Apparently independently rotating wheelset – a possible solution for all needs?

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ABSTRACT

The paper describes a patented innovative railway wheelset (*AIR Wheelset*) where the wheels are rotating supported by roller bearings and are torsionally connected via a shaft with proper stiffness. This arrangement can dramatically change maintenance operations while keeping optimal running stability at high speed. Better curving characteristics can be obtained by a version where the torque transmitted through the shaft is limited by torque limiters, possibly reducing rail corrugation and improving negotiation of tight curves.

1 INTRODUCTION

Independently rotating wheels (IRW) were developed in the last century for railway applications but, in practice, had some success only in trams. This is due to the lack of self-centring ability of a wheelset equipped with IRWs.

A new design (patented) of a wheelset is described in this paper, where the wheels are installed in the classical arrangement of IRWs but are connected via a shaft and possibly a clutch mechanism. The Apparently IRW wheelset (named *AIR Wheelset*) behaves as a conventional wheelset for large curve radii (higher speed) and as a dissipative limited-torque wheelset in tight curves (lower speed). It is expected that this arrangement leads to small modifications while running in straight track and may results in dramatic running dynamics improvements in tight curves, leading possibly to a large reduction of rail corrugation and wheels polygonization.

Another distinct advantage of the *AIR Wheelset* is that the axle is not rotating, leading to much higher safety coefficients, virtually eliminating any possibility of fracture in service. Wheelset maintenance is much easier, as wheels and bearings are the only parts subjected to maintenance. The *AIR Wheelset* is designed inspiring to the fail-safe philosophy, i.e. any failure in service does not jeopardize running safety. Its roots lie in the studies held in the '70s and in the '80s in the UK, Japan and Italy to reach a simple and effective solution. The optimal field of application of the *AIR Wheelset* is that of the full range of railway vehicles with inboard bearings, although the best performances can be obtained from the use in vehicle with axleload up to 25 t and a speed up to 200 km/h running in curvy lines.

2 HISTORICAL AND TECHNICAL BACKGROUND

2.1 Comparison of rail and road wheels

Road vehicles all have, with some marginal deviations, independently rotating wheels (IRW), i.e. wheels that although belonging to the same axle are not rotationally constrained. Driving wheels are normally connected through a differential gearbox, a gear mechanism that equally shares torque between the two wheels leaving their angular speed independent. Only in some niche applications, such as 4WD vehicle suitable for travelling on low-adhesion surfaces, differential gearboxes are supplemented by friction or viscous devices which link the wheels in some way, but their application makes the vehicle harder to steer and leads to higher tyre wear.

On the contrary, railway vehicles have always been equipped with a solid axle connecting the two wheels, realizing what is normally called a “railway wheelset”.

The motion of a wheelset with perfectly coned wheels was studied in the 19th century by Klingel who derived his famous equation relating the length of a sinusoidal lateral movement to the conicity of the wheels, the wheel radius and the track gauge. As a result of an initial lateral displacement or lateral velocity, the wheelset tends to return towards the centred position.

The self-centring ability of a wheelset with tapered profiles is vital to the railway vehicle, in the sense that although railway safety against derailment is guaranteed by wheel flanges which interact with the rail gauge corner, this contact should intervene only where needed, i.e. in narrow curves or through S&C, but wheel flanges and railhead should not interact in tangent track to limit wear as much as possible.

While on a road vehicle the vehicle trajectory is left to the driver’s judgment whose style may dramatically influence both comfort and tyre wear, no such freedom is left to railway vehicle which is fundamentally a laterally-guided, one-dimensional transportation mode, with bi-directional vehicles. Train drivers can only decide the motion along a predefined line (the track) acting on traction and braking forces. That’s why self-centring ability is needed on trains composed of numerous vehicles (with rotationally constrained wheels) while it should be avoided on basically mono-directional vehicles as cars and lorries (with IRW).

IRWs have undisputable maintenance advantages. It is a common experience that changing a punctured wheel only requires to unscrew some nuts or bolts. On some vehicles (such as motorbikes) also the brake calliper may need to be removed in advance, but this is a rather fast and straightforward operation.

