Inside Frame Bogies & AIR Wheelset: A Winning Marriage

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ABSTRACT

Inboard bearings bogies are spreading rapidly in the last years. Their superior characteristics in terms of lower total mass, unsprung mass and moments of inertia give the vehicles an excellent curving behaviour and a very high track friendliness. They also open new possibility to overcome some maintenance issues of conventional wheelsets. In fact, as the wheels are easily accessible, a specific wheelset arrangement, named *AIR wheelset*, was recently developed and patented for these bogie frames.

The paper focuses on the introduction of the *AIR wheelset* on inboard bearings bogie frame design. The paper will consider both driving and trailing wheelsets, with and without torque limiter, in the same range of application of some of the existing bogie frames produced by worldwide rolling stock suppliers. With some detailed examples, it will be shown that the modifications required are very limited and that therefore the application of *AIR Wheelset* is relatively straightforward and may have a deep impact on reliability, availability and life cycle cost of the bogie. Some parts of the wheelset become in fact part of the bogie frame and the maintenance sequence is dramatically simplified generating considerable savings.

Keywords: AIR wheelset, inboard bearings bogies, track friendliness

1. INTRODUCTION

Inside frame bogies, equipped with inboard bearings wheelsets, exhibit superior characteristics in terms of track friendliness compared to conventional outside side bearings. This leads to lower track access charges that today and even more in the future will pave the way to a broader diffusion of this architecture. Although it dates back to the beginning of the railway history, this design is attracting today more and more favour by the designers thanks to a number of advantages that are briefly summarized in this paper.

Inside frame bogies open other interesting horizons for railway wheelsets and, generally speaking, bogie technology. Thought specifically for this kind of bogie frames, the *AIR wheelset* is a fully passive innovative wheelset arrangement developed to optimize running dynamics, wear and maintenance. In this design the wheels are only *Apparently Independently Rotating* (from which the acronym *AIR Wheelset*) as they are connected by an internal transmission shaft (passing through the hollow stub axles and the external non rotating “spacer”), but they can perform relative rotations if the connection between the wheels and the shaft is completed with torque limiters, that intervene when the choosen limit torque is reached.

In this paper the practical applicability of the AIR wheelset on the inside frame bogies is demonstrated by considering both trailing and driving wheelsets in the same range of application of exisiting bogie frames. It results that trial and extensive applications of the *AIR Wheelset* to inside frame bogies is particularly straightforward.

2. TRACK FRIENDLY BOGIES

Developments in bogies architecture have always been focused towards the increase of track friendliness of the vehicles. Beyond the obvious aim to reduce track damage and the resulting higher unavailability of the rail network for maintenance operations, track access charges (TAC) are the driver that is putting more and more emphasis on this point. This is becoming the key factor as in modern railways maintanence costs have a high impact on the toll to access the infrastructure (it is estimated in about one fifth of the total). TAC is not anymore only from the vehicle mass, but also considering the dynamic component of the wheel-rail forces that define the so-called *track friendliness*. It is easy to understand how wheelsets and bogie arrangement in general play a crucial role in the success of the economic railway operation. Train Operating Companies (TOCs) tend therefore to purchase or to lease rolling stock with a high track friendliness.

Historically, the success of the bogie is related to the fact that grouping two or more wheelsets in a bogie allowed to reduce the rigid wheelbase with respect to earlier two-axle vehicles, improving the geometric negotiation of curves. On the other hand, as the wheelsets are constrained also in lateral and longitudinal direction, the steering capability of each of the wheelsets due to conical shape of the wheels is reduced as well, resulting in a certain amount of *angle of attack* α which obviously depends on curve radius. While axle load and unsprung mass are the main cause of vertical track damage, the most important vehicle parameter that influences the curving attitude of a bogie allowing the natural steering ability of a wheelset is the *primary longitudinal stiffness* k_x of the suspension between the wheelset and the bogie frame as shown in Figure 1. This parameter is one of the most important features of a bogied vehicle [1]. It is often defined as the *primary yaw stiffness* k_α considering the rotation of the whole wheelset around the vertical axes. This stiffness costrains the wheelset preventing its radial positioning along the curve, generating creepage and therefore creep forces in longitudinal and lateral direction. It should not be forgotten, however, that a low primary yaw stiffness may unacceptably decrease the critical speed at which instability phenomena (*hunting*) appear.

