EXPERIMENTAL ANALYSIS OF WHEEL NOISE EMISSION AS A FUNCTION OF THE CONTACT POINT LOCATION

Andrea Bracciali, Fabio Piccioli
Dipartimento di Meccanica e Tecnologie Industriali
Università di Firenze
via Santa Marta 3 – 50139 Firenze, Italy

Phone +39 055 4796292
Fax +39 055 4796400
E-mail: bracciali@ing.unifi.it

ABSTRACT

Recent analyses show that the wheel noise emission depends on the lateral position of the contact patch area on the wheel tyre. This displacement from the nominal position is such that different wheel modes are excited resulting in a different frequency and amplitude composition of the wheel related noise component. In this paper the results of a test campaign held on the ETR500 Italian high speed train are shown. Thanks to a specific device mounted under the axlebox comprising a microphone and a windshield, it has been possible to measure the wheel noise continuously up to 300 km/h in tangent track and in curves. The behaviour of wheels in different condition of line curvature is shown, together with the results from a new type of constrained layer damped wheel.

KEYWORDS

Wheel noise, damping, contact point

1. INTRODUCTION

Though several microphone array solutions exist and are extensively used to separate the wheel and the rail components in the overall trackside noise, it proves very hard to repeat such measurements in absolutely repeatable conditions in numerous trackside locations along a given railway line. As the wheel emission is acknowledged to be particularly important at high speeds and, at those speeds, at high frequency, the use of a specific wheel noise measuring device mounted under the axlebox can be useful to measure continuously and under all conditions the wheel contribution.

It is a matter of fact that every body vibrates as a weighted sum of its eigenmodes, provided that they are excited by a mechanical input acting at the eigenfrequencies. The wheel-rail contact nominal (geometrical) interface point can be easily calculated from the wheel and the rail profiles and from the wheelset and track gauges, and the wheel natural (free) response can be estimated with numerical FEM calculations or measured under the application of known forces through experimental modal analysis.

During the normal run of a train, the bogie dynamics and attitude are such that the wheels rarely touch the rails in the nominal position, resulting in a wheelset angle of attack (yaw angle) and a lateral displacement different from zero.
Two parameters affect the excitation under displaced conditions: the different spins given by a non-zero angle of attack and the Y/Q Nadal's ratio between the lateral force and the vertical force. It is widely known that only a proper combination of wheel and rail profiles results in a regular and continuous conicity variation, i.e. a conicity that is normally quite low for centred running and that softly increases modulating centring effect without generating undesired hunting phenomena. For the classical UIC60 rail with a 1/40 angle, a wear profile with optimal coupling properties has been adopted after UIC studies. This profile, called ORE 1002S, is such that the contact point moves regularly and evenly from the nominal point to the wheel flange. On the contrary, by using the same wheel profile but with rails with an inclination of 1/20, as used for example in Italy, there exists the possibility that the wheel touches the rail in two points, one on the wheel tread and the other on the wheel flange. In this case the Y/Q ratio is not univocally determined by the common normal to the profiles but, being the static problem overconstrained, any combination of Y/Q that does not induce derailment is allowed.

Under these conditions, the exact determination of the wheel excitation would require a simultaneous measurement of the lateral wheelset displacement, the actual track gauge and the vertical and lateral forces acting on the wheelset. Clearly this measuring set-up is quite expensive and complicated, requiring optical (laser) transducers for profile measurement and strain gauge rotating (telemetry) arrangement for force estimation.
The wheelset attitude (angle of attack and ripage force) depends on numerous mechanical bogie and car body parameters, and normally is different for front and rear bogies and for leading and trailing wheelsets for each bogie. Speed, moment of inertia, local friction conditions, suspension behaviour, wheelset curving (steering) capabilities make the problem very difficult to be solved with sufficient reliability.

Despite these difficulties, noise measurements under the axlebox with known general conditions, including speed, line curvature, wheel and rail profiles and weather conditions, can at least indicate whether lateral forces and wheelset attitude can significantly affect the wheel emitted noise. In this work the results from a test campaign conducted in October, 2000 on the high-speed Italian train ETR500 are shown. Tests conducted in the 175-300 km/h speed range on the Direttissima line allow the comparison of the wheel emission under different lateral accelerations. Also the emission of a damped wheel is shown, highlighting the different emission of the two type of wheels.

