A new wheelset maintenance concept
R. Gallo\textsuperscript{1} S. Cantini\textsuperscript{1} D. Minini\textsuperscript{2}
LucchiniRS SpA, Lovere, Italy\textsuperscript{1}; LucchiniRS SpA - LMF Unit, Lovere, Italy\textsuperscript{2}

Abstract
Train operators make every effort to maximize fleet availability and minimize related maintenance cost; in this context, wheelset life cycle cost is one of the more relevant operational effort. Moreover, thanks to the market opening to new railways undertaking, a new generation of train operators are approaching this field in an alternative way compared to traditional ones. These operators are not train “experts” but simply offer a new type of service to passengers.

It is worth noting that wheelset constitutes a main cost in terms of wagon/trainset life cycle cost: actually railway undertakings are obliged to store a significant amount of parts or complete wheelsets to ensure the availability of their coaches and continue searching for the cheapest sources to reduce their costs of maintenance. In the same way maintenance service for wheelsets must be carefully planned in order to reduce outlay related to wagon stop.

The above reflects a main task idea: define a thorough procedure for assessing maintenance step carried out by in service experience, different levels of maintenance practice and new development in terms of design, material innovation and non destructive test. In addition, the study of the reliability of the component, through the proper engineering framework and correct failure mode effects and critical analyses approach, enables a definition of complete packages of maintenance rules.

The present paper describes an example of innovative wheelset design which integrates design optimization, managing process upgrade, special axle protection and dedicated in service inspection plan, keeping into account performances of the selected inspection method as well as axles fracture mechanics. This a different approach to wheelset maintenance, both preventive and corrective, can offer a simple solution also in terms of cost reduction without compromising the safety level of components. Furthermore a different service can be offered to operator in order to reduce costs due to maintenance operations and inventories.

It is clear that these wishes will be fully implemented better if future railway operators and sector relevant standards such as TSI will allow to use this innovative approaches. Together with vehicles and their subcomponents supplier, track, substructure and operational procedures, these new approaches that are based on a better evaluation of actual wheelset material damage mechanisms and load inputs, lead to a consequent measurable increase of safety and reliability.

Index terms: Maintenance, Design, FMECA, PMA, Risk Assessment, NDT, Cost.

1 The wheelset maintenance cycle
The evaluation of cost impacts on wheelset in service inspection and overhauled starts from the study of the maintenance cycle. Maintenance is “combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function” [1]. Wheelset maintenance includes all the measures to be applied on the component depending on its mission profile, the specific inspection interval and on the component life, from periodic in service inspection to off service disassembly and substitution, repairing activities, and quality control.

The case study is based on maintenance standard procedure adopted in the European network, as the EN15313 [2] and the main operators internal rules and, for the freight wagon wheelset, the VPI 04 [6] and the additional checks visual inspection as for EVIC [7] and ECCM [8].

Table 1 shows the inspection intervals for different wheelset application compared in terms of distance run and time. Although operators tend to minimize the costs of maintenance, they are required to operate in a way that should follow the indication of the standards, where applicable, for example the EN15313 [2] or the GM/RC2496 [4]. Standards provide to operator the minimum requirement to follow in order to guarantee the safe service of the vehicle. Or, according to internal rules, not to follow the recommended method of meeting the requirements of the standard, operators should assure itself that, the method it is following, is as effective, and no less safe, than the method that is recommended in the standard. Obviously, any deviation from standard process may assure the complete safe operation of the wheelset in service. This is what wheelset designers, suppliers and, especially, the maintenance workshop under ECM [9] directive must ensure through the definition of the maintenance intervals and plans also based on the return from the exercise.
2 The design of a wheelset maintenance program

Design a wheelset maintenance program it is the key for the responsible of the vehicle maintenance to identify the critical point in order to guarantee for the operator the safety and availability of the wheelset during the service, as defined in the example reported in table 2.

Table 2: FMECA for a HST

<table>
<thead>
<tr>
<th>Description</th>
<th>Function</th>
<th>Failure mode</th>
<th>Failure cause</th>
<th>Failure description</th>
<th>Failure effects</th>
<th>Critical grade</th>
<th>Criticality Factor</th>
<th>Insuficiency Factor</th>
<th>Preventive Maintenance</th>
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Basically, the capability of the wheelset shall be evaluated through the FMECA (Failure Mode, Effects, and Criticality Analysis) and PMA (Preventive Maintainability Analysis) study of a wheelset. Moreover, thus lead to define the LCC (Life Cycle Cost) of the components.