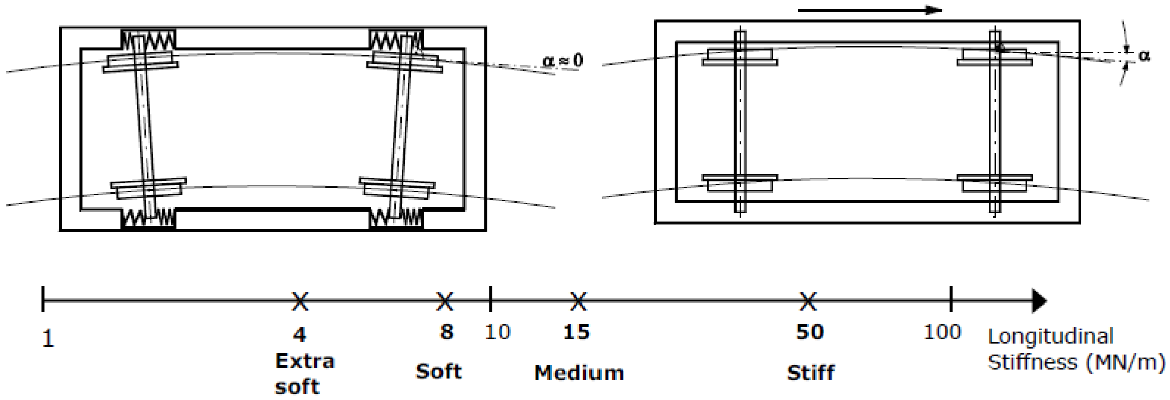


Figure 1. Different curving behaviour between a "flexible" bogie with soft suspensions (left) and a "stiff" bogie with rigid suspensions (right) [2] plotted vs. the typical values of longitudinal primary stiffness for passenger vehicles [3]

Figure 2 shows how the angle af attack α for the first wheelset of a bogie of a typical passenger vehicle with rather stiff longitudinal primary suspension (k_x = 31.6 MN/m) assumes noticeably high values in sharp curves with radius up to 1000÷1500 m, while for larger curves it can be neglected. This is the reason why high speed trains, that run in large curves with high cant deficiency h_d (or high non-compensated acceleration a_{nc}), need not to be equipped with a soft longitudinal suspension, while high k_x values are needed to prevent hunting at high speed considering also potential failures of anti-yaw dampers.

For mainline trains the conflict between guidance and stability is more relevant, as the speed is relatively high (up to 200 km/h) while the portion of service in sharp curves (Zones 3 and 4 of EN 14363) may be significant. Therefore, several solutions to overcome this conflict were developed and tested over the years.

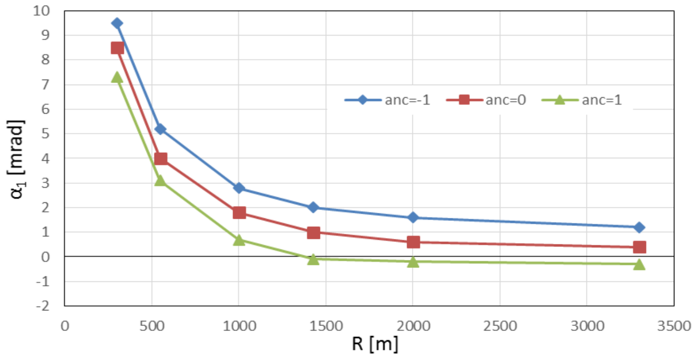


Figure 2. Angle of attack of the first wheelset of the ERRI wagon estimated by multibody model for different values of non-compensated acceleration.

Radial steering of bogies, including passive and controlled steering and self-steering were studied extensively. Although some vehicles are equipped with this kind of bogies, the overall impact on the market has been rather low. For example, mechatronic bogies were the subject of many researches, showing promising results [3], but only some prototype vehicles were equipped with this bogies. This is due to the highly sophisticated solutions intrinsic in this kind of bogies, where linkages and levers between the wheelsets or active and semi-active actuators are implemented, reducing the reliability and the availability of the vehicle and increasing the maintenance costs.