As railway wheels wear, they need to be changed from time to time. The standard maintenance operation requires to remove the wheelset from the vehicle, uncouple the suspensions, lower the wheelset (or lift the vehicle), then install a new or overhauled wheelset. After off-line axlebox and bearings removal, wheels have to be pressed off typically with the help of a high pressure oil injection in a dedicated groove.

2.2 Literature analysis

IRWs were initially used on railway vehicles to reduce longitudinal forces in tight curves, leading to solutions that are still in service with satisfaction in many trams. This solution intrinsically allows the use of low floor arrangements, where the wheels are connected by a “bridge” similarly to road vehicles. Architectures including IRWs are nowadays common in light rail and tram vehicles and are not further described here.

During high-speed running (approximately *v*>200 km/h), vehicles with conventional (coned) wheels may suffer lateral instability ("hunting") phenomena, i.e. self-excited lateral movements of the whole wheelset and of the bogie in the typical range 5÷8 Hz. Displacements are limited only by the shocks resulting from sudden interaction between wheel flanges and rail gauge corner. The appearance of hunting was a nightmare for railway engineers until the wheel-rail contact theory was developed in the '50s and the '60s of the last century, leading to the publication of the first railway vehicle dynamics software packages.

As IRWs have no self-steering effect and therefore no critical speed, their possible adoption in high speed vehicles originated many hopes especially in the '60s and the '70s, when commercial speeds of 300 km/h were looked for in Europe and in Japan. Nevertheless, they were never adopted for the reasons described in the following.

The review paper by Dukkipati et al. (1) summarizes all the experiences about IRWs until the end of the '80s. At that time it was already clear that most of the advantages claimed by the use of IRW in terms of running stability and curving were achievable but a major drawback could not be avoided.

In 1977, Hayden et al. (2) solved an 11-*dof* model of the dynamics of a bogie to analyze the influence of the bogie architecture on the critical speed, i.e. the speed at which an initial displacement does not damp out but increases. Although the model has all the limits intrinsic to the step solution of a system of linear differential equations, Figure 1 shows that the critical speed decreases when the torsional stiffness of the axle decreases. For the special case of k_{AX}=0, i.e. the case of IRWs, the critical speed is always zero as the stiffness matrix of the bogie is singular and an eigenvalue of the system is zero. This "*implies that there is no preferred equilibrium point and that the wheelset may wander randomly from side to side in response to track irregularity*". While severe hunting is prevented, "*there does exist the possibility of greater flange wear*".

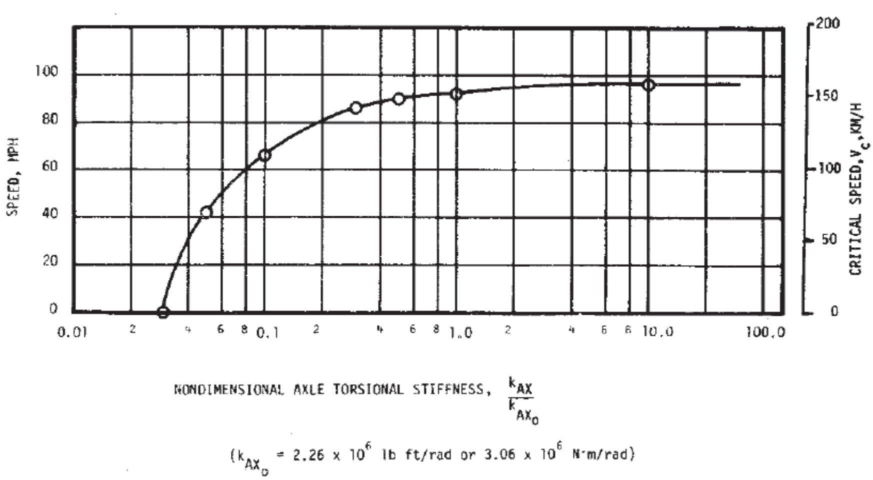


Figure 1. Effect of axle torsional stiffness on critical speed on nominal 11-DOF model (2).

