Acoustic effectiveness of damped wheels and impact on life-cycle cost of different typologies of passenger trains

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Abstract

Railway noise reduction at the source is the preferred way indicated by the European legislator, although certainly the hardest to be obtained from an engineering point of view. A cost-benefit analysis of the available solutions should drive the political decisions. This paper describes the impact of a specific low noise wheel, whose noise reduction effect was proven in normal service, on the Life-Cycle Cost of different types of vehicles. The analysis is conducted on several types of passenger rolling stock, i.e. high speed trains, both conventional and tilting, Electrical and Diesel Multiple Units. All direct and indirect costs associated with this kind of damped wheel are taken into account during the entire life cycle of the vehicle.

1. Introduction

Rolling noise is the main source of railway noise in a wide range of speeds, approximately up to 250÷300 km/h where aerodynamic noise becomes prevailing. The interest in trying to reduce rolling noise at the source is therefore evident and many efforts are continuously made to offer reliable industrial products at a reasonable cost.

As known, rolling noise is generated by the surfaces of the various bodies involved in the phenomenon (wheels, rails, sleepers, ballast, superstructure) vibrating under the effect of wheel-rail contact forces which, in turn, are mainly due to the *combined* roughness of the wheel and the rail.

The *combined* roughness is given by the energy sum of the roughness of both the wheel and the rail *minus* the effect of the so-called *contact patch filter* that depends on the vertical load and on the local geometry features (curvatures) of the contacting bodies. It was proven that artificially changing the wheel and rail profiles to reduce noise generation is not effective, beyond all other problems (vehicle dynamics, maintainability), and this option is nowadays not considered to be realistically feasible.

Wheel roughness is certainly dominating on tread braked vehicles with cast-iron blocks; numerous and constant efforts, not described here, are in progress at European level to introduce sinter or synthetic blocks capable to keep wheel roughness to levels comparable to wheels mounted on disc braked wheelset. For the latter case, wheel and rail roughness are often similar, with rail roughness becoming prevalent on corrugated track, which is a rather common situation in tight curves (approximately R<400÷600 m) typical of metro and commuter lines.

Acting on roughness can be done by longitudinal rail profile rectification (via grinding, planing or milling operations) and by wheel reprofiling typically with underfloor lathe. Nevertheless, specific grinding techniques, like offset grinding or oscillating block grinding, are not widely accepted partially due to some limitations (they can not reshape the transverse rail profile); wheel reprofiling is normally done only in case of heavy polygonization or, more frequently, when wheel flats are present with some defined geometric characteristics (length, depth). As a matter of fact, roughness control is made only where heavy rail corrugation is visible, well above the limit of what an acoustician considers a "rough rail". It is worth to underline that also rails in apparent good condition may be quite loud, i.e. high roughness can be present on a rail in normal service without being visually noticeable.

The last possibility is working on radiation properties of the bodies involved. Track related measures are quite various and can be complicated; as their description lies outside the scope of this paper, here it is only reported the recent conclusion that carefully designed rail dampers can reduce noticeably rail noise (up to approximately 5 dB) but that their effect on overall noise is much lower (in the order of 2÷3 dB) if not used in conjunction with low noise wheels [1].

This consideration introduces to the content of this paper, which starts from the position that some damped wheels exist in normal service and from the observation that their effect on overall noise was relevant, especially in the medium to high speed range. One of the classical arguments against the use of "low noise" wheels is their extra cost as both first fitting and spare parts, neglecting not only all the other associated costs (maintenance, disposal) but, even more important, the advantages given by their use and the associated savings.

While it is clear that in very loud situations the use of low noise wheels can not solve the noise problem, in many "border" cases their use can save the erection of noise barriers whose cost is nowadays is the order of 1 M€/km of double track. The paper will show how the costs associated to the use of damped wheels are only a tiny fraction of that value, even if considered for the entire life of a train.

2. The Lucchini Sidermeccanica *Syope®* wheel

2.1. Description of the treatment

Lucchini Sidermeccanica SpA is a steel making company that designs wheelsets for all railway, mass transit, metro and tram applications. One of the fields that were considered to be more important in the near future was that of railway noise and the related activities (training, purchase of the instrumentation, laboratory set-up) started in 1995. All the main treatments available at that time were tested in the new born laboratories, and the best candidate was selected on the basis of industrial and commercial reasons.

The *Syope®* treatment, as it was called from the name of the Greek goddess of silence, is used to provide levels of damping much higher than the *rolling damping* [2].