Inside frame bogies come from the earliest days of railway, as steam locomotives with external cylinders used internal journal bearings [4]. They intrinsically have a lower mass and a lower moment of inertia around the vertical axis. This allows the designer to both shorten the wheelbase and reduce the primary yaw stiffness. The design of modern anti-yaw dampers, with superior properties compared to the same components produced just a few decades ago, complete the frame and leads to lightweight, stable and highly track friendly bogies. Inboard bearings wheelsets, on their side, are lighter and reduce considerably unsprung masses. Modern bogie design benefits also of the availability of hydrodynamic bushings that have become one of the key factors to reduce track damage due to longitudinal forces, as the are soft during steering (low rotational speed around the vertical axis) while they are stiff during hunting (high rotational speed around the vertical axis).

The success of inside frame bogies is noticeable. The detailed market analysis shown in [5] is therefore outdated. Recent estimates from private communications lead the authors to estimate the total number of inside frame bogies produced in the last years in eccess of 10.000. The impact on the market of these kind of bogies and it is estimated that possibly all system integrators will develop similar solutions and that these will become the standard in the near future, at least for some categories of railway vehicles.

3. EXISTING INSIDE FRAME BOGIES

To the authors knowledge, three are the inside frame bogies that were made publicly available and displayed in trade fairs:

- the *Flexx Eco* family produced by Bombardier;
- the *SF7000* and its derivative produced by Siemens for the *Desiro City Thameslink* in the UK;
- the inside frame bogie produced by Hitachi Rail for *IEP* trains in the UK.

It is not the scope of this paper either to judge the properties of each of these bogies or to score their performances. The only reason of showing some details is pertaining the application of the *AIR Wheelset* that will be described below. It is worth to highlight that the authors had no access to technical drawings so the conclusions are estimations based only on the observation of displayed bogies.

The *Flexx Eco* family (used in Great Britain for Class 220, Class 222 and Class 172) descends from the B5000 bogie developed by British Rail in the ‘80s [6]. A version of the *Flexx Eco* designed for the *ICx* train for Deutsche Bahn (later branded *ICE4*, see

[7]) with a maximum operating speed of 250 km/h and an axle load up to 19 t was displayed at the trade fair *Innotrans 2014* (Figure 3). It is worth to highlight that in this bogie the primary vertical dampers are not used as damping is provided by rubber springs of the Metaconesuspension.

Figure 3. Flexx Eco bogie on display at the *Innotrans 2014*.

The *SF7000* bogies (motor with wheel trade brakes and trailer with disk brakes) equipping the Desiro City Thameslink are shown in Figure 4. They are designed for a maximum speed of 160 km/h with an axle load up to 16 t. The new concept adopted by Siemens allowed to reach a total mass of the motor bogie of about 6 t, while the previous *SF5000* used for similar vehicles was about 9 t.

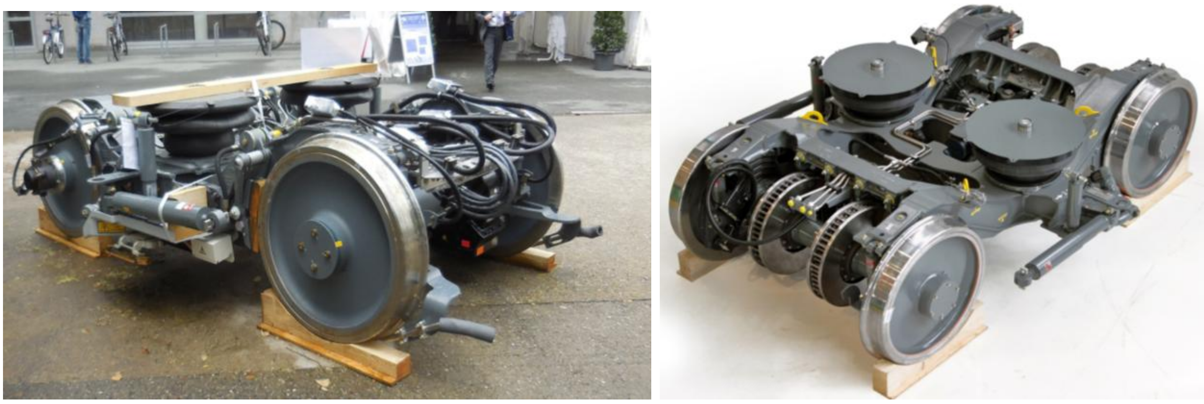


Figure 4. Motor version of the SF7000 bogie showed at *IASVD 2015* in Graz (left) and trailer version (right, copyright: JB2011).

