advantages on logistics

While the size and the mass of conventional wheelsets obliged to fully equip many workshops over a given territory (in practice there was a full wheelset overhaul shop in every large or mid-size city), managing only wheels changes the repair practice, logistics and the spare parts supply chain.

Local depots may fix with limited equipment (possibly only a vertical lathe) most of the defects encountered during normal operations. New wheels, new bearings and new brake discs can be supplied as spare parts to local workshops that may assemble new complete wheels in a reduced time and with limited costs.

Fully worn wheels, bearings that needs to be overhauled or brake discs that have reached the end of their useful life can be shipped at once with reduced weights and costs.

Major overhaul (wheel replacement, bearings check / cleaning / re-greasing, discs reprofiling / replacement) could be therefore centralized is a few workshops in a country.

2.8. Advantages on life cycle cost

Stub axles become robust parts that belong to the bogie and that require in practice no maintenance. Their cost is therefore spread on the entire life of the bogie. Possibly, this part could be designed, produced and assembled by the bogie manufacturer instead of the wheelset manufacturer. This is completely different from the conventional design, where the wheelset is supplied as a whole with higher costs.

Maintenance cycles completely change, leading to reductions of the overhaul time and as a consequence of the overhaul direct costs in the order of 25% [7]. One of the most important factors in cost reduction is the reduction of non-destructive testing (NDT) on the stub axles that can be inspected less frequently or even continuously.

Bearings size, dictated by adjacent part, is such that in many applications they should last over 10 million km., i.e the entire life of the vehicle when properly greased. The initially higher cost of the bearings can therefore be easily recovered considering that they last “for life”.

The use of the torque limiter greatly reduces wheel and rail tear and wear, limiting longitudinal forces that are one of the fundamental parameters to calculate direct costs according to European regulation (see Regulation (EU) 2015/909 of 12 June 2015, point 5.2.h “longitudinal stiffness of vehicles and horizontal forces impacting on the track”).

Track access charges (“TACs”) may correspondingly be reduced, paying the possibly higher cost of the solution for itself in a very short time. As currently the Variable User Charge in the UK allocates 85% to track maintenance and renewal, 70% of which linked to vertical rail forces and 30% to horizontal rail forces. Even under the very cautious hypothesis of a reduction of 60% of the “longitudinal surface damage”, this leads to a reduction of around 15% of the infrastructure access charge.

3. DESCRIPTION OF THE AIR WHEELSET

3.1. Description of the subassembly “Bridge”

The bridge is a non-rotating sub-assembly made of three components, i.e. the axlebridge, a torsionally stiff transmission shaft and two stub axles.

The axlebridge **B1** can be made with an almost arbitrary combination of materials and shapes, as it is only subjected to static loads and to (limited) dynamic loads. This makes it much safer than a conventional axle that is subjected to rotating bending. Its design can be made according to standards for bogie frames instead of those for wheelsets. The transmission shaft **B2** is made by a cylindrical thick pipe welded to end splined shafts. This component doesn’t exist in conventional wheelsets. It is lowly loaded (in the order of 40 MPa) and, in any case, a failure would lead to a conventional IWR arrangement without safety issues (hunting is automatically prevented!). The stub axle **B3** houses the bearings and its shape is very similar to those used in trams. It doesn’t rotate (similar consideration to those discussed for the axlebridge apply) and can be made for example by steel or ADI cast iron. The sub-assembly is

mounted by inserting the transmission shaft **B2** in the axlebridge **B1** and then bolting the stub axles **B3**. Appropriate design of the bolting connection and the use of anti-unlocking devices allows getting the necessary level of safety without any practical drawbacks.

3.2. Description of the subassembly "Wheel"

The sub-assembly wheel used in the AIR Wheelset differs from conventional wheelsets mainly because of the fact that it is not fitted on wheel seats on the axles, thereby reducing the relevant stresses and avoiding any potential damage (scratches) on stub axles.

