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Experimental analysis of wheel noise emission as a function of the contact point location

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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 programme held on the ETR500 Italian high-speed train are shown. Thanks to a special device mounted under the axle box 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.

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 difficult to repeat such measurements under 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 axle box can be useful to measure the wheel condition continuously and under all conditions.

Each 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

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FEM calculations or measured under the application of known forces through experimental modal analysis.

During the normal operation 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 provides a centring effect without generating undesired hunting phenomena. For the classical UIC 60 rail with a 1/40 conicity angle, a wear profile with optimal coupling properties has been adopted as a result of 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 other hand, by using the same wheel profile but with rails with an inclination of 1/20, as used for example in Italy, it is possible that the wheel touches the rail at two points, one on the wheel tread and the other on the wheel flange. In this case the Y/Q ratio is not uniquely determined by the common normal to the profiles. However, since the wheel is restrained, 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 a strain gauge rotating (telemetry) arrangement for force estimation.

The wheelset attitude (angle of attack and lateral creep 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, and wheelset curving (steering) capabilities make the problem very difficult to solve 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 noise emitted from the wheel. In this study the results from tests 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 comparison of the wheel emission under different lateral accelerations. Also the emission of a damped wheel is shown, highlighting the different emissions of the two types of wheels.

2. The test programme

Italian State Railways (FS) contracted the University of Firenze to perform noise measurements within the framework of a scheduled test programme for aerodynamic drag measurements. Due to this particular scheduling, it has not been possible to control the test programme to obtain the best results for noise measurements; in particular, it has not been possible to have trains run at speeds below 175 km/h on the test line, thereby excluding the opportunity to evaluate the noise at low speeds where the track component should be dominant. The test section was the high-speed "Direttissima" Firenze–Rome line near Firenze, where the maximum speed is 300 km/h. The data from a transfer run from Milan to Firenze are also given as examples of results on tangent track. It is not intended here to give details on the tests 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 1990s to replace the earlier three-piece wheel. Because of its low weight and optimized lateral and vertical static stiffness, it became the standard for ETR500 high-speed Italian trains and the Alstom Italian Pendolino family (ETR450/460/470/480). Lucchini CRS, the research and development branch of the wheel 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 srl. The new wheel, called *Syope*®, has the main advantage that it does not require any modification in the actual wheel and vehicle structures nor to the maintenance operation; moreover the solution can be applied in principle to any disc-braked wheelset. It cannot be applied to tread-braked wheels because of the limited thermal resistance of the polymer.

The first decision taken related to the number of *Syope*® wheels to be used during the tests, where they were 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 (4 second class, 1 restaurant and 3 first class coaches) and it was decided to machine only some wheelsets. The final composition of the train is shown in Fig. 1, where it can be observed that the bogies have been treated in pairs belonging to adjacent coaches, for trackside measurement reasons.

The test programme was very protracted and the noise measurements were not carried out throughout the whole programme, while some tests concerned only trackside measurements during train passages. Of the numerous tests specified by the only measurement protocol available at the time of the 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 length of 20 m either side of 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 Ref. [4]. Although only one line is measured over a long distance, the corrugation spectrum has been compared to the limit

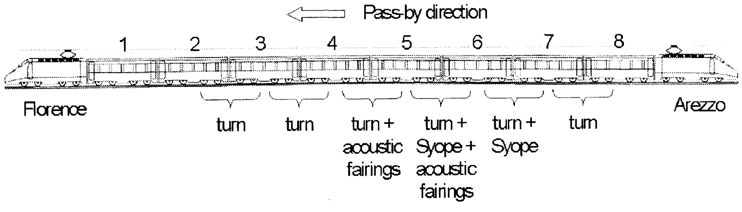


Fig. 1. Test train with wheel position "t" turned, "s" *Syope*®.

given in Ref. [2] for the acceptance of a site for vehicle type testing. The RAS software has been modified accordingly to accept very long CAT files, thereby dramatically improving the certainty in the estimated amplitude for longer wavelengths.