The last bogie considered here is the one produced by Hitachi Rail (Figure 5). These bogies are used for the trailer bogies of the Class 800 and Class 801, which is designed for a maximum operating speed of 200 km/h. Similar bogies with inboard bearings are produced by Hitachi also for motor bogies with wheel trade brakes and trailer bogies with wheel tread breaks and two disk brakes per axle [9].

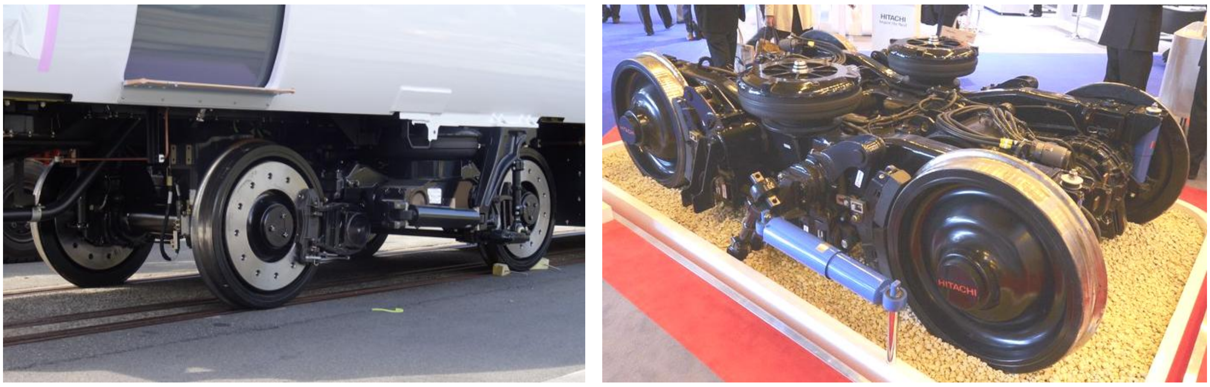


Figure 5. Hitachi inside frame trailer bogie for IEP trains (left). An inside frame motor bogie on display at the trade fair *Railtex 2013*.

It is not surprising that the described bogies have been developed for the UK, where track access charges are more relevant and therefore, track friendliness has always been an important goal to achieve. For these reason, in the ‘80s the British Rail Research started the devolpment of a track friendly bogie also for freight vehicles: the *LTF25*. It was designed using passenger vehicle techonology and inboard bearings with the aim to reduce the unsprung mass and dynamic track forces, but the high costs of the bogie and some concerns about axle fatigue with inboard bearings led to the failure of project [10]. Few years later a similar end occurred for the LeiLa bogie, developed during a German and Swiss project, which was designed with inboard bearings and passive radial steering technologies.

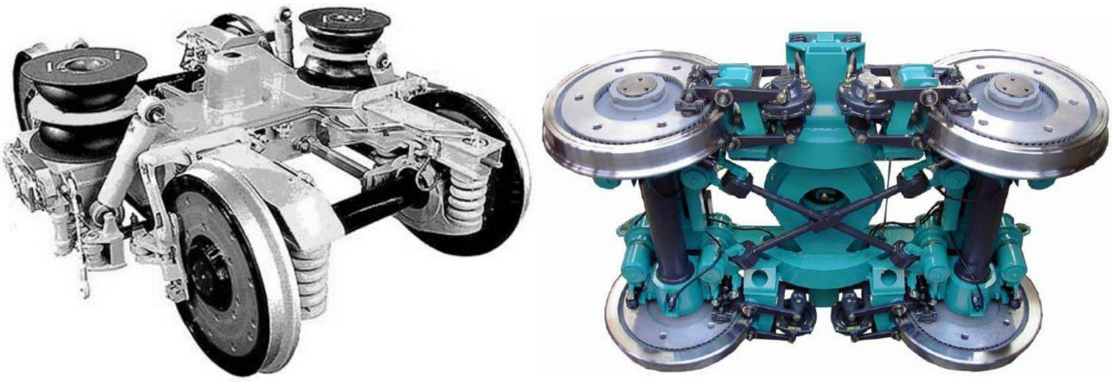


Figure 6. LFT25 bogie (left) and LeiLa bogie from beneath (right) [10]

Another useful example of inboard bearings bogie dated 1956, is the “futuristic” *Budd Pioneer III truck*, shown in Figure 7, which used inboard bearings, external brake disks and a central reduction gearbox for the power transmission. Initially produced for the prototype of ligthweigth coach, with little modifications it has found large application in the Silverliner EMUs, in service from 1963 to 2012. Several others examples of bogies descending from the *Budd Pioneer III* can be found in USA metros and trains.