The wheel **W1** is very similar to those used in conventional wheelsets with minor differences. The hub is normally longer and larger (often reaching a "square" ratio) to house the bearings. No manufacturing or design issues arise from this design. Brake disks **W2** are absolutely identical to existing solutions. Bearings **W3** are used in a very new arrangement to cope with torques due to lateral loads that are reacted by them. The reader interested in this topic can get more information in ref. [5]. Abutments **W4** are one of the key elements of the design as safety against axial displacements of the wheels, that sometimes happens as described in [10], is prevented by *positive* surfaces and not by relying on friction in a coupling obtained by interference. The sub-assembly is mounted by bolting the brake discs **W2** onto the wheel hub **W1**; bearings **W3** are mounted and axially located by abutments **W4**. Once the sub-assembly is ready, it can either be stored or immediately installed on a vehicle. It is worth reminding that changing this sub-assembly *does not require* removing the bridge or any other component.

3.3. Description of the AIR Wheelset assembly

The AIR Wheelset is assembled by using the previously described sub-assemblies and other additional components.

Abutment rings **A1** are used to axially lock the inner rings of the bearings, offering the same improvement on safety of abutments **W4** seen above. The external flange **A2** packs the assembly and houses the torque limiter. The torque limiter **A3** provides the AIR Wheelset unique features in terms of track friendliness and running dynamics. The assembly sequence starts mounting the wheel sub-assembly on the bridge sub-assembly, then locking the rings with abutments **A1**, preparing the torque limiter **A3** on the external flange **A2** and then bolting the latter on the wheel. Once again, proper design of all the bolted connections ensures the desired level of safety.

4. RISK ANALYSIS THE AIR WHEELSET

4.1. The European approach to railway safety analysis

The Regulation (EU) 402/2013 [11], which is the Regulation on a common safety method (CSM) for risk evaluation and assessment (CSM RA), is part of a wide-ranging programme of work by the European Union Agency for Railways (the Agency) and the European Commission to ensure that high safety levels in European railway are maintained, and, if reasonably practicable, improved.

The intention of the CSM RA is to harmonize processes for risk evaluation and assessment and give to all European railway actors the same standard for the application of these processes. The CSM RA applies when any technical, operational or organization change is being proposed to the railway system. If the change has an impact on safety, the proposer (entity that implement the change) must decide on whether it is significant or not by using criteria in the CSM RA. If the change is significant, the proposer must apply the risk management process. If the change is not significant, the proposer must keep a record of how it arrived at its decision.

In cases where a change is determined to be significant, the risk management process of CSM RA must be carried out by the proposer. The framework of the risk management process is based on the analysis and evaluation of hazards using one or more of the following risk acceptance principles: 1) Application of codes of practice; 2) Comparison with similar system (reference system); 3) Explicit risk estimation.

If a proposer of a change applies one or more of the three risk acceptance principles in the CSM RA regulation correctly for all identified hazards, and implements suitable control measures, this should mean that the risk has been reduced to an acceptable level for the change being effected.

4.2. Application to the AIR Wheelset

The AIR Wheelset has several innovative features compared to the conventional solution and for this reason its application certainly has a significant impact on safety. This required the application of the requirements of Annex I of EU Regulation 402/2013 [11] in order to determine the level of risk associated with its use, starting from the assumption that the AIR Wheelset is used under the same operating and environmental conditions as a conventional system (which is characterized by an acceptable risk level).

The work carried out was focused on:

- determining the codes of good practice used for the design of the AIR Wheelset;
- the comparison of the AIR Wheelset with a reference system corresponding to the traditional wheelset;
- analysis of any differences between the two systems and further identification of appropriate actions to mitigate the risk.

For a new application of an already universally accepted system, the risk assessment has to be oriented to the evaluation of both the deviations from the reference system and the level of risk of the innovative system once the mitigation actions suitable to maintain, or improve, the level of risk of the original system have been implemented.

Fig. 1 shows the hazard log describing the safety process used. The AIR Wheelset was split into three subgroups (Bridge, Wheel and Wheelset), each consisting in a series of sub-components, and the following items are listed:

- the codes of good practice used for its design;
- a brief description of its functionality and failure mode;
- the rates of frequency and severity of the hazard and the consequent level of risk;

- the mitigations identified to bring the level of risk to an acceptable level;
- the level of risk after the mitigations;
- the comparison of the risk level between the conventional system and AIR Wheelset.

The advantages in terms of safety of the AIR Wheelset arise mainly from the use of a non-rotating axlebridge and from the use of positive locking of the bearings by means of flanges and screws.