Table 2 and table 3 prompt out which are the topics where a train maintenance manager may work on in order to reduce the cost and time and maximize the availability of the vehicle:

- reduce the number of inspections (visual and non-destructive test);
- avoid off service of wheelset (due to unexpected works of repair) and, especially:
- avoid any type of scrap (fretting, corrosion, deep impact scratches).
Table 3: PM Analysis for a HST

<table>
<thead>
<tr>
<th>Detection</th>
<th>Unit</th>
<th>Service</th>
<th>Maintenance action</th>
<th>Key No.</th>
<th>Interval</th>
<th>Action limit (min)</th>
<th>Material cost</th>
<th>Active (G€/yr)</th>
<th>Min.</th>
<th>Max.</th>
<th>Upper level detection cost (G€)</th>
<th>Upper level accuracy (CM)</th>
<th>Upper level frequency (CM)</th>
<th>Vehicle service cost (G€)</th>
<th>Vehicle vehicle</th>
<th>Vehicle</th>
<th>Operational level</th>
<th>Operational level</th>
<th>Vehicle life cycle cost (G€)</th>
<th>Vehicle life cycle frequency (CM)</th>
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| Material |        |         |                    |         |          |                     |              |              |      |     |                                |                         |                         |                          |              |        |                  |                  |                 |                         |
|----------|--------|---------|--------------------|---------|----------|---------------------|--------------|--------------|------|-----|--------------------------------|--------------------------|--------------------------|--------------------------|              |        |                  |                  |                 |                         |

The above table indentifies the significant point in terms of safety and eventual consequences for the service. Designer had to identify the major causes that can lead to discern about the failure mode and effect, the critical grade for safety and service operation performances. Once identified the main failure case, designers identify the possible improvement action, as calculation or geometrical evaluation, additional features in machining/overhauling process or during inspection. Preventive maintenance analysis helps train manufacturer to evaluate the maintenance cost of the vehicle during the service period starting from each single component. An action on wheelset improvement has influence also reducing the CM (corrective maintenance) cost.

It is worth noting that inspection and maintenance steps of each critical component should be as well synchronized in order to reduce the overall train downtime: this is the job of train manufacturer first, and to ECM [9] later.

The activities to be performed on wheelset in order to maintain a suitable safety level varies from visual inspection for ballast impact or corrosion to automatic NDT for overall integrity assessment; these inspection may be ruled by standard and or mandatory prescriptions such as for the VPI [7] on freight wheelset wagon. Surface axle inspection (inspection workshop has to remove the paint for surface integrity inspection) have a strong impact on freight fleet management cost. Moreover, as consequences of investigations results on railways accidents of the last 5 years, ( especially of railway freight transportation ) EVIC and ECCM prescriptions were highly recommended by ERA and nowadays are part of standard inspection plan.

2.1 Axle inspection according “EVIC” and ECCM

Additional visual inspection was introduced in European freight wagon fleet, EVIC [7] (European Visual Inspection Catalogue) and the “European Common Criteria for Maintenance (for freight wagon axles) – ECCM [8]”. The visual inspection of the European wheelset population, was introduced since April 2010 and since May 2011, application is mandatory for freight fleet. To summarize the objectives of control are:

- to inspect the axle status according the criteria in the EVIC [7] catalogue;
- to remove axles from service not fulfill the catalogue requirement (immediately / after unloading);
- Improve the status of the axle surface in terms of treatment of local and severe defects and of large and heavily corroded areas, strongly and uniformly pitted surface.
- Complete NDT on all axle sections in the medium wheelset maintenance level;
- Complete Magnetic Testing (MT) on the total axle surface in the highest wheelset maintenance level. to handover removed axles to maintenance with appropriate treatment and Non Destructive Testing (NDT).
- NDT of the whole axle during medium and heavy maintenance (which increases the probability of crack detection and results in more checks / higher frequency of maintenance tasks)
- to record a set of minimum data for the inspected axles (Return of Experience);

This requirements are already widely adopted by the freight wagon keeper (because of the time based frequency inspection frequency) and rules are yet defined also in the EN15313 [1] valid for any type of fleet. As consequence, the related cost for the above activities have a strong impact on the transport activities, since the related inspection are in charge of the freight wagon keeper.
3 Impact cost analyses of current maintenance policy

Considering the maintenance intervals as for the table 1, cost invoiced from workshop for inspection depends on the frequency and type of controls performed. Table 4 shows estimated cost for wheelset life for a freight application according the prescription of the ECCM [7] (EN standard) and VPI [6] rules. The cost are based on an average values of employment and material cost on European market [5]. The same consideration should be applied also for passenger fleet.