2. THE TEST CAMPAIGN

Italian State Railways FS asked the University of Florence to perform noise measurements within the frame of an already scheduled test programme for aerodynamic drag measurements. Due to this particular scheduling, it has not been possible to "drive" the test programme to obtain the best results for noise measurements; in particular, it has not been possible to have train runs at speeds below 175 km/h in the test line, missing the possibility to evaluate the noise at low speeds where the track component should be dominant. The test section has been the high-speed "Direttissima" line Florence-Rome near Florence, where the maximum speed is 300 km/h. Also the data from a transfer run from Milan to Florence are given as examples of results on tangent track. It is not intended here to give details on the test campaign beyond those strictly needed to explain the measurements of interest. The reader is referred to the paper [1] recently presented at the 13th International Wheelset Congress in Rome.

The monobloc simple curvature wheel under test was developed by FS in the early '90s to eliminate the former three-pieces wheel. Thanks to its low weight and optimised lateral and vertical static stiffness, it became a standard for high speed Italian trains ETR500 and all the Alstom Pendolino Italian family (ETR450/460/470/480). Lucchini CRS, the research and development branch of the wheels manufacturer, Lucchini S.p.A., developed a retrofit treatment consisting of a curved metal sheet with a constrained polymer, developed and patented jointly with 3M Italia s.r.l.. The new wheel, called *Syope*®, has the main advantage that it does not require any modification in the actual wheel and vehicle structures and in the maintenance operation; moreover the solution can be applied in principle to any disc braked wheelset mainly for limited polymer thermal resistance.
The first decision taken was about the number of *Syope*® wheels to be used during the tests, where they had to be fitted and the definition of the roughness of the surface of the tyres. The test ETR500 trainset has 2 locomotives and 8 coaches (four 2nd class, one restaurant and three 1st class coaches) and it was decided to machine only some wheelsets to have the same wheel out-of-roundness. The final composition of the train is shown in Figure 1, where it can be observed that the bogies have been treated in pairs belonging to adjacent coaches, for trackside measurement reasons.

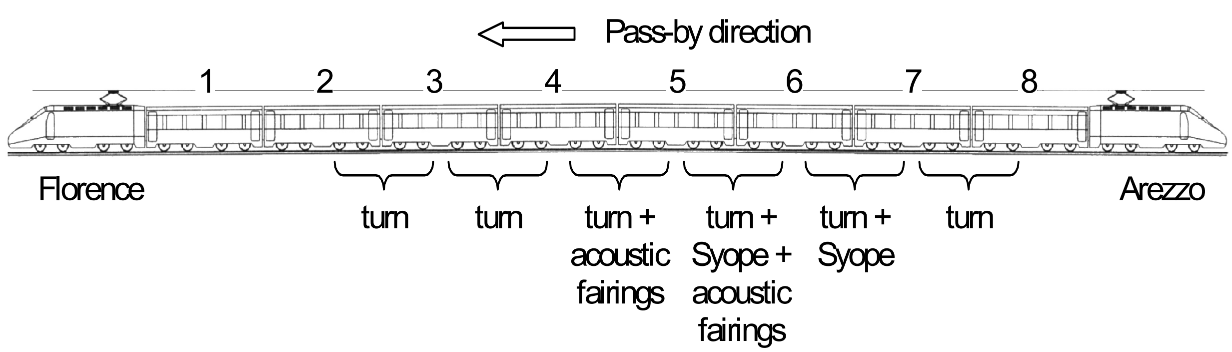

Figure 1: Test train with wheel position "t" turned, "s" Syope®.

The test programme was particularly articulated and the measurements have not been performed during the whole campaign, while some tests concerned only trackside measurements during train passages. Of the numerous tests requested by the only measurement protocol available at the moment of tests, i.e. the draft of the European and International Standard prEN ISO 3095 [2], only rail corrugation measurements are described here.
Rail corrugation has been measured with a trolley based on acceleration measurements integrated twice. The equipment, called CAT (Corrugation Analysis Trolley), is described in ref. [3]; only one trace, at the intersection of the vertical axis of the rail, has been measured continuously on the surface for a certain length (±20 m) centred on the trackside noise measuring position. Both the rails have been measured; corrugation data have been processed with the specific software RAS – Roughness Analysis Software – described in [4]. Although only one line is measured and for a very long distance, the corrugation spectrum has been compared to the limit given in [2] for the acceptance of a site for vehicle type testing. The RAS software has been accordingly modified to accept very long CAT files, thereby increasing dramatically the resolution at longer wavelengths.
It can be seen from Figure 2 that the average spectrum of both rails slightly exceeds the ISO proposed limit; nonetheless it seems that it is quite acceptable following the rules stated in Annex D of such standard.