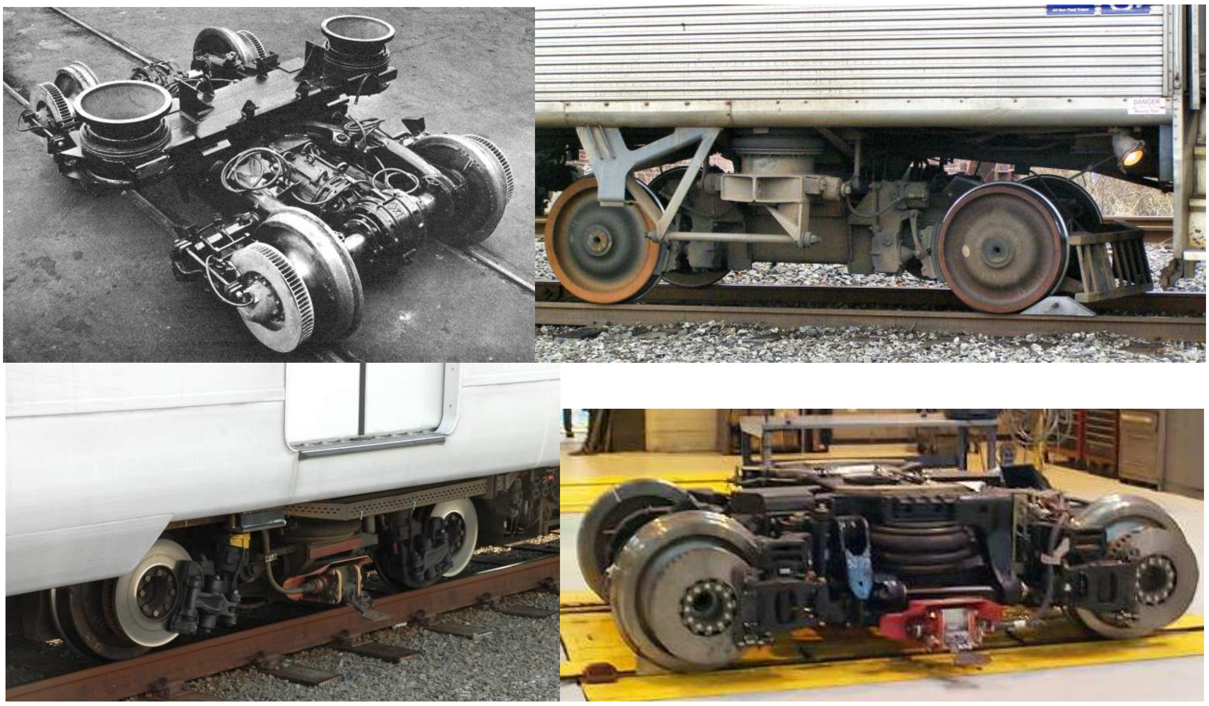


Figure 7. Above the Budd Pioneer lightweight truck (left) and a modified version used in the Silverliner II [11]. Below two inboard bearings bogies for WMATA metro in USA

4. THE AIR WHEELSET

One of the features that catch the eye about inside frame bogies is that the wheels are in sight and apparently easily accessible. Wheel changing looks therefore possible as for cars and lorries, but the obvious difference with road vehicles is that railway wheels are forced (pressed or shrunk fitted) of the on axle. Wheel assembly and disassembly requires procedures more complex than on road vehicles, and they can be source of unpleasant problems [4]. Moreover, the position of the axleboxes between the wheels require the use of on-board hotbox detectors, and lead to a more difficult access to the axleboxes. All these problems can be overcome by the concept of the *AIR wheelset* whose rolling bearings are fitted in the wheel bore. With this arrangement the bearings, the brake discs and the wheel itself are just one component that can be serviced at a time dramatically reducing the cost of maintenance [12]. The conventional axlebox therefore disappears.