Similar results were obtained by Doyle et al. (3) (Figure 2), confirming that bogies equipped with IRWs have no critical speed. Both these references show that reducing the torsional stiffness of the axle lowers the critical speed.

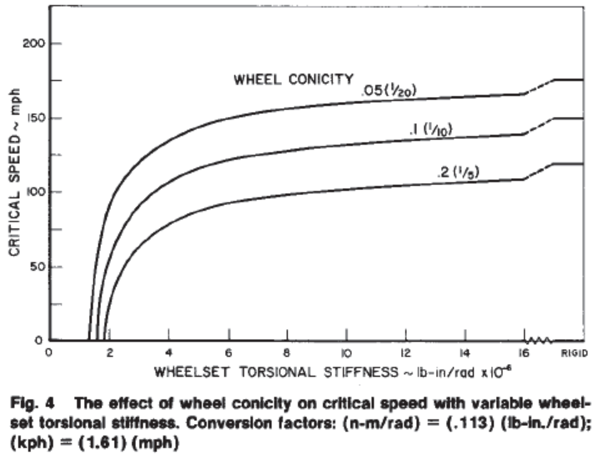


Figure 2. Effect of axle torsional stiffness on critical speed with varying wheel conicity (3).

Some researchers (4, 5, 6) found experimentally that wheelsets equipped with IRW may run displaced but without wheel flange providing that the wheelsets have a specially designed profile. During some tests on real vehicles, abnormal longitudinal vibrations were measured on the axleboxes. This demonstrates that the adoption of IRWs on existing vehicles is not trouble-free and that at least the stiffness of the primary longitudinal suspension has probably to be redesigned.

A search revealed that some inventors patented solutions (now expired) for motor wheels where torsion bars are used as transmission shafts. In patent (7) the wheels are rigidly connected via a hollow axle and the torque is transmitted with a long, flexible torsion bar, while in patent (8) wheels are connected through a differential gear mechanism and are therefore torsionally disconnected (they are subjected to the same torque when the motor is on but angular speed may be different). In the first case the wheelset can be considered conventional (torque is transmitted by the axle) while in the second case the wheels can be considered independent (when motor is off the torque is zero). So, none of the two inventions deals with problems arising from low torsional stiffness of the connection between the two wheels, at least when the vehicle is trailed.

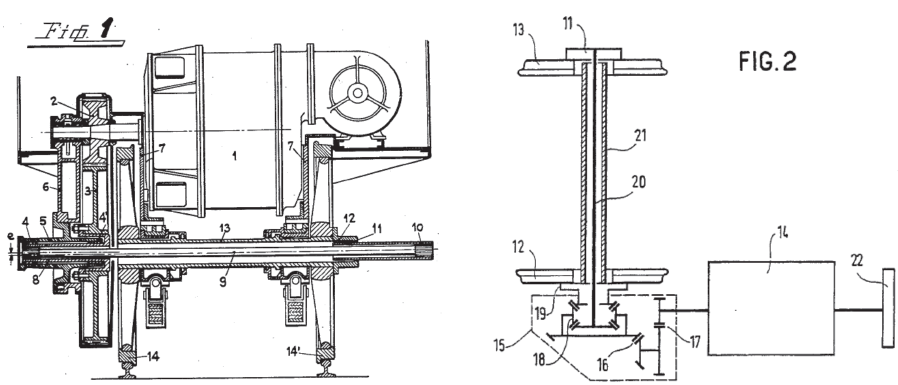


Figure 3. Torsion bar used to drive a motor axle on a conventional axle (left, (7)). Torsion bar included in a differential gear mechanism to drive independently rotating wheels (right, (8)).

The centring effect of wheel profiles on IRW wheelsets is limited to the so-called "gravitational stiffness", i.e. the fact that the resulting centring effect is not due to longitudinal creepage forces but to the different angle at the two wheel-rail contacts.

This conclusions gives rise to some concerns, as already in 1977 Doyle (2) noted that "*it has been determined that wheel conicity cannot be designed because the wheel contact geometry wears rapidly to a "worn wheel" profile*". King (9) reports the Müller suggestion "*... designers should accept the wear forms of tyres and railheads as they are defined in the stable (worn) form...*".