It can be seen from Fig. 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 the standard.

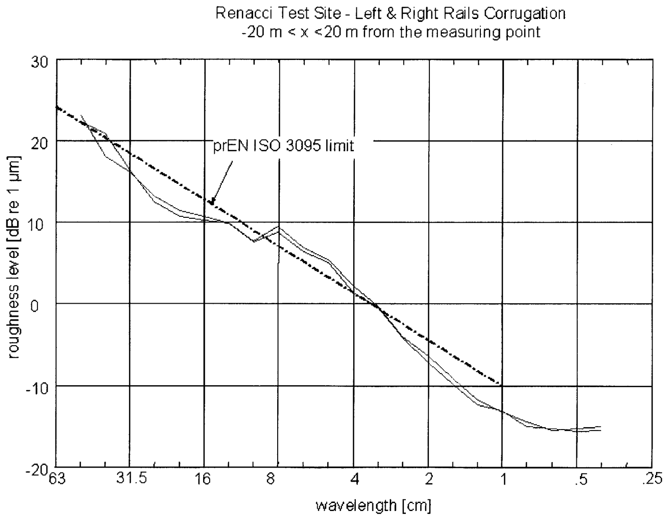


Fig. 2. Average corrugation spectra for both the rails at the Renacci measuring site along the Firenze–Rome "Direttissima" high-speed line.

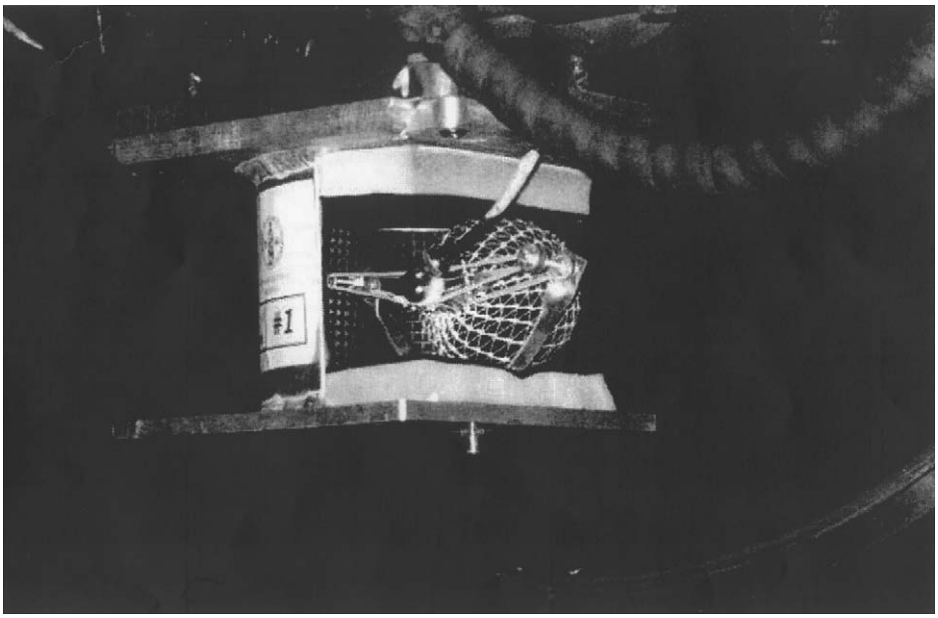


Fig. 3. One of the wheel noise measuring devices mounted under the axlebox.