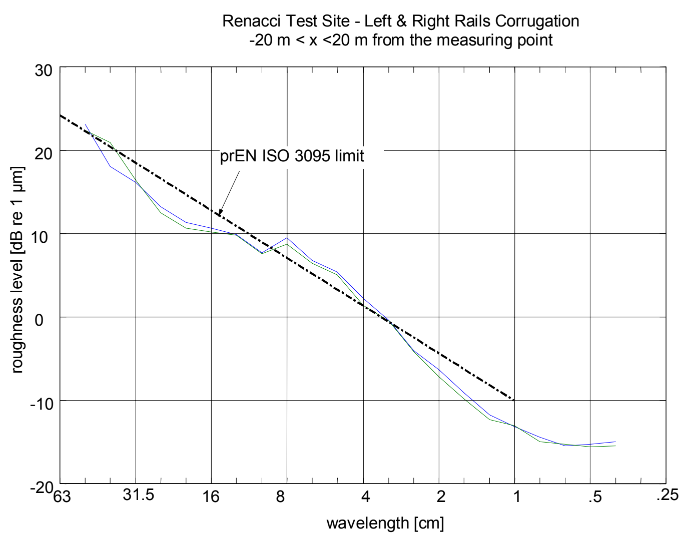

Figure 2: Average corrugation spectra for both the rails at the Renacci measuring site along the Firenze-Roma "Direttissima" high speed line.

Noise measurements under the axleboxes were performed by using some specific devices developed during 1993-94 to measure the noise emitted by the wheel [5÷7]. They are composed by a wind protection and two parallel plates; the microphone is elastically suspended in the airflow shade given by the wind protection (Figure 3).

To accelerate the tests and to compare several wheels, four identical devices were mounted under three coaches as shown in Figure 4. Theoretically, the support of the device allows a quite fast rotation of the device such that it would have been possible to measure after each change of direction; unfortunately, as the tests were conducted night time during a traffic interruption, only a couple of minutes were available for turning. As this time was supposed to be insufficient, two devices (#1 and #4) were permanently operating in the Firenze-Arezzo (south) direction while the others (#2 and #3) were operating in the opposite direction (north). The only results presented here are those relative to the latter combination of measuring points, for which also trackside data are available.

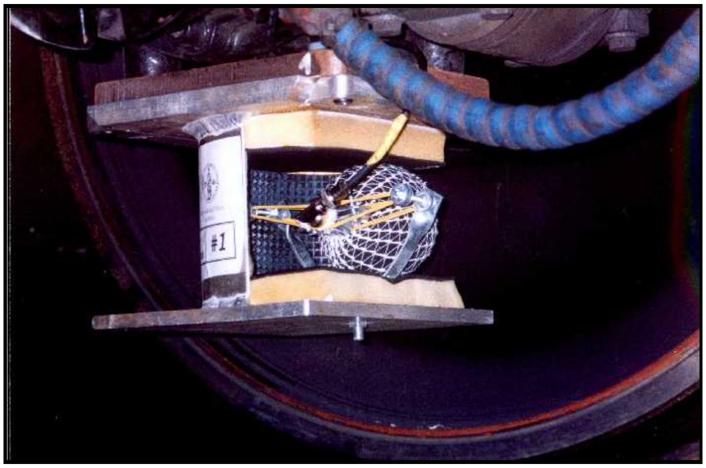

Figure 3: One of the wheel noise measuring devices mounted under the axlebox

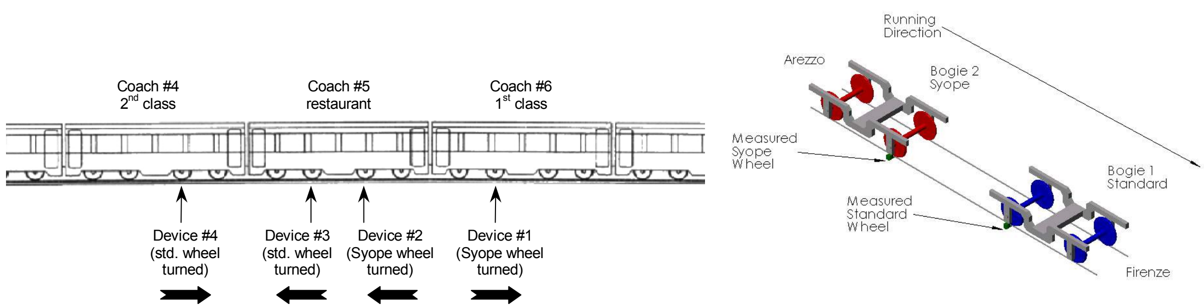

Figure 4: On-board wheel noise measuring devices position and orientation. Right and left curves are relative to the configuration shown on the right. Only data relative to devices #2 and #3 are shown.