In more recent times, Wickens (10) cites Heumann saying that "*he argued that after reprofiling to a coned tread, tyre profiles tend to wear rapidly so that the running tread normally in contact with the rail head is worn to a uniform profile. This profile then tends to remain stable during further use, and is largely independent of the original profile and of the tyre steel*".

Designing profiles is therefore an activity that is intrinsically fruitless and this is true also for the case of IRW wheelsets. Self centring due to gravitational effect has always demonstrated to be insufficient, such that already in 1970 Becker (11) closed the debate giving evidence that "*extensive experimental experience has shown that, indeed, the kinematic oscillation is absent but that one or other of the wheels tends to run in continuous flange contact*". Resulting flange wear is therefore absolutely unacceptable.

2.3 Other types of IRW vehicles

Old literature amply justifies why no conventional railway vehicles equipped with bogies use IRWs today. The only effective and successful example of the use of IRWs is the family of vehicles produced by the Spanish company Talgo, but these vehicles have a particular architecture and don't use conventional bogies but portals with steered single wheels (known as *rodal* or *Talgo truck*). What follows therefore doesn't apply to these vehicles.

In more recent years only a few papers dealt with special applications of the IRW concept. This is attributable to the low interest that the technical community deserved to this concept for the reasons already discussed. Vehicle dynamics at high speed is nowadays effectively simulated through commercial software packages and running daily at 300 km/h is safe and comfortable. There is no need any more to resort to the IRW technique to avoid hunting.

The few references found concentrate on the possible applications of IRW to the so-called "mechatronic bogies", i.e. those bogies where axle orientation is managed by the proper combination of actuators and a control strategy, leading to "controlled steering" vehicles where the wheelsets have the best (radial) orientation and therefore minimize wheel and rail wear. Although interesting from a scientific point of view, to the author's knowledge the application of mechatronic bogies is not widespread yet; some applications of a similar concept, the so-called "self-steering bogies" techniques, were applied to bogies with conventional wheelset whose attitude is managed by linkages actuated by the rotational carbody – bogie frame angle. Neither mechatronic bogies nor passively steered wheelsets are further addressed in this paper, as they require the use of advanced technology (with the related reliability issues) and lie outside the scope of this paper.

In the case of low floor trams, already discussed, the absence of self-centring capabilities is such that tyres are often cylindrical and it is accepted that these vehicles run laterally displaced with some flanges continuously interacting with the grooved rail.

It can be summarized that the IRW technique is used only on low-speed vehicles with specific needs but is not used at all on conventional railway vehicles.

3 CURRENT MARKET PERSPECTIVES

Inboard bearings existed since the early railway era as steam locomotives often had external cylinders with rods that were not compatible with conventional axleboxes. When journal bearings were substituted by roller bearings, inboard bearings almost disappeared, with only few exceptions such as the Budd Silverliner EMU (USA, 1963), the Commonwealth Engineering 2000 Class railcar (Australia, 1979) and, more recently, the Leila Bogie (12). To the author's knowledge, none of these bogies was used on large scale.

More interesting for the scope of this paper is the story of the inboard bearings bogie B5000 developed by British Rail in the '80s. Thanks to its interesting dynamics characteristics in term of track friendliness, vehicles mounting it have the lowest track access charges to the UK railway network. The bogie is now built by Bombardier Transportation under the brand name *FLEXX Eco*. Class 220 Voyager UK (in service since 2001, 288 bogies), Class 222 Meridian UK (in service since 2003, 303 bogies) and Class 172 Turbostar UK (in service since 2011, 186 bogies), are good examples of the favour that that bogie received in its mother land.

Other manufacturers developed inboard bearings bogies for the UK market. Siemens is going to supply up to 1200 cars of the Desiro City Thameslink train which uses SF 7000 bogies (13, 14) and Hitachi has just rolled out the first units of Class 800/801 with specifically designed bogies (15).