Basically, the treatment consists of a steel layer constraining a special adhesive polymer sheet. The polymer was developed by 3M for aerospace applications and was selected after a careful evaluation of mechanical, chemical and physical properties. Such a polymer based on acrylate technologies has several important features that gave to many industrial applications the possibility to solve not only sound reduction but also bonding aspects and sealing needs.

The polymer has a special structure completely homogeneous in every part, this structure has during the application process micro movements that fill all the microprofile of the materials involved with a strong improvement in performances also just after a few minutes from the application. This aspect can solve also many of the problems due to thermal differentials, especially when the materials bonded together are not the same and then are affected by different contraction or expansion; this is one of the reason of choice in aerospace applications where the thermal delta is very wide and strong.

The product does not contain volatile or corrosive components so the surface covered with the polymer does not suffer absolutely any chemical corrosion also along the years. Splash tests conducted in U.S. certify good resistance when the join along the thickness is cleaned with the normal industrial cleaning products.

Nevertheless being the product a “solid glue” it has been possible to cut the polymer in the correct shape without the problem of perimetral adhesive excess and does not require special attention during deliveries and during the joint life.

As a distinctive feature, the *Syope*® treatment can be retrofitted on any existing disc-braked wheel under the condition of an axial symmetric web, as the panel mounting process, a combination of cold forming and rolling, does not allow the use of more complicated webs. The only limitation is that wheel mounting on the axle can be done only at room temperature (press-fit) as the heating necessary for shrink-fit would damage the damping polymer.

At the moment Lucchini is working on a modified version of the treatment, specifically adapted to wheels with web-mounted brake discs, named *Syope Braw*® [3].

2.2. Acoustic performances of Syope® treated wheels

The behaviour in service and during numerous test campaigns is described in a number of papers [4, 5, 6, 7, 8, 9] to which the reader is referred for further details. Roughly speaking, the observed $L_{pA,max}$ (*overall* A-weighted maximum level, measured at 25 m from the track axis with the Fast time constant during pass-by) reduction, treating the wheels of an existing vehicle with the *Syope*® treatment is in the order of 3 to 5 dB, without any treatment or modification applied to the track.

2.3. Technical considerations

The use of “special” wheels is always debated as the inevitable associated costs and complications (maintenance, disposal, non-destructive testing, risks associated to objects mechanically mounted on the wheel, etc.) must be carefully addressed.

The development of the product received a fundamental help in the early stages thanks to Fiat Ferroviaria SpA, now Alstom Ferroviaria SpA, that allowed the installation during 1998 of the very first damped wheels on the ETR470-0, a 3-elements EMU high speed tilting train that Fiat used in those years for testing and demonstration.

The experience gained in several years of testing and service allows to say that:

- wheels installed in year 2000 travelled for more than 5 years before the end of the useful life and for more than 1.1 million kilometres without any reduction of safety (i.e. detachment of the steel constraining plate);
- no special attention or procedure was needed during the service. For the final user, the wheel treatment can be defined as a “fit and forget” measure that effectively reduces noise without any impact on maintenance procedures;
- withdrawal and disposal followed the usual procedures as no risks or additional costs are associated to the treatment. Scrap steel can be re-melt in the electric arc furnace without generating noxious gases (dioxin).

3. Life Cycle Cost analysis and the implication of Syope® wheels

3.1. Introduction

Life-cycle costs (LCCs) are all the anticipated costs associated with a project or program alternative throughout its life. This includes costs from pre-operations through operations or to the end of the alternative.

LCC analysis is the systematic, analytical process of evaluating alternative courses of action early on in a project, with the objective of choosing the best alternative to employ scarce resources. The courses of action are for the entire life of the project and are not for some arbitrary time span (e.g, the 5-year plan). By applying the principles of LCC analysis, it is possible to evaluate several designs and select the one with the lowest LCC [10].

Generally speaking, LCC analysis is employed to evaluate alternative design configurations, alternative, manufacturing methods, alternative support schemes, etc. The LCC process includes [11]:

- defining the problem or project (scope),
- defining the requirements of the cost model being used,
- collecting historical data/cost relationships/cost data,
- defining the schedule, and
- developing the estimate and analyzing the results.

A successful LCC application will:

- forecast future resource needs, which when evaluated can identify potential problems or impacts;
- influence R&D or preliminary design decision making; and
- support future strategic planning and budgeting.