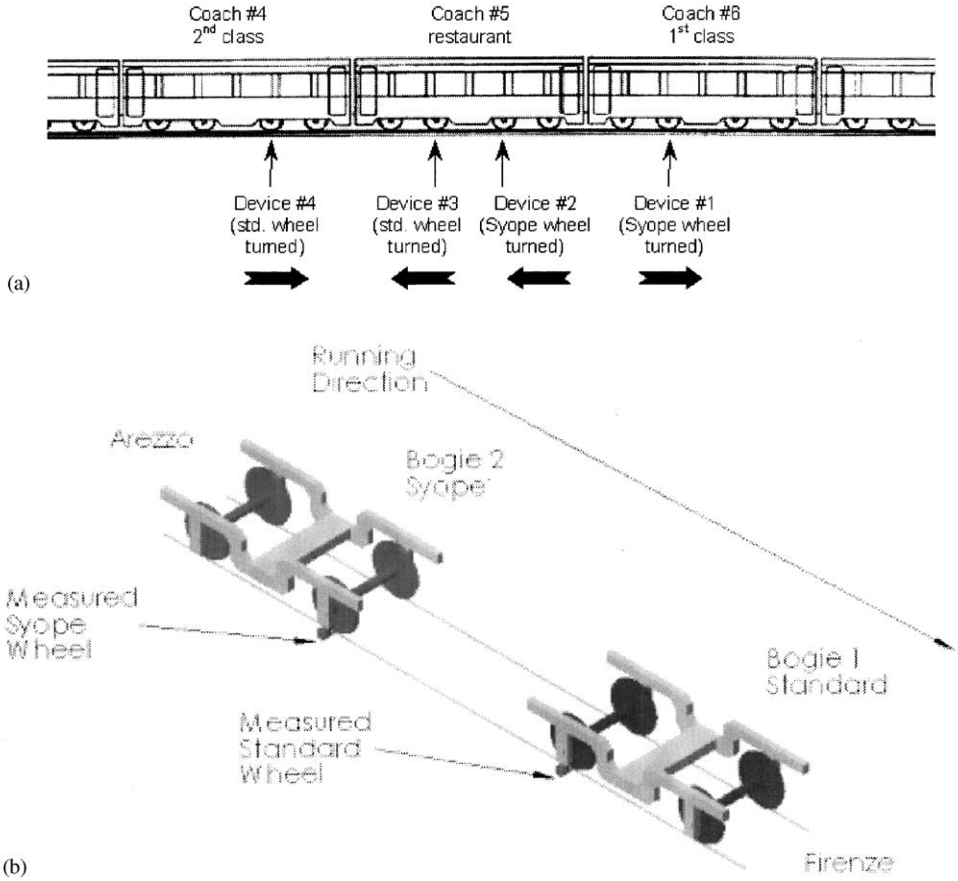


Fig. 4. On-board wheel noise measuring devices position and orientation. Right and left curves are relative to the configuration shown on the right. Only data relative to devices #2 and #3 are shown.

Noise measurements under the axle boxes were made using some special devices, developed during 1993–1994, to measure the noise emitted by the wheel [5–7]. These include wind protection and two parallel plates; the microphone was elastically suspended behind the wind shield (Fig. 3).

To speed up the tests and to compare several wheels, four identical devices were mounted under three coaches as shown in Fig. 4. Theoretically, the support system for the device allows rapid re-positioning of the device such that it would have been possible to measure after each change of direction; unfortunately, as the tests were conducted during a night-time traffic possession, only a couple of minutes were available for reversing. As this time was judged 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 trackside data are also available.

Sound pressure signals were analyzed and recorded using a real-time 1/12 octave band dual channel analyzer with a sampling frequency of 11.2 kHz per channel. A test run log file was 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 summarized in Fig. 5 and in Table 1.

3.2. On-board measurements on the Milan–Bologna line

During a transfer run all the devices were oriented in the running direction, and the signals were collected simultaneously at two microphones. A-weighted sound pressure levels from the standard wheel and the *Syope*® wheel resulting from a 12 km long track which was almost all tangent and with a 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 made on the basis of cumulative curves. L_A results are summarized in Table 2.

