

# Dovetail Tyred Wheels – Application to a DMU

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## Abstract:

Tyred wheels are perceived as “out-of-fashion” and are not even considered by current European standards. Nevertheless many railway enterprises still have in their assets vehicles or entire fleets equipped with tyred wheels. The maintenance of this component drains a large amount of time and money. The paper describes the results of a joint project in which a University, a workshop and a train operating company developed, implemented and successfully tested a new maintenance methodology that looks very promising. Design and assembly criteria are discussed, as well as the impact on existing vehicles. Results were so promising that plans exist at the moment to extend this approach to other vehicles and possibly also to new rolling stock

**Keywords:** Tyred wheel, positive coupling, maintenance, rolling stock, DMU, line tests

## 1. INTRODUCTION

Although tyred vehicles are residual in modern fleets, the economic resources that the overhaul of their wheelsets drain are noticeable. Two of the authors recently publish a set of papers reinterpreting the role and the importance of tyred wheels.

Very briefly, the authors reached the conclusion that tyred wheels were designed in the past according to practice without having the possibility of conducting detailed numerical analyses that on the contrary are widely available nowadays.

This resulted in a quite inefficient design, leading to wheels that were heavy and not optimized from a structural point of view. The presence of tread braking, a standard 50 years ago, is today much less important and, in practice, confined to freight wagons. The use of disc braking and the availability of Finite Element codes with solvers able to simulate non-linearities, allowed to show that many wheel centres were subjected to plastic strain during tyre fitting [1]. The thickness of the tyre in the fully worn condition, dictated by the need to guarantee a proper coupling (avoiding spinning) between the tyre and the wheel centre during both stop and drag tread braking, proved to be largely in excess of the one needed when the thermal input given by tread braking is avoided [2].

But the authors realized that the death of tyred wheels was dictated by other factors. First, high-speed trains cannot be equipped with such wheels for clear centrifugal forces reasons; second, tread braking was recognized as deleterious for tyred wheels already in the ‘60s, forcing all freight wagons to be equipped with monobloc wheels; third, maintenance practice for tyre wheels was a real nightmare for the reasons discussed in detail in [3].

While the problem of unsprung masses and spinning can be easily solved with a proper design [2], maintenance had to be faced taking into account workshop practice that include machine tools, checking tools and allowable deviations (tolerances). During the analysis of all these factors, it was readily realized that modern workshop practice is extremely

different from the one available at the beginning of the railway era. Today, all machine tools are equipped with a CNC (continuous numerical control) and the availability of CMM (coordinate measuring machines) is common in nearly all workshops.

Together with a re-analysis of the machining, assembly and checking phases, the idea of dramatically simplifying the architecture of the tyre-wheel centre mating emerged.

A minor modification to the shape of wheel centres and tyres that was believed to significantly reduce maintenance costs was then proposed [3]. The basic idea was at that time to machine on the mating parts a dovetail self-locking shape capable to eliminate the need of the retaining ring. This was moreover compatible with the possibility of purchasing fully finished tyres, similarly to what happens in the case of “elastic wheels” for light rail vehicles.

The outcome of the research indicated that with a preliminary FEM calculation and a carefully studied maintenance cycle, no machining of any kind was probably needed on wheelsets after fully-machined tyres were fitted on fully-machined wheel centres.

An extremely important “side effect” of the introduction of this process was the possibility for wheel centres and axles to exploit *really* infinite life as they are not replaced as in the case of monobloc wheels (scrapped when fully worn) and of axles (whose wheel seats need to be machined from time to time limiting their useful life).

## 2. FRAMEWORK OF THE ACTIVITY

Testing any modification requires the availability of the vehicle, of the railway enterprise and of the network. TRENORD declared its interest in performing the activity and a task force was therefore setup to carry on the project.

TRENORD is a train operating company, owned for 50% by Lombardy Region and for 50% by Trenitalia S.p.A., that is active mainly in the North-West of Italy. The company owns a large variety of locomotives, hauled and self-propelled vehicles, ranging from single- and double-deck passenger cars

to EMUs and DMUs of different kind. Some of these vehicles were originally equipped (and homologated) with tired wheels, making the possible application interesting for a relatively large number of vehicles.