Differently from conventional Independently Rotating Wheel (IRW) arrangements, which cannot be applied to mainline railway vehicles because of the lack of the self-centreing effect due to the absence of a torsional link between the wheels, the *AIR wheelset* introduces three main features (Figure 8):

- the bearings arrangement is designed to support vertical and lateral forces (and the related moment) and achieves the same rating life of conventional TBUs [13];
- the wheels are connected each other with a shaft (subjected only to torsional load) to maintain the self-centreing capability on straight track of a conventional wheelset;
- the use of a torque limiter avoids extreme longitudinal forces that produce wear and corrugation (see below).

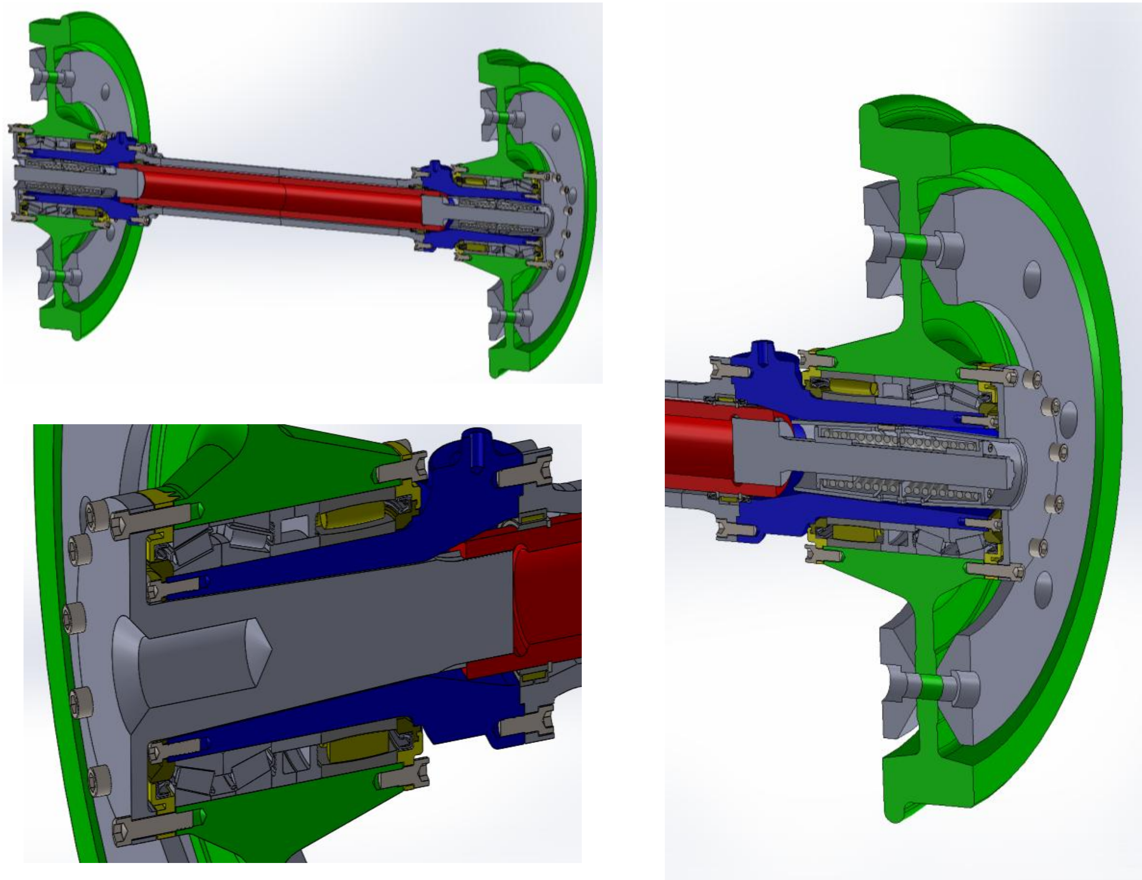


Figure 8. General layout of the *AIR wheelset* (top left); cross section of the *AIR wheelset* with (right) and without (bottom left) torque limiter. Design optimized for an 18 t/axle vehicle with maximum speed of 270 km/h.

The connection between the wheels and the transmission shaft can be done with rigid joints, and therefore the wheelset behaves like a conventional wheelset, or by the use of a specifically designed torque limiter. The latter lets the wheels to rotate independently in curves, when the relative torque between the wheels reaches the limit value selected by the preload of the torque limiter [14]. The limit value can be selected in a rather wide range to accommodate the specific vehicle characteristics and operating conditions (curve radius, cant, adhesion coefficient), in order to manage at the best the longitudinal creep forces generated at the wheel-rail contact in a curve.