Table 4: cost estimation for axle life overhaul

<table>
<thead>
<tr>
<th>Overhaul (EVIC + EWT included)</th>
<th>ECCM</th>
<th>VPI</th>
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</thead>
<tbody>
<tr>
<td>300000</td>
<td>€19,1</td>
<td>€19,1</td>
</tr>
<tr>
<td>600000</td>
<td>€570,0</td>
<td>€520,0</td>
</tr>
<tr>
<td>900000</td>
<td>€19,1</td>
<td>€19,1</td>
</tr>
<tr>
<td>1200000</td>
<td>€570,0</td>
<td>€520,0</td>
</tr>
<tr>
<td>1500000</td>
<td>€570,0</td>
<td>€520,0</td>
</tr>
<tr>
<td>Reduced life time</td>
<td>€26,0</td>
<td>€36,0</td>
</tr>
<tr>
<td>LCC per axle/km</td>
<td>€1.784,2</td>
<td>€2.838,2</td>
</tr>
<tr>
<td>Total per axle/km</td>
<td>€0,0012</td>
<td>€0,0019</td>
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</table>

When assessing the costs as for the above table, the following assumptions was taken in consideration:

- The maximum mileage of a wheelset is 1'500'000 km on average;
- Maintenance is done every 300'000 km on average including revision of bearings;
- Heavy maintenance is executed after 600'000 km on average;
- Reprofiling wheel not included;
- EWT and EVIC control were included;
- A scrap ratio of 3% of axles is considered;
- A cost of a technical skill is considered (as for non destructive testing)

The main estimated cost is due to the periodical non destructive test, according to VPI [6], that consist in the removing of paint from the axles, rust removal (or sandblasting), performing ultrasonic and magnetic particle test and finally repaint the axle. Cost related to the vehicle downtime is not considered in this evaluation although a different approach shows a remarkable uptime reduction time also for the above described activities (having big impact on the spare amount of wheelset).

4 Wheelset design optimization

The cutback of maintenance costs through inspection intervals optimization can only be accomplished starting from design and manufacturing process. The role of the designer is important to define the final geometry of the wheelset, in particular the effort ought to be concentrated on axles in order to obtain the whole service life. Moreover, considering that in average axles life is longer than other wheelset components’ life, it is very important to preserve axle seats from fretting fatigue and/or fitting/unfitting damages.. The main topics in design phase and optimization are:

a) The better knowledge of wheels (and other components) fitting pressure may reduce the scrap of axles during maintenance due to scratches and diameter reduction (under service limit).

b) FEM analysis on transition seats study and optimization reduce the fretting phenomena, that typically appears on the end of wheel seats inner side.

c) Seats cold rolling process induce compression stresses in order to improve fatigue characteristic and avoid fretting phenomena (e.g. axle box seats)

d) Design stage together with NDT techniques knowledge should help in optimizing the geometry for a better inspection sensitivity of axles

e) Material properties in terms of notch sensitivity and crack propagation as well as NDT reliability (POD curves) and service real load spectra are necessary for the fine tuning of inspection intervals

Introduction of hollow bore should decrease the mass of wheelset, increase the sensitivity and reliability of NDT analyses (POD curves)

4.1 Wheelset protection

In service inspection or during off service maintenance operations, surface protection of the axles needs to be checked and restored. Moreover, as prescribed in same standard or guideline, in order to perform NDT such as MT or VT it is necessary to completely remove the paint with additional cost ([6]). In several case, often in freight fleet, due to the type of service or due to the lower track maintenance level, it is necessary to continuously restore the paint under the vehicle during normal visual inspection in order to prevent corrosion, or, in more critical situations, restore the surface from ballast impact (if allowed by design).
The research and development of new wheelsets protection systems having EN13261 [3] prescriptions as starting point, are following two different approaches:

a) Define a level of protection based on single layer coating solution able to protect the wheelset and easy to restore or to remove.

b) Define a level of total protection, not only against the corrosion but also the ballast, that can be therefore called “permanent” because this will not be removed during overhauling.

Both approaches show advantages and disadvantages, linked not only to aspect related to cost but also application and depot activities.