Limitations and common errors made in the LCC analysis process are not discussed here, while it is crucial the definition of the typical system profile. It is generally recognized that it is necessary to perform an LCC analysis early in a project's life, or it loses its impact to make a cost effective decision on which alternative is best. This is particularly evident in those systems for which most of the LCC is the operational support. An example of the impact of the R&D development is shown in Fig. 1, together with an LCC profile for system acquisition where operation and support costs are the greatest part of the life-cycle cost.

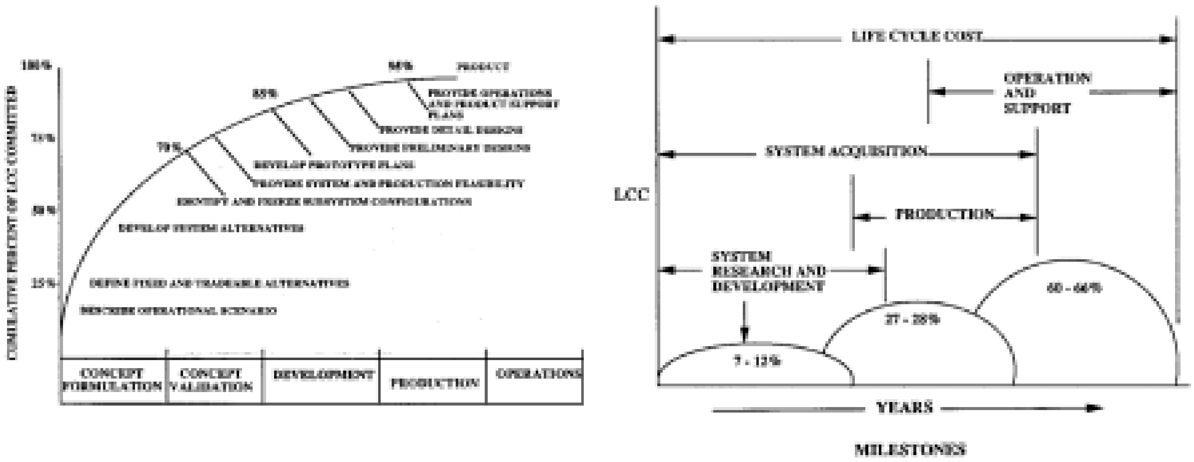

Fig. 1. Actions affecting LCC (left) and typical LCC profile for system acquisition (right) (from [11])

3.2. Application of LCC analysis to rolling stock

Rolling stock purchasing is a complex activity that involves many technical, economical and environmental issues. Train operating companies (TOCs) have developed in the years, often with the help of consultancy experts (typically from military applications), their own models to evaluate LCC.

While R&D, engineering and manufacturing costs are relevant to the industry, operating costs are associated to normal service and therefore are sustained by TOCs that, on their side, control the efficiency of their rolling stock in terms of RAM indices (Reliability, Availability and Maintainability). The procurement of new rolling stock is therefore normally accompanied by a Technical Specification including an in-depth decomposition of the vehicle and the allocation of availability, maintainability and reliability with associated indices (MTBF, MTTR, and the like).

At the same time, an analysis of the faults and of their impact on service has to be done with the classical FMECA (Failure Mode, Effects, and Criticality Analysis) applied to the Function Block Diagram (FBD) of the vehicle in order to find the Reliability Block Diagram (RBD). This last document is particularly important as redundancy is taken into account and the calculation must be performed on all the mission profiles identified by the customer.

For the railway sector, criticalities of the failures can be classified on the type of service disruption that is consequent to the failure as follows (from the most to the less severe):

- event of level 1: train stopping during or the service or rolling stock substitution before service;
- event of level 2: large delay (greater than that indicated in the technical specifications);
- event of level 3: heavy deterioration of performances or comfort with associated delay;
- event of level 4: noticeable deterioration (without consequences on service regularity but requiring an extra maintenance at the end of service);
- event of level 5: light deterioration (extra maintenance required at the next scheduled maintenance session)

It is evident that maintenance plays a central role in the identification of times and costs, and it can be split in preventive (programmed, on-condition and predictive) and in corrective maintenance. In order to reduce the occurrence of undesired train stops, there is a general tendency towards preventive maintenance that can only be defined with continuous refinement of statistical models based of repair records and with the fundamental help of diagnostics.

All the associated activities have an impact on the LCC, both in the design phase, where all the problems should be addressed at their best, and in the operation phase. The supplier will involve the sub-suppliers in the definition of the aforementioned indices while the customer will require from the maintenance workshop similar estimations of the associated costs.