The advantages of the application of a torque limiter to an outboard bearings bogie multibody model are shown in [15]. However, in this way the longitudinal creep forces are limited according to the maximum value allowed by the torque limiter and therefore the longitudinal energy dissipated at the wheel-rail contact (known as *Tgamma*, in this case $T_x\gamma_x$) is reduced as well. This effect does not impact on the curving capability of the vehicle as the steering torque is not eliminated as occurs in conventional vehicles with IRW. A good setting of the torque limit is the one corresponding to an equivalent adhesion limit in the range 0.30÷0.35. In this way the vehicles continues to steer in mild curves as well as in sharp curves, but in the latter the wheels may rotate dramatically reducing wear and corrugation.

Therefore, the main scope of the torque limiter is to prevent excessive longitudinal forces when unsual high values of adhesion coefficient (higher than 0.35, typically of dry weather and in nearly all metros in the world) are met in sharp curves. This feature in addition to the good characteristics offered by a bogie frame designed for inboard bearings will give an optimal curving behaviour, with no influence at all on running dynamics and reducing wear and tear in sharp curves.

The selection of the bearings by itself would require a long description. The reader may refer to [13] where the philosophy is described in detail. This arrangement is innovative by itself as it separates the bearing of lateral and vertical loads and the resulting torques. This will be certainly one of the key features in the development of the *AIR wheelset*.

Safety is improved as well, as the *AIR wheelset* architecture leads to lower stresses in the axle. This is due to the fact that, as in inboard bearings wheelsets, lateral forces on curved track reduce the bending moment of the axle due to vertical forces [4]. Moreover, the axle is not rotating (it is an *axlebridge*, in fact) and this avoids in principle the catstrophic failures that continue to be observed in railway axles.

About braking, the *AIR wheelset* may be equipped with brake discs mounted on the wheel web as well as additional brake discs mounted externally and connected directly to the wheel. In conclusion, either 2 or 4 brake discs may equip the *AIR wheelset*, ranging from light rail to heavy and high speed applications.

5. APPLICATION OF THE AIR WHEELSET TO INSIDE FRAME BOGIES

The *AIR wheelset* is designed as a replacement wheel for inside frame bogies. Once the original wheelset is removed, the new one can be installed immediately without major modifications.

In detail, the following areas or component may require some attention:

- traction rods, if present, may be reconnected to the new stub axle which replaces the original inboard axleblox;
- primary suspension dampers, if present, may be reconnected to the new stub axle without any modification;
- brake units / calipers can be reinstalled without any modification, both for web-mounted brake discs and tread brakes;
- grounding contacts need to be replaced with a new solution.

In Figure 9 the *AIR wheelset* for an 18 t/axle vehicles is compared to the *Flexx Eco* wheelset. In this case the stub axle is specifically designed to equip a *Metacone* spring, like the one used in the *Flexx Eco* bogie.