Amongst these, ALn 668 were built in the '50s by FIAT Ferroviaria and had a huge success around the world. With an 1A'-A'1 wheel arrangement, self-propelled by two in-line 6-cylinder diesel engines and a 5 shifts mechanical gear coupled with a hydraulic torque transmission joint, their simplicity and reliability made them probably the most affordable and long-lived vehicle in the history of Italian railways.

TRENORD operates today a fleet of around twenty ALn 668 vehicles of different series on the non-electrified lines in the Milan area. Relevant for this activity is the line Brescia-Edolo that runs partly along the spectacular shores of the Iseo Lake. The line does not currently fall under the jurisdiction of ANSF (the Italian Railway Safety authority) but it is under the direct control of the USTIF Office of the Ministry of Transportation. According to Italian laws in force, the Director of Operations is the only responsible for the traffic on the line and of its consequences.

### 3. SAFE DESIGN OF THE DOVETAIL COUPLING

The drawing of the wheelsets of ALn 668 (that dates back to 1957!) was modified only in the basic features required to apply modified tyres, leaving the rest of the drawing unchanged. In order to speed up the testing phase, it was decided to modify one ALn668 vehicle and to test it (obviously without passengers on board).

Although at a design stage it was possible to reduce tyre thickness for a disc braked vehicle, ALn668 is tread braked and the original interference and tyre size were kept unchanged. This means that tyre-wheel centre locking forces are exactly the same as in the traditional design.

Looking at the original drawing (Fig. 1), a thick abutment on the field side and the retaining ring on the flange side are evident. From FE calculations, an average pressure of around  $p=33.7$  MPa resulted on the 90 mm-wide tyre/wheel centre mating surface in the worst condition (minimum interference). With a friction coefficient of  $\mu=0.33$ , this coupling can bear a lateral shifting force of  $Y_{max}=2.25$  MN if the retaining ring is missing or removed, a condition that may rarely happen [4].

An interesting case on "heavily" braked wheel is the complete recovery of the interference due to a tyre overheating especially during drag braking. In this case, lateral shift is prevented by the retaining ring, whose maximum strength (around  $Y_{max}=2.52$  MN) is limited by yielding.

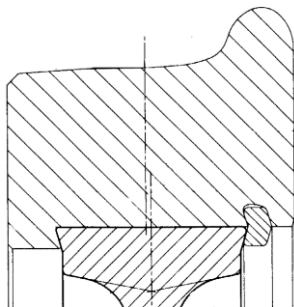


Fig. 1 Typical drawing of the tyre-wheel centre coupling.

The first drawing of the dovetail coupling, shown in [3], was discarded as FEM calculations in the elasto-plastic

domain suggested to select a different combination of mating surfaces. While both the eventually tested designs have no abutments or retaining rings at all, the male / female combination was reversed (the tyre becoming hollow) (Fig. 2, Fig. 3). The shape ("positive") mating of the surfaces guarantees that even in the case of relative tyre-wheel centre spinning there is no possibility for the tyre to displace laterally.