Sound pressure signals have been analysed and recorded by using a real-time 1/12 octave band dual channel analyser with a sampling frequency of 11.2 kHz per channel. A test run log file has been compiled with the position along the line, the actual speed and the time of the measurement.

3. TEST RESULTS

3.1 Trackside noise levels recorded at Renacci (d=7.5 m, h=1.2 m)

Several treatment configurations were tested, including worn and turned wheelsets, aerodynamic and aeroacoustic fairings. Results are summarised in Figure 5 and in Table 1.

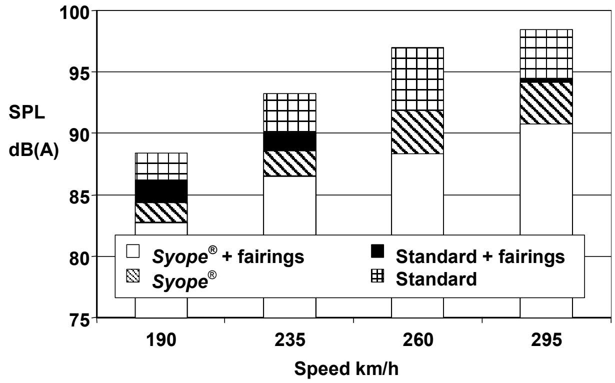

Figure 5: Trackside noise at 7.5 m for different turned wheels solutions and bogie fairings. The effect of acoustic treatments to fairings is negligible (not shown).

Speed km/h	Standard dB(A)	Standard + fairings dB(A)	*Syope*® dB(A)	*Syope*® + fairings dB(A)
190	88.4	86.2 (-2.2)	84.4 (-4.0)	82.8 (-5.6)
235	93.2	90.0 (-3.2)	88.6 (-4.6)	86.5 (-6.7)
260	97.0	91.9 (-5.1)	91.8 (-5.2)	88.3 (-8.7)
295	98.4	94.4 (-4.0)	94.1 (-4.3)	90.8 (-7.6)

Table 1: Trackside measured noise $L_{pA,max}$ with different wheels and under different noise reduction condition.

3.2 On-board measurements on the Milano-Bologna line

During a transfer run all the devices were oriented in the running direction, and the signals were collected by two microphones at a time. Noise (A-weighted sound pressure level) from standard wheel and *Syope*® wheel resulting from a considerably long track (around 12 km), almost all tangent and with constant 180 km/h speed, have been grouped in three homogeneous sections. It is suggested that the differences depend mainly on (unknown) track conditions. To eliminate spurious data, a selection has been done on the basis of cumulative curves. L_{pA} results are summarised in Table 2.

	Section 1	Section 2	Section 3
Length	3500 m	4000 m	4500 m
Gain	-6.3±2.4 dB(A)	-6.2±1.9 dB(A)	-7.1±2.3 dB(A)
Censored gain (percentiles)	-7.4±1.5 dB(A) (5%-90%)	-6.2±1.5 dB(A) (5%-100%)	-8.0±1.0 dB(A) (5%-85%)

Table 2: Noise reduction offered by Syope® *wheel compared to standard wheel for the transfer run at 180 km/h. The average gain on the whole section is –6.6±2.3 dB(A).*

3.3 On-board measurements on high speed "Direttissima" Firenze-Roma line

During the test runs, the speed usually increased very rapidly to the planned test run speed. Obviously the measurements taken during braking have been discarded, as the noise produced by braking is not strictly related to wheel noise. As a result from the speed profiles of the whole runs considered here, the largest number of samples (around 50%) is relative to speeds is the range 200÷250 km/h, around 18% is relative to speeds greater than 250 km/h and the remaining

32% to speeds between 100 and 200 km/h and it is, moreover, not uniformly distributed. This uneven distribution made it impossible to derive from the data completely meaningful results as those shown in [5÷7], but, as already mentioned, it was impossible to modify the speed during the test runs.

An example of the noise measured under the axlebox for the standard turned wheel and the *Syope*® turned wheel and the gain offered by the *Syope*® is shown in Figure 6. The two wheels are only 16 m apart, requiring no correction of the samples position.