In the first case, the use of components not subjected to rotating bending fatigue is a clear advantage well known from machine design practice. The axlebridge is, in fact, subjected to the average (static) load given by the vehicle weight and the dynamic (fatigue) component is limited to the one arising from running dynamics (vehicle-track interaction). This dramatically reduces the risk of fatigue failures compared to a conventional (rotating) axle.

For the second case, the practice shows that lateral wheel displacement happened in a non-negligible number of cases. Moreover, damages to wheel seats on the axles are typical of the press fit assembly method. By using the chosen selection of bearings and packing elements (spacers, abutment, screws, washers, etc.) the risk of lateral displacement is totally prevented, furthermore eliminating completely the risk of damages on the mating surfaces. Components life is therefore increased, together with an overall increased safety.

Continuous monitoring adds a high value to the new design. It is, in fact, the only kind of wheelset for conventional vehicles that allows to keep continuously an eye of safety critical components. Modern advances in microelectronics, sensors and processing devices allow to get an unprecedented level of continuous check on stub axles, bearings and even on the axlebridge. It comes out that safety is greatly improved at reasonable costs.

5. CONCLUSIONS

The present research analyzed the risk introduced by the adoption of a novel wheelset design. The evaluation of the hazard performed according to European legislation and standard risk analysis practice showed that the AIR Wheelset introduces no additional risks compared to conventional wheelsets.

Furthermore, the easier maintenance practice [7] contributes in limiting the residual risk as routine and overhaul operations involve less workforce and takes less time, thereby reducing the possibility of mistakes during such activities.

The increased safety of the AIR Wheelset concept was proven, showing that it not only does not worsen the current level of risk of existing wheelsets, but that it may be very successful in this respect if all the remaining activities (detailed design, tests, homologation steps) are correctly conducted and assessed.

It may be concluded that the risk level of the AIR Wheelset concept is at least equivalent (green cells) and often better (light blue cells) than that of traditional wheelsets (Fig. 1).

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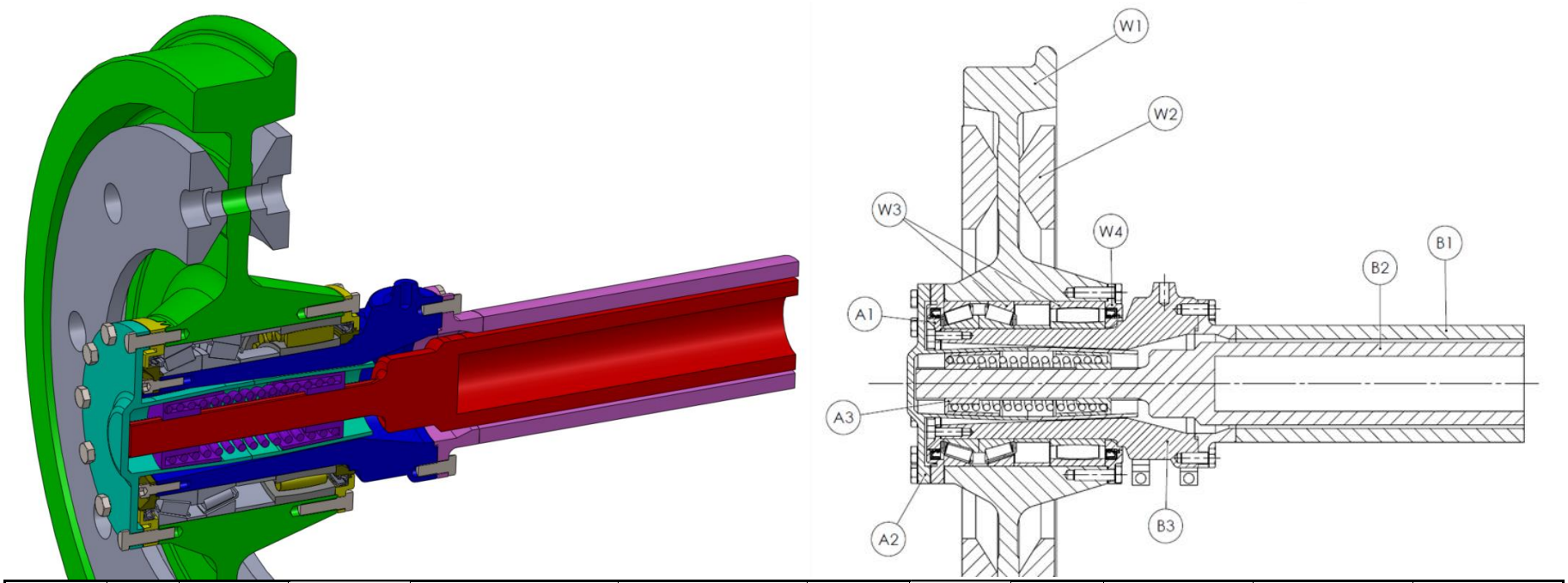