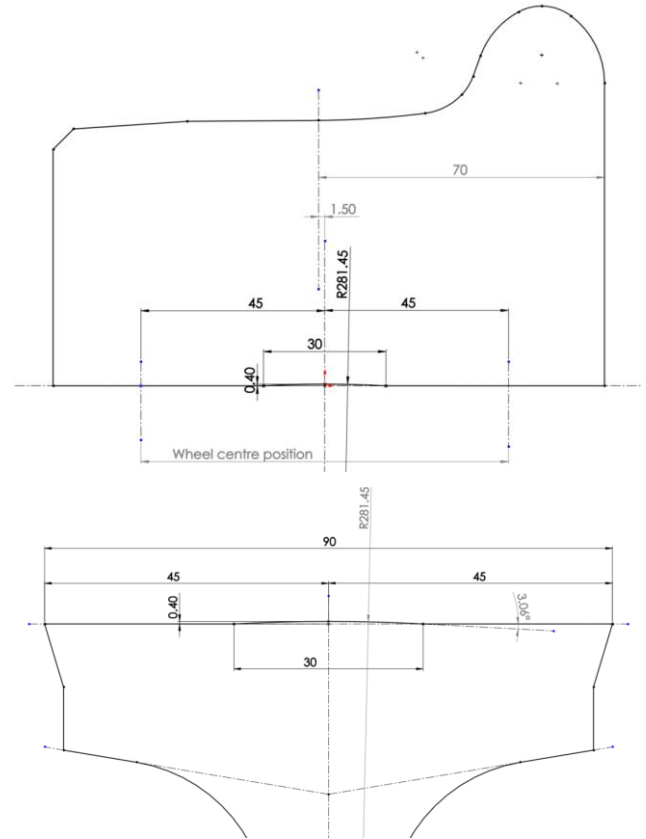


Fig. 2 Toroidal coupling machined on ALn668 driven wheelsets

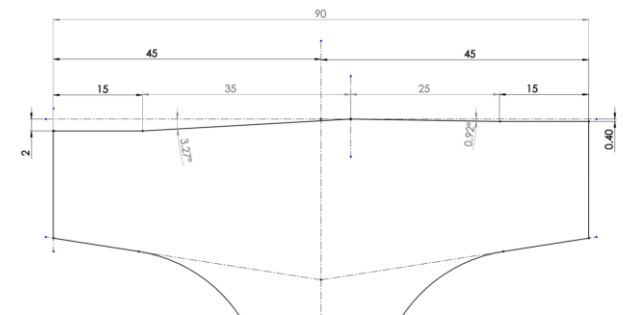


Fig. 3 Asymmetric reverse dovetail coupling on ALn668 trailed wheelsets

Considering a wheel load of about  $P= 66$  kN (axleload 13.5 t), the maximum lateral force acting on a driving wheel is  $Y_g=0.7 P = 46.4$  kN towards the gauge side and  $Y_f=0.42 P = 27.8$  kN towards the field side [5].

To check the ability to withstand axial forces, FEM simulations were performed applying a force that is ten times the maximum lateral force at the wheel rail contact, i.e.  $F_{proof}= 0.46$  MN, uniformly distributed around the tyre. Examples FEM results in the fully elasto-plastic domain are shown in Fig. 4 and Fig. 5. It is worth to highlight that the

wheel centre steel is more ductile compared to the one used for tyres, and therefore plastic deformations primarily occur on it. During lateral shift, when plastic deformations occur, the radial stiffness of the wheel centre becomes a driving factor.

Although the approach originally proposed was intended to be applied only to disc braked wheels, the ALn668 is a tread braked vehicle and a check was performed also supposing that the interference is fully recovered during a drag braking (zero mating pressure).

Safety coefficients  $F_{max}/Y_g$  or  $F_{max}/Y_f$  are described in Table I, considering 3 mm as the highest admissible lateral shift of the tyre. In most cases the coupling is able to fully transmit the proof load also in the case of no pressure on the surface. In this case, in fact, the positive coupling is sufficient to prevent the fully lateral shift of the tyre. Only in one case (asymmetric dovetail with force to the field side) the coupling cannot completely withstand the load, nevertheless, the safety coefficient remains  $\gg 1$ .

TABLE I. SAFETY COEFFICIENTS (S.C.) OBTAINED BY MEANS OF SIMULATIONS OF AN 0.46 MN AXIAL LOAD APPLICATION ON THE TYRE.

Kind of coupling	Max slope [%]	S.C. with $p=33$ MPa [-]	S.C. and shift with $p=0$ [-]
Toroidal Gauge side	5.35	$F_{max}/Y_g > 10$	$F_{max}/Y_g > 10$ ( $\Delta X=2.2$ mm)
Toroidal Field side	5.35	$F_{max}/Y_f > 16.7$	$F_{max}/Y_f > 16.7$ ( $\Delta X=2.8$ mm)
Asymmetric Dovetail Gauge side	5.71	$F_{max}/Y_g > 10$	$F_{max}/Y_g > 10$ ( $\Delta X=1.7$ mm)
Asymmetric Dovetail Field side	1.6	$F_{max}/Y_f > 16.7$	$F_{max}/Y_f = 6.7$ ( $\Delta X=3.0$ mm)