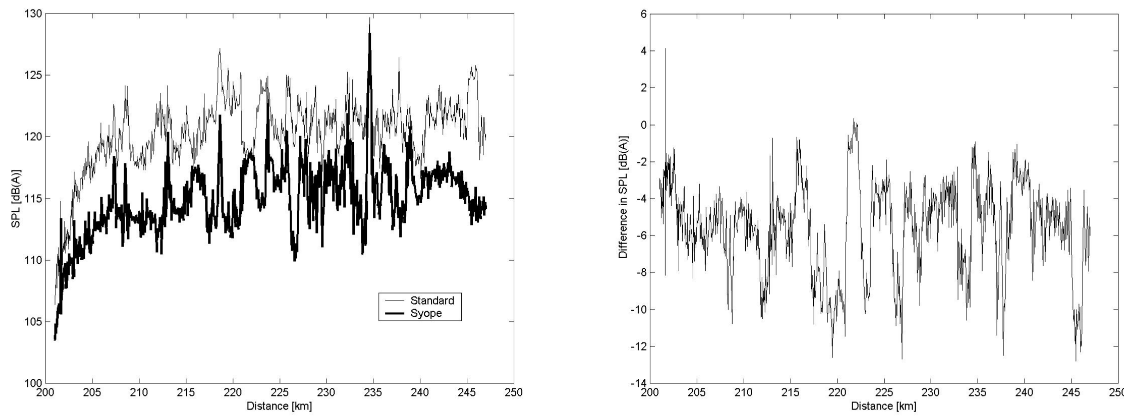

Fig 6 Time history of L_{pA} emitted by the wheels during a run 2402 at a test speed of 200 km/h (left). Gain offered by Syope® *wheels (right)*

From all the collected data it is possible to derive the following consideration:

- the noise level is extremely high (up to 130 dB(A) and over) and the dynamics of the measuring chain has been used almost entirely. Only a few records (5 samples in a total of 14 test runs) resulted in an overload and they have been properly removed from the analysis;
- the noise levels are extremely variable (up to 5 dB(A), see also Figure 2 in ref. [8] for an example of the noise variability under a railway vehicle) also at constant speed, due to the intrinsic instability of on-board noise measurements and of line profile and details (curves, tunnels, rail joints, switches,...). The implications of this evidence are discussed later;
- the gain offered by the *Syope*® wheel shows a large variability. Always referring to Figure 6, for considerable lengths the reduction is around -10 dB(A) (km 217 to 221) while in other sections the gain can also be positive (km 221 to 223) showing that the damped wheel is noisier than the standard wheel!

The observation of this phenomenon draw up the attention to the pattern identified, as in almost all the test runs a similar behaviour was observed. A correlation has been found between the curvature of the line and the noise emitted. Figure 6 shows the details of test run 2402; to reduce the number of samples and to obtain more stable results, the data have been grouped for line sections of 200 m, and they are shown together with the curvature derived from the line description. It can be observed that the gain of the *Syope*® wheel is smaller in left curves while it is higher in right curves. The noise emitted by the standard wheel remains constant or even increases in the right curves, while the noise emitted by the *Syope*® wheel decreases. This shows that the actual position of the contact point and the presence of driving forces have a large importance especially for the damped wheel; generally speaking, the exact contact point location depends mainly, once the rolling stock has been fixed, by the line curvature, the superelevation and the speed.

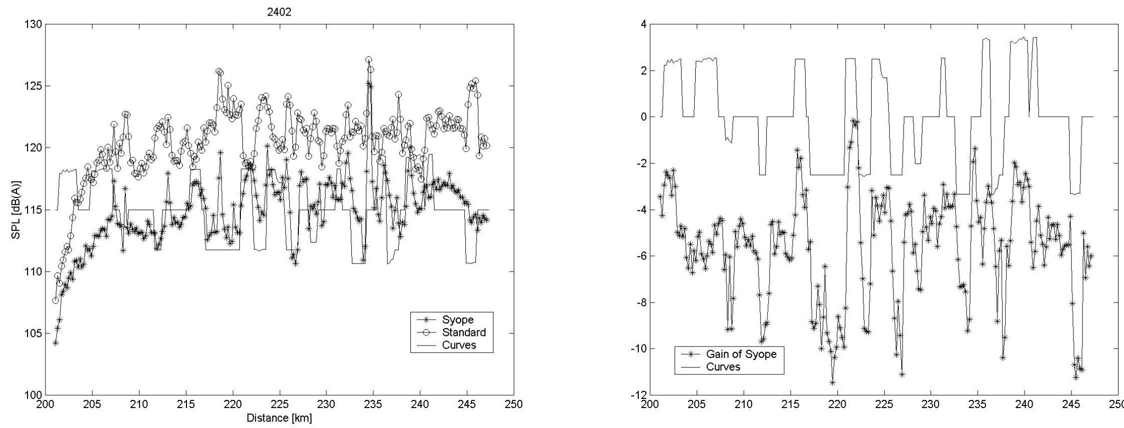

Figure 7: As Figure 6 with data grouped following a distance-based criterion (1 sample=200 m). The curvature multiplied by 10000 m^{-1} is also shown.