Being the topic too large to be discussed here, the reader is referred to specific textbooks and literature for further details.

3.3. Implication of the damped wheel on LCC

The *Syope*® wheel is normally proposed as an additional feature to be applied on existing or new rolling stock. Limiting the analysis to new rolling stock, for which an LCC analysis can be conducted “from the cradle to the grave”, it is fundamental to evaluate the impact of the treated wheel on a vehicle’s cost, including all direct and indirect aspects. This identification is fundamental in order to understand if the use of such wheels requires a different LCC model or if it is sufficient to input in the model the extra cost of the treated solution.

The activities that can be linked to the pre-delivery phase of a new rolling stock, already shown in Fig. 1, may be affected by the use of a damped wheel. They can be analyzed as follows:

- *concept formulation*: if the new train typology allows the use of damped wheels (i.e. if the wheelset is disc braked with discs mounted on the axle) and the wheels are therefore axisymmetrical, there are normally no additional activities related to the use of damped wheel, in the sense that the normally desired wheel characteristics (strength, stiffness, weight) can be obtained *independently* from the damping. It is fundamental to observe that shrink fit is not possible and that only press-fit can be used. This means that there are no costs associated to this phase under the indicated hypothesis;
- *concept validation*: validation of the solution including safety assessment of the vehicle. In this case the use of the treatment is neutral as it does not affect the mechanical properties of the wheel [12]. No specific procedures need to be used to evaluate the behaviour of the wheel in service under the usual loads. No extra costs are therefore associated to this phase linked to the use of *Syope*® wheels;
- *development*: the development of the vehicle can proceed forgetting the use of damping treatment on the wheels. The only difference is a very small increase of mass and moments of inertia whose effect can be neglected for example in the vehicle dynamics calculations due to the intrinsic uncertainties linked to this type of simulations. No extra costs are requested therefore at the development stage of a new vehicle;
- *production*: wheelsets are normally supplied to the vehicle manufacturer by a highly qualified sub-supplier, and their installation is not affected at all by the use of the damping treatment on the wheels. There are therefore no additional costs associated in the vehicle production phase.

As shown in Fig. 1, operations can be a relevant part of the total LCC. Also in this case it is necessary to evaluate the effects of the use of a damped wheel on the forecast overall cost of the vehicle for its entire life. Activities and consequences can be analyzed as follows:

- *availability*: it is by far one of the most important indicators for service revenue, and in the management of a fleet one of the most common target is the definition of the desired part of fleet that is available for daily service. It can be said that the use of damped wheels does not affect in any way the fleet availability, i.e. there are no failures associated that can reduce this parameter. No extra costs need therefore to be included in the LCC model to take into account the possible reduction in the availability associated to the use of damped wheels;
- *reliability*: no reduction in the reliability of the wheelset subassembly is to be expected by the use of damped wheels. Being a non-structural treatment, the constrained layer damping technique leaves unaltered the behaviour of the wheel, neither introducing new modes of failure nor changing the failure rates for the usual wheels. There are therefore no associated costs;
- *maintainability*: wheelset maintenance is a complex subject, but it can be said that for routine operations (for example ultrasonic testing or visual check), no modifications to the standard maintenance routines is requested. Wheel reprofiling can be done with the usual tools and machine tools (either underfloor or parallel lathe). The use of damped wheels leads to no modifications in the LCC calculation scheme.

As a consequence, *Syope*® wheels are “neutral” for the LCC calculation that can be used by simply increasing the cost of the wheel of the amount related to the damping treatment. Also for the disposal at the end of life, there are no additional costs associated.

4. Simulation of the impact of *Syope*® wheels on LCC

4.1. Introduction

Alstom Ferroviaria SpA, formerly FIAT Ferroviaria SpA, is one of the companies of the Alstom Transport group. Based in Savigliano, in the North of Italy, the company has an almost one century of experience in designing and manufacturing rolling stock for Italian and European railway administrations. As an example, all the tilting trains running in Italy were built in Savigliano, and the same will apply with the new Trenitalia ETR600 and Cisalpino ETR610 (tilting train, max speed 250 km/h).

There is a general tendency to purchase passenger rolling stock with distributed power with electric or diesel power (the so called EMU or DMU, i.e. Electrical or Diesel Multiple Units). The reason for this market orientation are outside the scope of this paper; it is only noted that this architecture is even more favorable than the conventional loco+coaches architecture allowing a better control of the status of the rolling stock, a better maintenance and lower associated costs. The treatment of the wheels with noise reduction measures is therefore easier, as the trainset is seen as a whole and not as a puzzle of different and often changing vehicles.