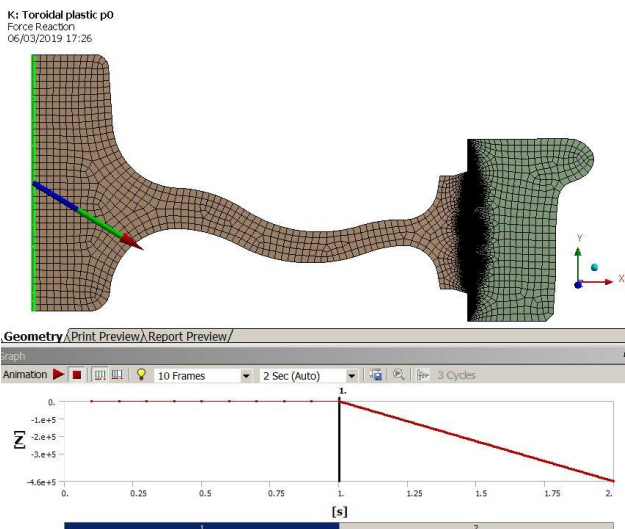


Fig. 4 Fully non-linear FEM model estimating lateral force needed to shift the tyre. The considered value is the maximum evaluated during the application of a large lateral force uniformly applied along the tyre.

#### 4. MACHINING, ASSEMBLY AND TOLERANCES

TRENORD currently outsources part of the wheelset overhaul activity to Nuova Comafer, and this was the case for this modification on ALn 668 wheelsets. Nuova Comafer developed the machining cycle in order to consistently save time and money in case the dovetail tyre modification is applied on a large scale.

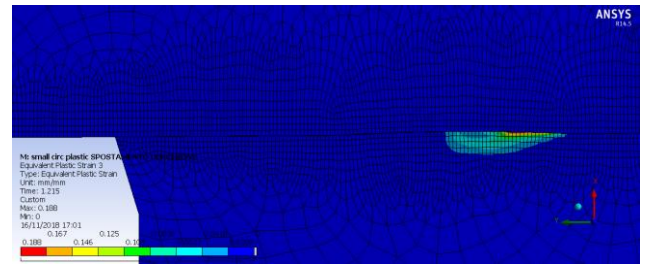


Fig. 5 Plastic deformation on the toroidal coupling resulting from the application of the maximum lateral force that the coupling can transmit.

Following one of the basic principles of machine design, i.e. interchangeability, all the components were machined separately on CNC lathes and then assembled.

Machining did not show any critical or peculiar phase. Common tolerances available on modern machine tools allowed to largely remain below 0.1 mm in terms of both radial and axial runouts. All parts were checked with manual gauges as well as with the large CMM available at the company shop.

Tyres were then heated up to 300 °C, within limits stated by UIC codes. Because of the lack of abutments, assembly was possible only vertically, by leaning the hot tyre on a flat surface and lowering the wheelset (axle + wheel centres) on a specifically designed jig (Fig. 6).

One of the most critical features to obtain was the respect of the stringent limits on tolerances and unbalance stated by [5]. The goal of the entire project was in fact to prove that it was possible to assembly a new wheelset (or replacing worn / defective tyres if needed) without any further machining.

The relevant parameters and the results obtained were:

- requirement on radial run-out for passenger vehicles with speed  $\leq 160$  km/h:  $\leq 0.5$  mm (obtained 0.2 mm);
- requirement on axial run-out for passenger vehicles with speed  $\leq 120$  km/h:  $\leq 1.0$  mm (obtained 0.3 mm).

About residual unbalance, the greatest measured value was 66 gm, while [5] requires a maximum of 75 gm for vehicles with maximum speed in the range  $120 < v \leq 200$  km/h (no unbalance is prescribed for vehicles running at  $v \leq 120$  km/h as for the present case). When the assembly of two wheel centres and the axle is correctly balanced, the application of perfectly axisymmetric treads obviously does not introduce any unbalance.

This results are particularly promising and they not only allow to perform line tests but let presume that similar results can be obtained also on other vehicles, also at higher speeds.

#### 5. LINE TESTS

The DMU ALn668.1036 was equipped with the four wheelsets in the Iseo depot and then tested on 21 and 22 November 2018. Routes included both flat track run at the maximum vehicle speed (90 km/h) as well as steep sections ( $i=26\%$ ). The vehicle was tested in running order (no payload) with 4 people on board including two of the authors (Fig. 7 and Fig. 8).



Fig. 6 Lowering a trailed wheelset on a hot tyre resting on the specifically designed mounting jig with calibrated shims.



Fig. 7 The ALn668.1036 vehicle before the tests on the roundtable in Iseo, Italy, 21<sup>st</sup> November 2018.



Fig. 8 A nice picture shot along the Iseo shore during a stop for traffic reasons.