This behaviour has been verified in all the test runs. The data have been grouped for homogeneous line sections (tangent track, left curves, right curves); within each category, and also to overcome some inevitable uncertainties and local deviations, only data between 10 and 90 percentiles have been retained (this procedure is correct as the average remains undisturbed while only standard deviation decreases). These results are shown in Figure 8 and in Table 3: it can be seen that in the tangent track the gain is around 4.5 dB(A).
These results are an average in all the speed range; a finer analysis is performed on the single run looking at L_{pA} levels and spectra, depending on the attitude of the wheel, for the whole run and in a stretch of the line where the speed is reasonably constant (Tables 4 and 5).
As a zone where the speed is almost constant can be recognised in each run, for example for run 2402 between km 206 and km 223 with a speed of 200 km/h, it is possible to analyse this zone in order to eliminate the influence of the speed.
As the number of data recorded is different for tangent track, right curves and left curves, the statistical influence of each value is not the same; for example, available data for left curves are almost half of other two conditions. Recording data in a homogeneous way would have required a specific test campaign where different speeds are held in different line sections with the required mix of tangent track, left and right curves and hopefully with the same condition in terms of track infrastructure (tunnels, bridges, viaducts, superstructure, etc.).

Data were acquired continuously, so they are strongly affected by local track imperfections, like rail joints and switches; these events are not representative of the noise intrinsically emitted by the wheel. For this reason a further analysis has been done trying to isolate an array of values that can be considered not affected by local events (Figure 9). The values are moreover selected from consecutive stretches of the line in order to minimise the effects of possibly different track conditions. The results of this analysis can be considered representative of the noise emitted by each wheel in each condition (tangent track, right curve, left curve).

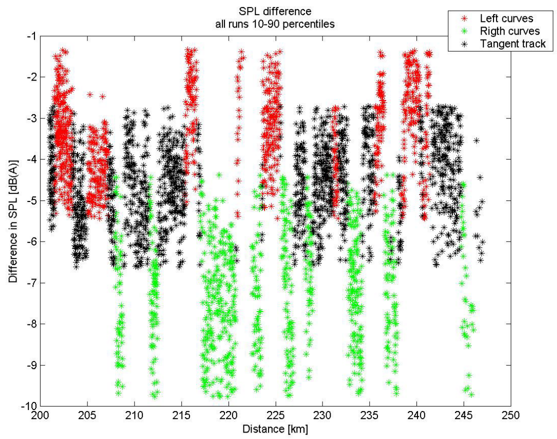

Figure 8: Difference between the noise emitted from two wheels 10-90 percentiles for all test runs (independently from the speed)

	Tangent track	Right curves	Left curves
% of track	48	26	26
% of samples	43	26	31
Average *Syope*® gain	-4.6±2.3 dB(A)		
Single stretch	-4.5±1.6 dB(A)	-6.8±2.1 dB(A)	-3.3±1.6 dB(A)
Single stretch (samples considered)	-4.5±1.0 dB(A) (10%-90%)	-7.0±1.4 dB(A) (10%-90%)	-3.3±1.1 dB(A) (10%-90%)

Table 3: Average Syope® *gain for all runs independently from the speed*

	Tangent	Right	Left
Average Gain dB(A)	-5.1±1.4	-8.0±2.0	-3.8±1.6
Min speed (km/h)	88	165	102
Max Speed(km/h)	204	203	204

Table 4: Average Syope® *gains for the whole run 2402 (all speeds)*

	Gain	Length	% tot. of length
Tangent track	-5.3±1.5 dB(A)	6900 m	40%
Right curve	-8.9±2.0 dB(A)	6400 m	38%
Left curve	-3.0±2.1 dB(A)	3700 m	22%

Table 5: Gain for different line sections at constant speed (201±1.35 km/h) of test run 2402 between km 206 and 223. The total gain for the 17000 m section is –5.6±2.7 dB(A)

Spectra derived from selected data are shown in Figure 10; two sets of results are illustrated: one for a stretch of run 2402 with a speed of 200 km/h, one for a stretch of run 2501 with a speed of 250 km/h. A spectrum is shown for each condition of line curvature. It should be noted that the line considered has tangent sections and both left and right curves with R=4000 m and cant h=135 mm. At speeds of 200 km/h, this results in a non-compensated acceleration of

a_{nc}=-0.11 m/s^2 (cant deficiency h_d=-17 mm) with lateral forces directed towards the curve centre; at 250 km/h it results a_{nc}=0.32 m/s^2 (cant deficiency h_d=50 mm) with lateral forces directed towards the external of the curve.