This "all British" bogie family has quite recently started to spread across Europe and beyond. Bombardier Transportation was in fact subcontracted by Siemens to manufacture 1390 FLEXX Eco trailer bogies for the ICx trains for DB (16), designed for 19.5 t/axle and operating at 250 km/h with 860 mm diameter wheels. Other vehicles with FLEXX Eco bogies are Class 5 coach for Norway (in service since 2011, 122 bogies), Crossrail (in design, 1170 bogies), Riyadh Metro (in design, 188 bogies) and Stockholm C30 (in design, 768 bogies).

After 25 years from the roll out of the first B5000 bogie the market seems ready for the massive introduction of this kind of bogies.

4 DEVELOPMENT OF A NEW TYPE OF IRW WHEELSET

4.1 New possibilities for IRWs on inboard bearings bogies?

Technology advances open new fields for the application of IRWs on inboard bearings bogies that were not possible only a few years ago. The design that will be described in the next paragraph benefits in fact by some recent innovations:

- inboard bearings cannot be monitored as required by TSIs (Technical Specifications for Interoperability) by trackside HABD (Hot Axle Box Detectors). The recent standard (17), supporting the TSI Rolling Stock, allows the monitoring of bearing temperature by means of transducers integrated in the axlebox. This technology is nowadays rather simple to put in service thanks to the development of sensors, electronics and software, certainly much more easily than 30 or 40 years ago;
- inboard bearings "forced" the development of TBU (Tapered Roller Bearing Units) with a large internal diameter (in the order of 180-185 mm). This is crucial for the development of the new design. No bearings with these performances were available in the past;

- NDT with ultrasound probes designed to check the axle from a central bore machined in the axle is nowadays a standard. This technique is well proven and hollow axles are widely used while they almost didn't exist when the first IRWs solutions were attempted.

4.2 Concept of the *AIR Wheelset*

The *AIR Wheelset* (18) is mainly intended to improve maintenance operations, reducing timed and costs. With the *AIR Wheelset* it will be possible to change a wheel similarly to what happens on road vehicles, without the need to lower the bridge that is designed for infinite life. It is the perfect companion of internal frame bogies.

The goals that were defined during the design of the *AIR Wheelset* are:

- it had to reduce maintenance time and costs, needing simple tools, less labour expenses and less workshop space;
- it had to improve safety, with specific fail-safe features;
- it had to improve reliability, with continuous monitoring of running conditions;
- it had to give superior running characteristics in narrow curves, while keeping a good behaviour at higher speeds;
- it had be available in both motor and trailed versions.

The *AIR Wheelset* satisfies all these goals. As wheels with bearings are mounted on a hollow axle that is not rotating, an external observer could see the wheelset as a conventional IRW wheelset. In the developed arrangement the wheels are nevertheless *not independent* as they are connected through a stiff shaft which rotates in the bore of the hollow axle. For this reason the acronym *AIR Wheelset*, i.e. *Apparently Independently Rotating Wheels Wheelset*, was created.

One of the most specific features of the invention is that the trailed *AIR Wheelset* may have the wheels and the shaft connected by friction limiters set at a predefined value of maximum transmissible torque. This limits longitudinal forces in narrow curves possibly effectively reducing rail corrugation formation and growth.

A sketch of the *AIR Wheelset* possible layouts is shown in Figure 4. The case of the trailed wheelset with torque limiters is shown in Figure 5.

4.3 Wheel design

The introduction of higher load capacity bearings in the wheel seat area required a larger hub diameter and a longer wheel bore. The design started from a typical wheel with web-mounted brake disks and showed no criticalities in terms of both wheel manufacturing (hot rolling and turning operations) and stress resistance. The design of both the original and the modified wheel was successfully assessed according to current regulations on wheel design (19, 20).

Stresses in the hub area results much lower thanks to the absence of fit while the rest of the wheel is practically unaffected by the new design. The *AIR Wheelset* is therefore compatible with the majority of existing wheels with minor changes in the design and tooling processes.