A thermal camera FLIR One Pro was used during the tests to observe the temperature reached by brake blocks and tyres. A particularly meaningful test was the application of 7 (seven) consecutive emergency stop brakings from the maximum speed (70 km/h) while running downhill on an around  $i=22\%$  line stretch. Fig. 9 shows the mounting location of the thermal camera and an example of a thermal image recorded during the last emergency braking. Wheel centre and tyre always remained below  $100^{\circ}\text{C}$ , with similar temperatures. This shows that the safety margin against tyre dismounting was largely in excess on this application. It is worth to remind that tyre thickness and interference indicated in UIC codes apply for *any type of rolling stock* (locomotives, freight wagons, passenger cars, etc.), *any*

*speed* and *any axleload*, confirming that old standards were largely oversized for a light DMU.

No tyre spinning and no tyre axial displacement were observed, confirming that the concept was reliable enough even under absolutely non-realistic conditions.

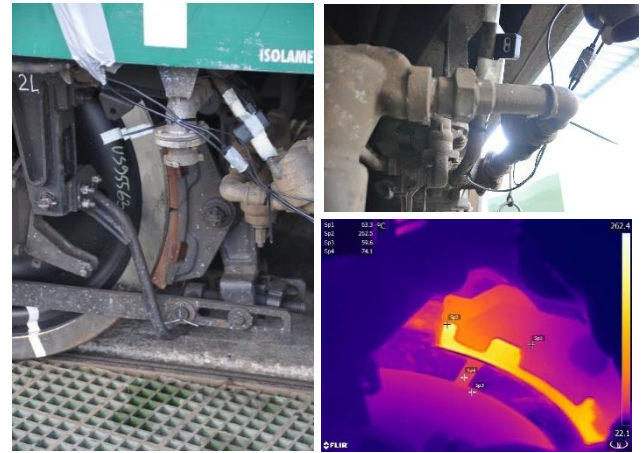


Fig. 9 Thermal camera framing one wheel and a thermal image shot during the last of seven consecutive emergency brakings.

## 6. FURTHER DEVELOPMENTS

As seen above in Fig. 6, mounting was possible only vertically and this contrasts with the need of managing tyre replacement in an easy way. Nuova Comafer is in fact use to replace both tyres on a wheelset with the axle resting *horizontally* on proper supports.

To solve this problem, the tyre was modified by introducing a small abutment and a constant slope of 1:75 (1.2 mm diameter difference on a mating length of 90 mm) (Fig. 10). This allows an easier mounting by simply pushing the tyre onto the wheel centre. Also in this case the coupling was simulated as described in paragraph 3, resulting in a safety coefficient  $F_{\max}/Y_f > 16.7$  towards the field side for the case with  $p=33$  MPa and  $F_{\max}/Y_f = 3.1$  in the case with  $p=0$ .

It is worth underlining that the size of the abutment is limited to avoid large asymmetry during tyre cooling given by the stiffening provided by ordinary abutments.

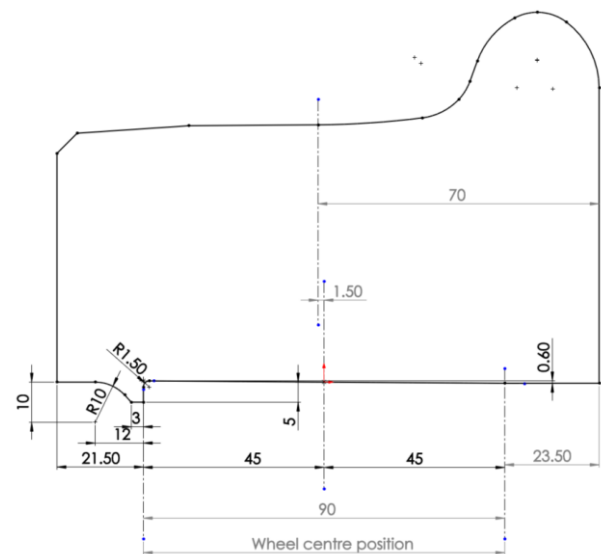


Fig. 10 Drawing of the final solution adopted for the dovetail coupling.

The chance of testing the new tyre mating geometry will be coupled with the availability of a new casted spoked wheel centre made of austempered ductile iron described in another paper given at this conference [7]. It is hoped that the fatigue tests, currently in progress [8], will be finished before the conference.