Fig. 1 Three-dimensional CAD model of the AIR Wheelset (left). Hazard matrix of the AIR Wheelset (right).

SUB-ASSEMBLY	Symbol	Name	Code of practice	Description and function	Failure mode	Hazard Description & Severity	Frequency of occurence	Risk level	Mitigation	Risk Level after mitigation	Risk level comparison
BRIDGE	B1 (light purple)	Axlebridge	EN 13749:2011	Fixed (non rotating) axlebridge Supports vertcal-lateral-longitudinal loads	Non-rotating bending fatigue under dynamic stresses superimposed to static stresses	Axle failure *Catastrophic*	Occasional	Intolerable	NDT + on-board NDT	Tolerable	Continuous monitoring possible Risk of other failure modes (loss painting, flying ballast) reduced
	B2 (red)	Transmission shaft	EN13104:2012 (loads)	Torsional joint between the wheels	Fatigue under torsion	None *Marginal*	Improbable	Negligible	N/A	Negligible	Same risk level
	B3 (dark blue)	Stub axle	EN 13749:2011 VDI 2230:2003	Fixed wheel support bolted to axlebridge	Non-rotating bending fatigue under dynamic stresses superimposed to static stresses	Wheel loss *Catastrophic*	Occasional	Intolerable	NDT + on-board NDT	Tolerable	Continuous monitoring possible
					Screw loosening	Wheel loss *Catastrophic*	Occasional	Intolerable	Screw locking system	Tolerable	N/A
WHEEL	W1 (green)	Wheel	EN 13979:2011 EN 13262:2011 (with modifications)	Derived from existing (homologated) wheels Lower stresses (no press-fit on the axle)	Wheel cracking due to excessive wear and tread damages	Wheel failure *Critical*	Probable	Intolerable	Wayside monitoring Periodic checks	Tolerable	Same risk level
	W2 (grey)	Brake disks	EN 13979:2011	Web mounted brake discs (identical to existing ones)	Loosening	Component loss *Critical*	Occasional	Undesirable	Screw locking system	Tolerable	Same risk level
					Thermal cracking		Occasional	Undesirable	NDT	Tolerable	
					Excessive wear		Rare	Undesirable	Periodic check	Tolerable	
	W3 (grey)	Bearings	EN 12082:2011 (with modifications)	Bearings (new arrangement mounted inside wheel hub)	Poor lubrification / Wrong sealing	Melting box *Catastrophic*	Probable	Intolerable	On-board Hot Axle Box detection	Tolerable	Same risk level
					Rolling Contact Fatigue		Occasional	Intolerable		Tolerable	
	W4 (yellow)	Abutment rings on outer bearings race	VDI 2230:2003	Outer bearings race abutments	Screw loosening	Wheel loss *Catastrophic*	Occasional	Intolerable	Screw locking system	Tolerable	Same risk level
WHEELSET	A1 (grey)	Abutment rings on inner bearings races + internal flange	VDI 2230:2003	Inner race abutments + axial locking	Screw loosening	Wheel loss *Catastrophic*	Occasional	Intolerable	Screw locking system	Tolerable	Risk of accidental wheel displacement (axial or angular) avoided
	A2 (light blue)	External flange + torque limiter housing	VDI 2230:2003	Wheel locking + connection to torque limiter	Screw loosening	Wheel loss *Catastrophic*	Occasional	Intolerable	Screw locking system	Tolerable	N/A
	A3 (dark purple)	Torque limiter	N/A	Torque limiter (let the wheel to rotate freely)	Failed operation safer (IRW)	None *Insignificant*	Occasional	Tolerable	Periodic checking	Negligible	N/A