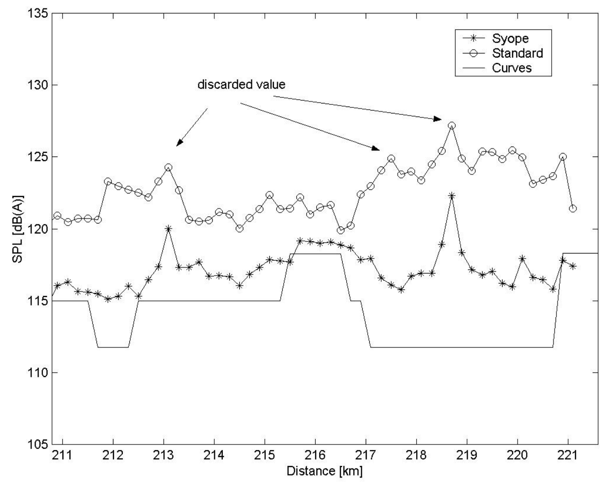

Figure 9: Zoom view of run 2402 (200 km/h) between km 211 and 221.

Overall gains of the *Syope*® wheel in the different track sections are shown in Table 6. They are mainly located at medium and high frequencies; however, it should be pointed out that a strong peak appears at approximately 650 Hz in the spectra of the standard wheel when the train runs at 200 km/h, while this peak does not appear neither in the spectra of *Syope*® wheel at 200 km/h nor in the spectra from both the wheels when the speed increases.

	200 km/h			**250 km/h**		
	Standard	***Syope*®**	**Gain**	**Standard**	***Syope*®**	**Gain**
Tangent track	119.8	114.4	-5.4	121.0	116.9	-4.1
Right curve	121.7	113.3	-8.4	124.0	116.7	-7.7
Left curve	119.5	116.9	-2.6	121.6	119.1	-2.5

Table 6: Gain in dB(A) for representative points of run 2402.

A similar peak at a slightly different frequency (about 700 Hz) was already observed in tests performed during 1994 (and partially published in [7]) at speed of 190 km/h with prototype ETR 500 train equipped with standard wheel. This phenomenon is probably connected to resonance (modal behaviour) of the wheelset and should be investigated with proper analysis.

The influence of the peak at 650 Hz on the overall noise can be evaluated in about 1 dB(A) in tangent track and left curves (the peak level is almost the same as that of the peaks at higher frequency) and 0.3 dB(A) in right curves. This appears in contrast with the results shown in Table 6, where the greatest variation in gain is for right curve; it should be pointed out anyway that the gain change is due to change in noise emitted by both wheels, and it is not proved that *Syope*® and standard wheel noise changes with speed in the same way. Moreover it should also be considered that varying the speed from 200 km/h to 250 km/h the non compensated lateral acceleration in both curves changes from negative to positive values, as previously stated, strongly affecting interaction forces between wheels and rails.