A single layer system, fulfilling standard requirements with thickness between 100µm to 200µm, allows to reduce the repairing activities time and allow surface NDT such as eddy current test (ET) without any interferences instead the MT inspection (which needs to remove paint).

A “permanent ballastproof solution” may have different application grade, fine tuned on each specific mission profile, and it is able to protect the axle for the whole life. Return of experience of LucchiniRS on its own system called Lursak® from HST China [15], shows that, coupled with bore probe UT for high sensitivity in service axle integrity inspection (from inner bore hole), there is no need to further remove painting and perform VT or MT inspections, neither in service or during L3 maintenance step.

4.2 Fracture mechanics and POD curves for ultrasonic inspection design

Service safety is surely linked to the wheelset design, but without a correct definition of inspection intervals and then a reliable application, even the best designed axle is not a safe component. A scientific approach for the management of inspection intervals is based on three pillar factors:

- Real load spectra
- Fracture mechanics for crack nucleation and evolution from a surface defect
- POD (probability of detection) curves for the given NDT method

A reliable availability of each of these aspects, in particular for the second and the third one, requires the study of the fracture mechanic and the statistical approach for NDT technique [12]. In railways application this approach is relatively new, nevertheless it has a strong impact in order to set up the correct inspection intervals. The probability to detect a defect in the components is strongly related to the NDT method used and evaluates not only the capability to detect the defect (the largest defect that it can miss during inspection) but also the component material and geometry, equipment performances and the human factor introduced by inspectors.

![Figure 1: Load spectra for an HST and crack propagation simulation outcome.](image-url)
wheelset from vehicle, to not remove paint or dismount any components, except for the axle box end cup for axle coupling. Compared to the method prescribed by VPI 04 [6], the reduction time for the (only) NDT inspection is about 70%. One step forward in increasing the in service inspection reliability is the adoption, also for freight axles, of hollow bore axles and the UT inspection from the bore surface.

Figure 2: rotating far end scan probe for full axle UT inspection.

The further development of Bore Axle Testing (BAT) enabled the inspection of all axle surface with a constant sensitivity, compared to standard UT of solid axles; this is due to the fact that the ultrasonic path is limited in all the sections inspected (while, for instance, when dealing the far end scan this is function of the inspected section distance from the probe). BAT can be easily performed on all the axle without need of dismounting any component (i.e. bearings, wheels, gears, i.e.) or without axle paint removal, as the axle surface is scanned by the internal side, and generally fully automatic scan reducing the impact of human error.

4.3 Cold rolling
Cold rolling is based on the combination of three simultaneously working physical effects, i.e. a deep layer of residual compressive stress in the surface of the component, a strength increase through plastic deformation and the elimination of micro notches and improvement of surface roughness quality (reduction of local stress intensity factor effect). The method aims clearly to increase the quality (in terms of fatigue resistance and in particular crack nucleation thresholds) on all the manufactured axles according to certain requirements as increasing of the surface hardness and of residual compression stresses. Process is to take into account during design stage, to avoid problems as small surface cracks on fitting components, drastically reducing the scrap ratio of axles due to fretting problems.

Figure 3: increase of hardness and residual stress layout on a motor axle seats

The effect of the deep rolling on propagation lifetime of railway axles confirmed the large increasing of the residual life of railway axles subjected to the cold-rolling manufacturing process, as predicted by the developed crack propagation model and full scale fatigue test [11]. The benefit of this process can be summarized as follows:

- the hardness surface values (up to 3 mm depth) is significant, leading to a better resistance to small relative slip between coupled components
- the compressive residual stress outline measured is significant, improving the fatigue behaviour of material reducing (enabling) the cracks propagation, increasing the axle lifetime
5 A new wheelset maintenance plan

All the features discussed in the previous chapters, such as design method in terms of axles geometry optimization, wheelset protection, NDT inspection optimization by crack propagation study, lead to a reduction of wheelset inspection step and time and wheelset overhauling scrap costs (i.e. related to wheelset ancillary components wheels substitution). Moreover, the downtime of the fleet is reduced because of:

- No visual periodic inspection (case of permanent protection as the Lursak® [15])
- No necessity of dismounting wheelset for paint blasting removal (no necessity of surface integrity inspection)
- Avoid MT superficial test by far end scan UT inspection
- No passive time for paint application / drying

The pillar of the maintenance improvements are the reduction of the inspection intervals and the reduction of the time of the controls in order to increase time of train availability and cut personnel cost and in particular:

- Action time and manpower time (for visual inspection and NDT)
- Optimize the vehicle/wagon downtime (avoid off service and spare wheelset)
- Reduction of manpower and total cost (€/1000 km)

Different scenario for freight wagon and EMU trainset application are considered for cost savings evaluation.