Stress analysis and coupling strength gave sufficient confidence to consider the opportunity of performing line tests before the end of the fatigue tests. At the moment of writing the tests are planned for the beginning of May 2019 (Fig. 11).



Fig. 11 The casted wheel centre that is going to be tested soon.

As the feasibility of replacing worn tyres by using fully machined new tyres respecting all tolerances was demonstrated, this opens new possibilities about the management of maintenance of vehicles equipped with tyred wheels. An ongoing study, performed in partnership with ABB Robotics and IPG Photonics for a railway enterprise that has a significant part of its fleet made of inboard bearings wheelsets, led to the design of a fully automated robotized tyre exchange station.

Although a specific paper [9] was not accepted at this conference, the project is nearly finished and the overall appearance of the station is shown in Fig. 12. It consists of two robots, two tyre induction heating systems, an underfloor cart lifting the wheelset up from the axleboxes and equipped with proper worn tyre laser heating systems. The station is completed by fully automated warehouses and automated guided vehicles (AGVs) for unmanned tyre storage and handling. The reader interested in more details can check [10] or contact the corresponding author.



Fig. 12 Screenshot of the simulation of the tyre exchange station.

## 7. CONCLUSIONS

The research described in this paper allowed to define the design phases and the detailed drawings to get a fully functional tyred wheelset starting from fully machined components. Life of wheel centres and axle becomes virtually infinite, and this looks very attractive together with the astonishing savings possible by adopting a new maintenance philosophy.

Workshop practice and tools proved to be perfectly adequate to achieve the desired results. A following specific testing campaign under severe conditions was therefore performed, confirming the positive outcomes of the whole activity.

The proper combination of techniques such as advanced structural optimization, mass reduction, noise reduction and simplified workshop practice are of absolute interest to save time and money. The supply chain will change noticeably as well as the availability of the vehicles.

## REFERENCES

- [1] A. Bracciali, G. Megna, "Stresses and strains in tyred wheels during tyre fitting process", Proceedings of The Fourth International Conference on Railway Technology, Railways 2018, 3-7 September 2018, Sitges, Barcelona, Spain.
- [2] A. Bracciali, G. Megna, "Tyred wheels without braking: structural optimization", Proceedings of The Fourth International Conference on Railway Technology, Railways 2018, 3-7 September 2018, Sitges, Barcelona, Spain.
- [3] A. Bracciali, G. Megna, "Re-design of tyred wheels to optimize maintenance.", Proceedings of The Fourth International Conference on Railway Technology, Railways 2018, 3-7 September 2018, Sitges, Barcelona, Spain
- [4] Joint Sector Group, "Final report on the results of the Joint Sector Group activities linked to the action plan defined under the Task Force Freight Wagon Maintenance", 17.12.2012, available on [www.jsgrail.eu](http://www.jsgrail.eu).
- [5] EN 13979, "Railway applications. Wheelsets and bogies. Monobloc wheels. Technical approval procedure. Part 1: Forged and rolled wheels" CEN, Brussels, 2011.
- [6] EN 13260:2009+A1, "Railway applications - Wheelsets and bogies - Wheelsets - Product requirements", CEN, Brussels, 2010
- [7] A. Bracciali, S. Masaggia, G. Megna, E. Veneri, "Quiet and light spoked wheel centres made of Austempered Ductile Iron", accepted for presentation at IWC2019, 16-20 June 2019, Venice, Italy.
- [8] L. Bocciolini, R. Bovi, A. Bracciali, G. Caianiello, G. Megna, L. Rota, E. Temporin, E. Veneri, "Manufacturing and testing of a tyred wheel with casted ADI wheel centre", accepted for presentation at IWC2019, 16-20 June 2019, Venice, Italy.
- [9] A. Bracciali, C. Brigo, S. Cattaneo, M. Franzosi, M. Lepori, G. Megna, "Fully Robotized Maintenance of Tyred Wheels", not accepted for presentation at IWC2019, 16-20 June 2019, Venice, Italy.
- [10] A. Bracciali, "Tyre exchange station of tyred wheel mounted on an inboard bearings passenger car bogie", video published on <https://youtu.be/xS-rDXDP3gE>, accessed on 29.03.2019.

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