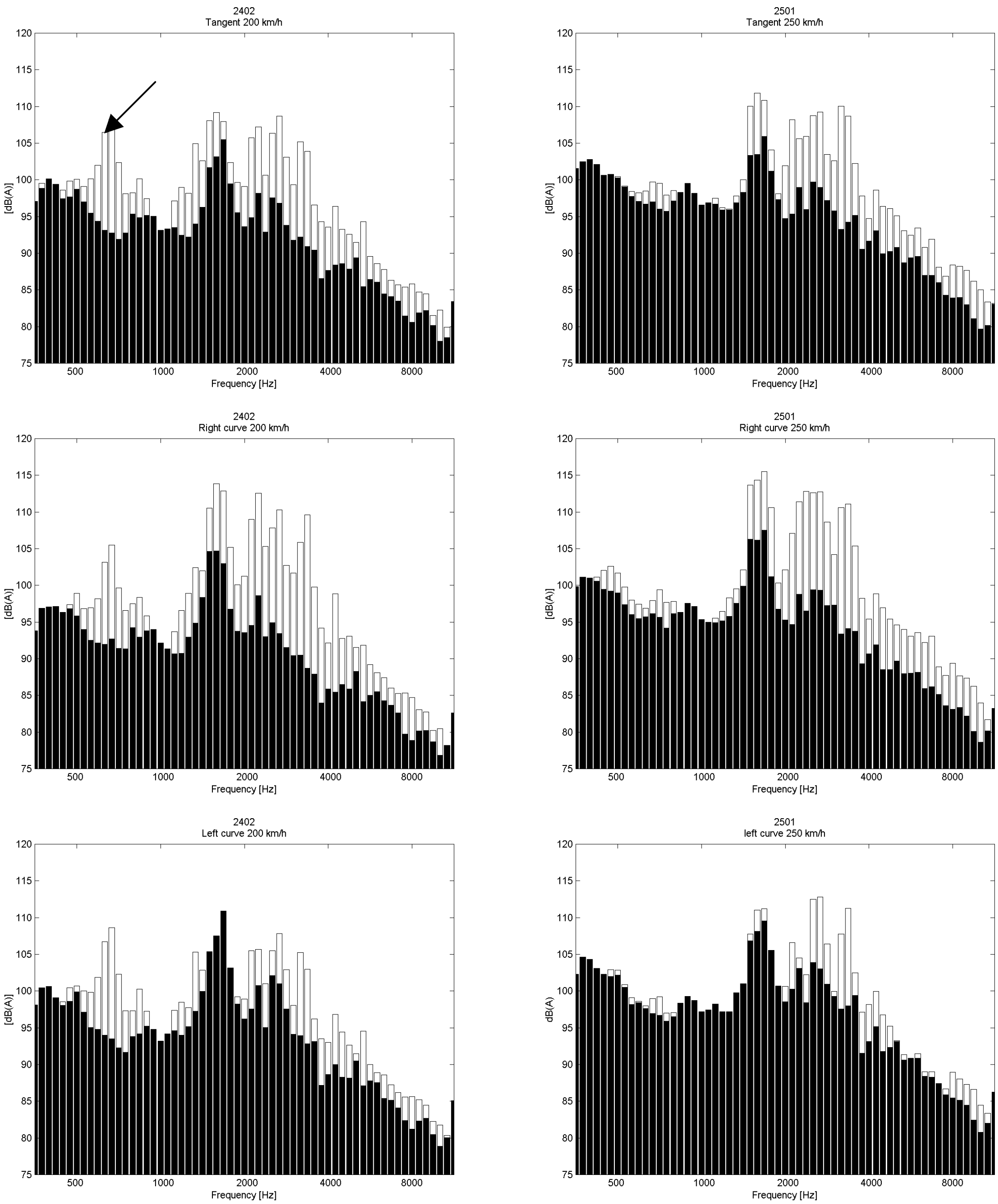

Fig 10 Spectra for Syope® *(black) and standard (white) for different line curvatures at 200 km/h (left) and at 250 km/h (right)*

Differently from previous works, it has proven impossible to define an L_{pA}-speed regression curve as the data are almost all grouped in the 200÷250 km/h range. Data at lower speeds are often measured either during braking (and therefore discarded) or during fast acceleration (transient) phases.

CONCLUSIONS AND FUTHER DEVELOPMENTS

During a test campaign the behaviour of a new type of damped wheel (*Syope®* by Lucchini CRS) has been compared to standard ETR500 wheels and to the different noise reduction solutions (fairings applied to bogie area). Measurements performed trackside and on-board are congruent and confirm that a combination of both damped wheels and fairings give the highest noise reduction. Whether it would prove impossible or non economic to apply both the solutions, *Syope®* wheels can give noise reductions higher than fairings in *every* tested situation. It should be noted that from maintenance point of view the *Syope®* wheels require no specific provisions as they can be used for replacement on any disc braked vehicle, while fairings can limit the visual inspection of some vital parts of the bogie.

Thanks to different data recording procedures, on-board measurements under the axleboxes showed a previously not observed typical noise emission behaviour depending on the line curvature. Unfortunately, due to the limitations in the test programme, it was not possible to conduct a deeper analysis, but the influence of the lateral contact point under the action of centrifugal forces is clear.

A strong resonance appeared at a certain speed that can introduce dangerous fatigue phenomena, discomfort in the passenger cabin, abnormal tyre wear. It is intended to perform an experimental modal analysis of the entire wheelset to verify the correspondence of the individuated frequency (around 650 Hz) and some wheel/axle eigenmode.

An agreement is going to be concluded with *FS Trenitalia* (the rolling stock owner) to repeat some measurements under more controlled conditions.

ACKNOWLEDGEMENTS

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