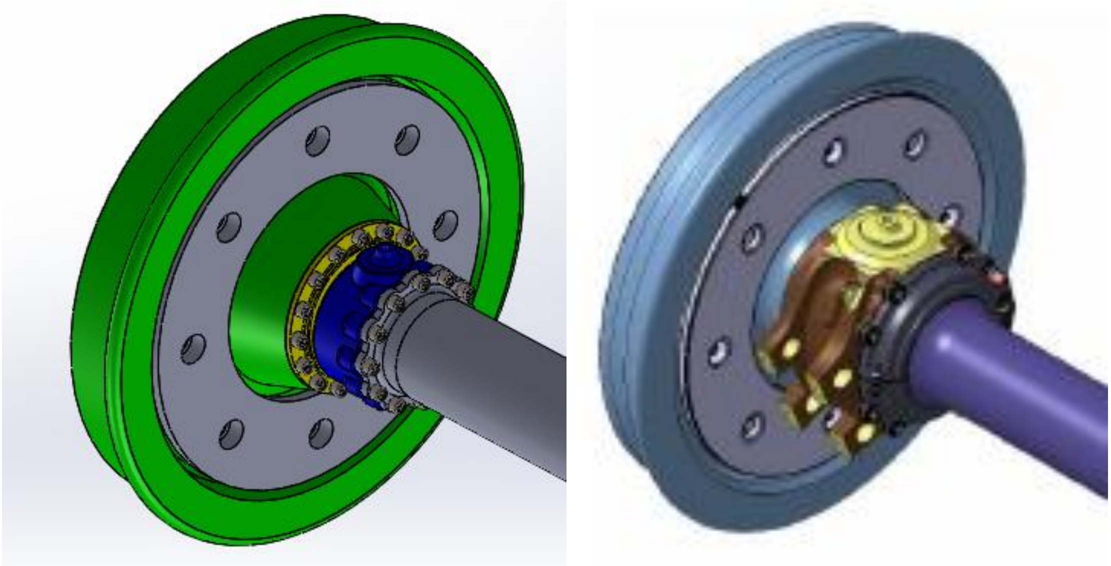


Figure 9. Visual comparison between the *AIR wheelset* (left) and a wheelset for inboard bearings bogies (rigth) [16]. The stub axle of the *AIR Wheelset* can be designed as a perfect replacement part of the axlebox of inboard bearings wheelsets.

The driving version of the AIR wheelset can be easily obtained with a standard reduction gearbox that transmits the traction torque to the wheels. Unless a very smart traction control system is implemented, only the version with rigid joint can be suitable to be used as driving wheelset to avoid the early substitution of the friction disks in the torque limiter. An overview of all the possible trailed and driving *AIR Wheelsets* is shown in Figure 10.

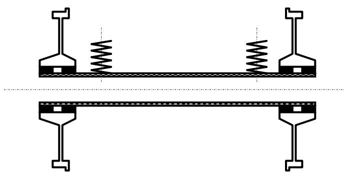
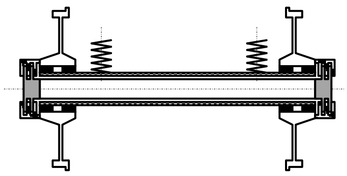
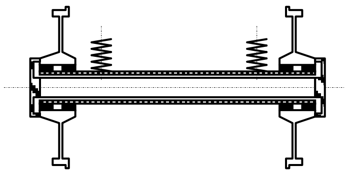
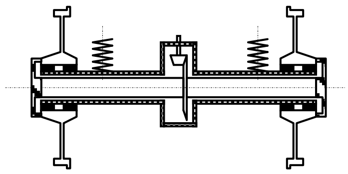
Maximum torque	Trailed *AIR Wheelset*	Driving *AIR Wheelset*
Zero (free)		Not applicable
Limited at 0.05 *PR* -0.2 *PR* *(torque limiter)*		Not applicable
Limited by wheel-rail adhesion limit *(rigid coupling)*		

Figure 10. Available architectures for the *AIR wheelset* (adapted from [5]).

6. CONCLUDING REMARKS

In this paper a critical review of inboard bearings bogie has been given, highlighting their recent impact on railway market. The excellent behaviour of this kind of bogies in terms of track friendliness without compromising maintenance and stability on straight track has generated an extensive application of these bogies to regional and commuter trains with speeds up to 250 km/h. As track access charges associated to vehicle track friendliness are going to be more and more relevant in the next years, these bogies have very likely a bright future not only limited to the UK network, where their development has always been an important challenge and where nowadays their use is widespread.

A novel wheelset with partially independently rotating wheels, named *AIR wheelset*, has been specifically designed to equip inside frame bogies. The torque limited version of the *AIR wheelset* in combination with the improved curving behaviour introduced by the compact and smart design of inside bogie frames will allow to achieve optimum performances in terms of track friendliness in sharp curves when the torque limiter is properly set. On the other hand, on straight track the *AIR wheelset* behaves like a conventional wheelset without any change on running dynamics.

The straightforward implementation of the *AIR wheelset* in these bogies was described highlithing the radical changes and the dramatic advantages that its adoption may introduce in the conventional railway practice. Wheelset maintenance processes is revolutionised, cutting time and costs to a fraction of the current ones.

AIR Wheelset may have therefore a deep impact on reliability, availability and life cycle cost of a train. Non rotating parts of the *AIR wheelset* can be considered belonging to the bogie frame. Therefore, monitoring conditions and maintenance procedures of wheelsets and bogie frames can be dramatically improved.

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