4.2. Simulation of the impact on several categories of EMUs and DMUs

The calculation of the LCC of a train is a complex activity that can not be done with the goal of writing a paper. The only possibility to have an idea of the impact of the application of damped wheels is to use already prepared LCC calculation schemes. As discussed above, the only modification requested by the introduction of damped wheels is the corresponding modification of the cost of the wheel. Values for the cost of the treated wheel were supplied by Lucchini Sidermeccanica. It is worth to note that as the mass production of *Syope*® wheels is rapidly expanding, further decrease in the *Syope*® treatment cost will be possible in the future.

The LCC database has four types of vehicles for which the model is fully developed and validated:

- a high speed (v_{max}=250 km) dual voltage tilting train with distributed power (EMU, 7 coaches, 8 wheels/vehicle), with an expected life of 25 years (three wheel changes expected);
- a high speed conventional trainset with distributed power (EMU, 7 coaches, 8 wheels/vehicle, v_{max}=250 km/h) , with an expected life of 25 years (three wheel changes expected);
- a regional train (EMU, 3 coaches on 2 motor bogies + 2 Jacobs bogies, 16/3=5.8 wheels/vehicle), with an expected life of 30 years (three wheel changes expected);
- a regional train (DMU, 3 coaches on 2 motor bogies + 2 Jacobs bogies, 16/3=5.8 wheels/vehicle), with an expected life of 25 years (two wheel changes expected).

The LCC model includes numerous sensible data coming from the customer and from the sub-suppliers that can not be detailed here for non-disclosure agreements between the parts; it is nevertheless important to highlight that the estimation of the impact of the use of damped wheels is conducted on trains already in service or in the delivery phase, and this ensures the maximum validity to the calculations. Different approaches to maintenance and different types of service are included in the simulations, and this gives the calculation an even greater validity, clearly slightly increasing the spread in the results.

Two calculations were performed:

- the evaluation of the impact on maintenance cost, a value that can be important to define if it is economically convenient to compare the application of low noise wheels on an existing fleet and the use of noise barriers;
- the evaluation of the impact on LCC on the new rolling stock, including the cost of the new trainset. This is the most important value because it gives an idea of the overall impact of the damped wheels for the entire useful life of the train.

The results are shown in Table 1. From these values it can be concluded that:

- costs associated to the trainset range from 0.26% to 0.87% of the LCC. It is likely that for more complex trains this value will further decrease, while for simpler trains it could increase;
- impact on operation costs only are similarly quite variable (from 0.54% to 2.3% of the LCC) mainly depending on the complication of the considered vehicle. Not surprisingly, the highest value is obtained for a rather simple vehicle (a trailing car with little equipment of a high speed non-tilting EMU) while for the lowest value is obtained for a motor car of a DMU trainset whose complication and associated operating costs are inevitably higher.

Table 1: Evaluation of the impact of damped wheels on operation costs and on LCC.

	Impact on operation costs %	**Impact on Life-cycle cost %**
Tilting EMU (250 km/h)		
Trainset (7 cars)	1.5%	0.74%
Motor car (#1)	1.3%	0.66%
Trailer car (#4)	2.0%	0.87%
EMU (250 km/h)		
Trainset (7 cars)	1.6%	0.79%
Motor car (#1)	1.4%	
Trailer car (#4)	2.3%	
Regional EMU		
Trainset (3 cars)	1.27%	0.35%
Motor car (#1)	1.08%	
Trailer car (#2)	1.14%	
Regional DMU		
Trainset (3 cars)	0.64%	0.26%
Motor car (#1)	0.54%	
Trailer car (#2)	1.55%	

To provide absolute figures, the LCC cost of the fleet of 20 non-tilting EMU is estimated in the order of 405 M€, 5.8 M€ of which are the extra cost associated to the use of the *Syope*® treated wheels.

5. Conclusions

The use of damped wheels with low noise emission is often debated as their use is inevitably linked to extra costs for wheel purchase. The evaluation of this alternative is only partly satisfactory as wheels are an important component whose cost contributes to the total LCC of the train together with many other important factors.

The evaluation of the extra costs associated to the use of damped wheels was therefore performed on different trainsets for high speed, long distance and regional passenger trains (either with electrical or Diesel traction) showing that the impact on costs is limited and that there is a distinct advantage in using low noise wheels in those situations where noise limits are not respected for a few decibels.

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