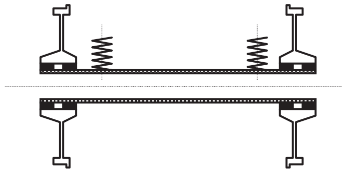
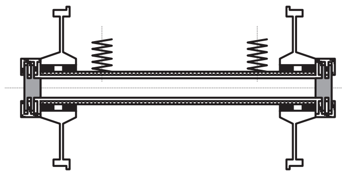
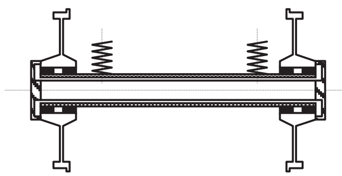
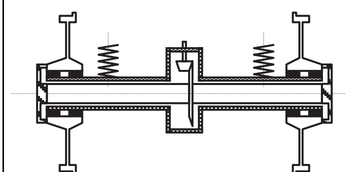
Maximum torque	Trailed *AIR Wheelset*	Motor *AIR Wheelset*
Zero (free)		Not applicable
Limited at 0.05 *PR* -0.2 *PR* *(torque limiter)*		Not applicable
Limited by wheel-rail adhesion limit *(rigid coupling)*		

Figure 4. Possible layouts of the *AIR Wheelset* (18). All solutions can be equipped with block brakes and/or up two discs per wheel (maximum four brake discs per wheelset).

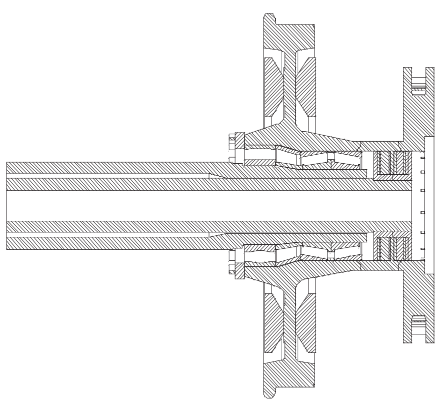


Figure 5. Partial cross section of an *AIR Wheelset* equipped with friction torque limiter and two brake disks per wheel.

4.4 Bearings design

European standards on the performance testing of railway bearings (21) considers a 1/2 factor in lateral load of bearings as the overall lateral force "applies to calculation of forces for one journal". This means that the lateral force is shared by the two axleboxes. Moreover, conventional wheelsets "equalize" the force on the two wheels through the axle. For example, if a force F is applied to the left wheel and a force –F is applied to the right wheel, bearings are not subjected to any lateral load. This clearly doesn't happen in *AIR Wheelset*, where the bearings of each wheel are substantially independent.

Units with two tapered bearings (TBU) mounted "back-to-back" (or in an "O" arrangement) are the current railway standard as they provide a reliable and economically advantageous way to support all the forces acting on an axlebox. The choice of the "O" arrangement is due to the fact that the axlebox must be firmly connected to the axle about torques acting along the vehicle axis.

AIR Wheelset bearings are loaded also by the torque generated by the lateral force acting on the wheel flange. Bearings had to be chosen looking for an increasing cross section of the bridge starting from the outer end, considering moreover both the speed limitations arising from the rotating outer ring of the bearings and the limited available space.

Two bearings are used on *AIR Wheelset*, one acting as a hinge (locating) and the other as a support (non-locating), a standard solution in machine design. This design satisfies all the requirements in terms of mounting sequence, tolerances, machinability, etc. of the wheel and of the bridge. It consists of:

- a tapered bearing unit mounted "face to face" (or in an "X" arrangement), with high lateral and vertical load capacity (locating);
- a CARB® bearing with very high radial capacity and a very high maximum speed (non-locating).

CARB® bearings were introduced by SKF in 1995 and allow high axial and angular displacements. All the other types of rolling bearings (ball, cylindrical rollers, needle, spherical, etc.) did not satisfy the requirements. These bearings are not commonly used in the railway sector and some development will be needed. With this solution for the first time a single wheel can withstand high vertical loads at high speeds. This is a noticeable improvement compared to classical IRW solutions (trams and light railway design for low speed and low axleload).

4.5 Bridge design

The *AIR Wheelset* design includes a bridge that is not subjected to rotating bending, so the classical approach to fatigue used in axles was not used. Loads on the bridge result from the superposition of the vertical static load on the axle and to lower forces in other directions (braking, steering, inertial). It can be assumed that bending in the vertical plane never reverses, i.e. the vertical load on a wheel never reaches zero (this conditions would lead to the uplift of the corresponding wheel).