5.1 Cost evaluation – freight axle and wagon

According to the new wheelset design approach as described in previous paragraph, it is possible to estimate and compare the axle maintenance cost appreciating the economic advantages. The case is based on the experience of the Freiset25® (dedicated freight wheelset) case developed by LucchiniRS for European market, where all the technologies advantages described, as shape optimization, far end scan probe and permanent protection were implemented (defined scenario S1).

Table 5: cost estimation for maintenance wheelset life

<table>
<thead>
<tr>
<th>Overhaul as [000] km</th>
<th>ECEM</th>
<th>VPI</th>
<th>New approach</th>
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<tr>
<td>300000</td>
<td>4.56</td>
<td>4.29</td>
<td>5.00</td>
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<tr>
<td>500000</td>
<td>4.31</td>
<td>4.16</td>
<td>4.90</td>
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<td>1000000</td>
<td>4.31</td>
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The following figures shown the saving (time and cost) related to a wagon (freight case).

Figure 4: estimated savings applying the new maintenance plan for a freight wagon (estimated time for wheelset control according VPI is about 13 working days)
Considering a freight wagon service life of 30 year and 60,000 km / year mileage, improving different NDT method and a better surface protection, compared to the ones prescribed by the VPI [6] and optimized design (off service wheelset cost not considered), the estimated annual savings, by the new concept of design and maintenance rules may be up to 30%. Considering a fleet of 50,000 wagon, the annual savings is about 1.9 million € and total life cost saving (30 years) about 31 million Euros.

5.2 Cost evaluation – high speed vehicle

figure 5Error! Reference source not found. prompts a saving analysis in terms of cost and time for an HST vehicle (8 cars configuration), considering a train service life of 30 year and 300,000 km year mileage (starting from china experience on CRH380A Error! Reference source not found.). In this case we estimated that the improvement crack propagation evaluation and POD simulation in the design wheelset evaluation might in a scenario 1 (S1) double the inspection UT intervals and enlarge the visual inspection and in scenario 2 (S2) quadruple the inspection UT.

![Figure 5: estimation saving applying new maintenance plan for a HST train set wheelsets](image)

It is to remark the advantages also from S2 (interval typical from European fleet) to S3 (further improvement). The estimated annual savings may be between 24% to 50%. Considering the only shift from S2 to S3 for a fleet of 100 train set, the annual savings could be up to 125 k€.

5.3 Cost evaluation – EMU commuter train

Same considerations can be applied also for a common EMU commuter train (service life of 30 year and 150,000 km year mileage). The estimated annual savings, considering the 3 scenario as previous case, may be up to 26%. Considering a fleet of 100 train set, the annual savings could be up to 250 k€ per trainset.

![Figure 6: estimation saving applying new maintenance plan for a commuter EMU train set wheelsets](image)
6 Conclusion and further consideration

Train operators make every effort to maximize fleet availability and minimize related maintenance cost; in this context, wheelset life cycle cost is one of the more relevant operational effort. Technology evolution of last decade introduced also in railway wheelset business, new concepts in terms of safety assessment and inspection plan design, and new solutions in terms of manufacturing processes and products.

An optimized design of maintenance plan may take benefit of last technology evolutions to:
- level up safety
- reduce costs of in service inspections
- reduce costs of overhauling operations and components inventories
- increase fleet availability by reducing maintenance downtime

Analyzing the data available for different vehicles and cost evaluation simulation for different scenario, from freight wagon to high speed service, maintenance costs reductions can be estimated in 30% for the freight application, 25% for HST and commuter train fleet.

To better understand the potential of new maintenance plan design approach, value stream mapping can be performed to determine other potential cost reduction in terms of scrap rate. This will involve an assessment of the entire vehicle system including the railways maintenance rules. With new technologies application it is evaluated that shall be possible to reduce the scrape rate for service defect from 4 % to less than 1%.

Additionally, feedback from service (REX), when effectively gathered and available, is a further driver for continuous improvement of maintenance plan [15].

7 References

[2] EN 15313: 2010 “Railway applications - In-service wheelset operation requirements - In-service and off-vehicle wheelset maintenance”.
[9] ECM certification Application guide including explanations Maintenance workshop certification scheme (2011) - ERA Safety Unit Safe Cert Sector