Fatigue validation of the bridge design was therefore done considering it as a part of the bogie subjected to high inertia loads. While fatigue limits for solid axle made of EA1N and EA4T steels are respectively 166 and 180 MPa including a safety coefficient of 1.2 (22), the DVS 1612 standard (23) normally used in the design of bogie frames indicates in 240 MPa the fatigue limit for the S355 steel in practice in the whole $0<R=\sigma_{min}/\sigma_{max}\leq1$ range. This carbon steel is largely used for bogie frame construction. Also the fatigue limit of castings made of G20Mn5 steel can be considered equivalent to that of S355, thereby allowing the bridge to be made as a combination of forged, welded and casted parts.

The bridge can be made with a geometry that better suits the needs of high strength and stiffness, leading to high safety coefficients. The current non-optimized design shows maximum stresses in the order of 100 MPa with an axleload of 20 t/axle for all load cases described in (19). This should avoid in the future catastrophes (24) due to axles failures under rotating bending fatigue. Being less critical, treatments developed to reduce the effect of impacts due to flying ballast (25) are not needed.

4.6 Shaft (torsion bar) design

As seen in par. 2.2, the *AIR Wheelset* needs to have the highest possible torsional stiffness to avoid an inadmissible reduction of the critical speed. A successful solution was found where the torsional stiffness of the shaft is approximately 40% of the stiffness of a conventional 160 mm diameter axle. Limited reduction in the critical speed can be efficiently tackled with minor suspension modifications.

European standard (22) indicates for trailed wheelsets a maximum torque of 0.2*PR* (where *P* is the vertical wheel load and *R* is the wheel radius), indirectly indicating that a maximum (differential) adhesion coefficient of 0.2 can be reached in practice. It is important to highlight that the single adhesion coefficient on each wheel can be higher, but that only the difference is able to produce a torque that stresses the shaft.

By convention, the torsional moment between running surfaces is selected at the value of 0.3*P'R* during braking, where *P'* is the proportion of P braked with with the method of braking considered. It includes the torsional moment due to braking and the torsional moment due to curving and wheel geometry. The shaft equipping the *AIR Wheelset* can survive this torque without problems, as a shaft of much smaller size is used for example on 1.88 MW electric motors of the E652 3kV DC locomotive of Italian railways (B wheel arrangement). It is able to make two axles slipping simultaneously (26).

The shaft design is based on stiffness and therefore results not critical from the stress point of view. In case of failure of the shaft the *AIR Wheelset* continues to behave as a conventional IRW wheelset, without impact on safety (no hunting develops). It can be detected and fixed when the vehicle is maintained without further limitations.

4.7 Friction torque limiter (clutch) design

Although the torque that has to be transmitted by the torque limiters is rather high, the dissipated power is rather small, less than 2 kW per axle in a wide range of speed and curve radius. For an 80 t, 4 axle vehicle this corresponds to an equivalent extra slope of 0.375 ‰, which is negligible. In any case this resistance is lower than the one offered by conventional wheelsets.

Considering that the torque limiter is immersed in the airflow outside the vehicle, no heating problem are forecasted. Monodisc dry friction clutches can be used. The one specifically developed for the *AIR Wheelset* is currently patent pending and will be shown in a future paper.

4.8 Braking the *AIR Wheelset*

Braking the *AIR Wheelset* is not much different from a standard wheelset, with the obvious provisions that no axle-mounted discs can be used. Braking the wheel can be done by conventional tread braking, by using web-mounted brake discs or by using discs mounted on an extension of the axle/wheel (Figure 6).

Figure 5 shows a solution where both web-mounted and external disks are applied. This means that up to a total of 4 discs "per axle" can be used. Perfectly symmetric braking does not generate torsion on the shaft; any dissymmetry (or partial malfunctioning) in braking forces is equalized by the shaft as in conventional wheelsets.

Figure 6. Two examples of brake discs mounted on the axle ends. The bogie to the right has internal bearings.

5 RUNNING AND CURVING BEHAVIOUR OF THE *AIR WHEELSET*

As shown above the reduction in the torsional stiffness can lead to a reduction in the critical speed, although the results from old linear models should be used with care.

To prevent such limitations, a fully non-linear analysis of a vehicle equipped with *AIR Wheelset* was made with a specific tool developed for a commercial railway vehicle dynamics package (27). The results are rather interesting but cannot be discussed here for space reasons. The reader is referred to paper (28) for further details. In any case it can be anticipated that no sensible reduction in the critical speed are forecasted by the use of the *AIR Wheelset*.

The use of torque limiters promises great improvements in the curving behaviour of a vehicle equipped with this *AIR Wheelsets*. Eadie et al. (29) showed that the longitudinal traction coefficient, measured on a high speed train, exceeds 0.2 only at speeds lower than approximately 100 km/h (Figure 7), that is a quite common speed in tortuous lines. While the adhesion used in tangent track is rather low (see the "cloud" of points in the ±0.1 traction coefficient range) and would never lead to sliding in the torque limiter, it is a common experience that most of the curves with radius lower than 500 m are prone to rail corrugation.

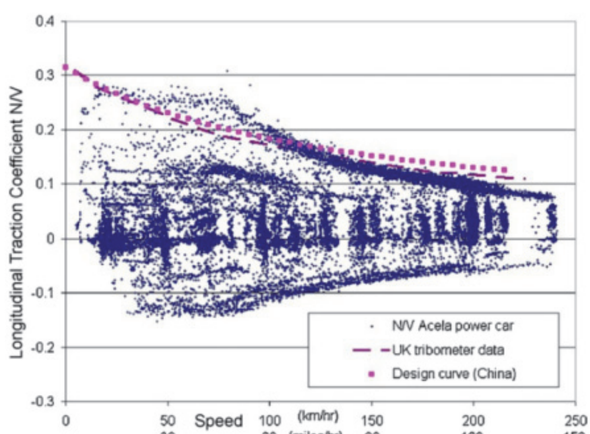


Figure 7. Longitudinal traction coefficient for the leading axle of the power car (29).

The possibility of a net relative rotation of the wheels along a curve leads to the non-necessity of the oscillatory stick-slip phenomenon that is intrinsic in a standard wheelset where the relative position of the wheels cannot change despite the fact that the distance run by the two wheels is different. More details on the complex wheel/rail interface issues arising from the adoption of the torque limiters on the *AIR Wheelset* will be published in (30) to which the reader is referred. It can be anticipated that with an accurate setting of the torque both rail and torque limiter low wear can be obtained, reducing maintenance costs.

Although extensive testing will be needed to verify the estimated performances, the *AIR Wheelset* promises to be a device that can effectively help to solve the never-ending conflict between guidance and stability. Stability is guaranteed as the *AIR Wheelset* is almost as torsionally stiff as a conventional wheelset, while curving attitude is dramatically improved in narrow curves thanks to the use of torque limiters. Friction damping supplied by torque limiters gives a new dimension to resonance phenomena typical in narrow curves with corrugated rails.

CONCLUSIONS AND FURTHER DEVELOPMENTS

A new patented wheelset, named *AIR Wheelset* was introduced. It is the development and the combination of conventional and IRW wheelsets, with the aim of designing a wheelset that can dramatically improve rolling stock maintenance practice (31).

Summarizing, the *AIR Wheelset* is composed of the following elements:
- a non-rotating *bridge*, made of structural steel;
- two *wheels*, which are not press or shrink fitted on an axle but that simply house the bearings;
- *rolling bearings* that support vertical, lateral and braking forces and the resulting torques acting on each wheel;
- a stiff *shaft*, which torsionally connects the wheels ensuring stability at high speed;
- the *torque limiters* which releases the wheels in tight curves maintaining a predetermined torque while allowing relative finite rotations.

The next steps in the application of the *AIR Wheelset* necessarily pass through a validation of the concept on a roller rig or under a test vehicle.

ACKNOWLEDGMENTS

The authors wishes to thank for their contribution Dr. Fabio Piccioli (Italcertifer, formerly University of Florence), Dr. Mauro Cavalletti (VI-Grade), Dr. Eddie Searancke (Bombardier),

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