3.3. On-board measurements on high speed 'Direttissima' Firenze–Rome line

During the test runs, the speed usually increased 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. The largest number of samples (around 50%) relates to speeds in the range 200–250 km/h, around 18% relate to speeds greater than 250 km/h and the remaining 32% to speeds between 100 and 200 km/h although it is not uniformly distributed. This uneven distribution of the data made it impossible to derive completely meaningful results which could be compared to the data shown in Refs. [5–7], but as already mentioned, it was not possible to modify the speed during the test runs.

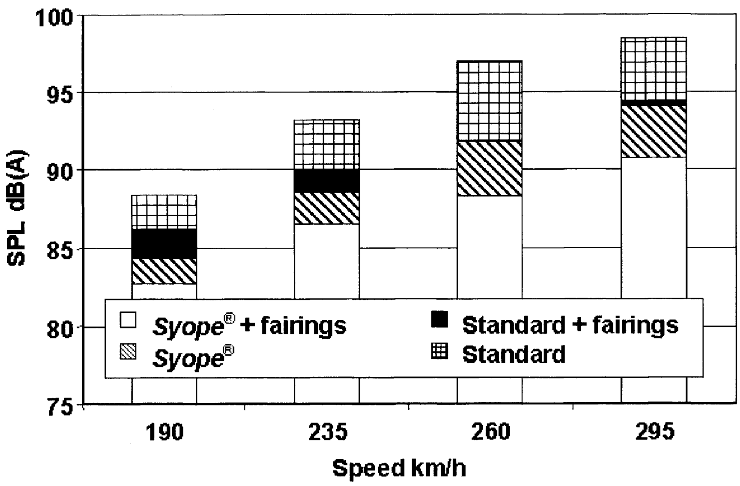


Fig. 5. Trackside A-weighted noise levels at 7.5 m for different turned wheels solutions and bogie fairings. The effect of acoustic treatments to fairings is negligible (not shown).

Table 1
Trackside measured A-weighted noise levels $L_{pA,max}$ with different wheels and under different noise reduction conditions

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 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)

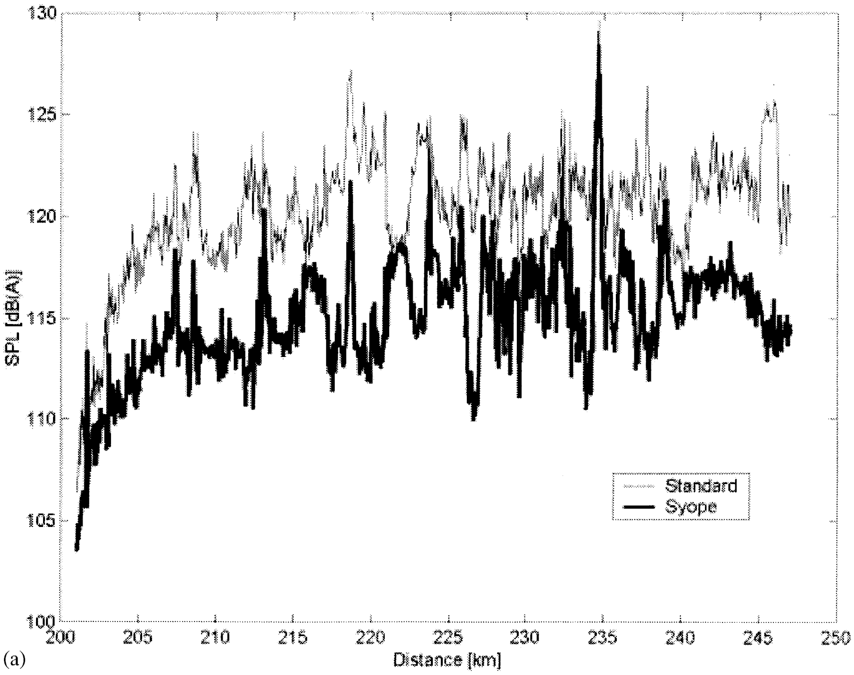
	Section 1	Section 2	Section 3
Length	3500 m	4000 m	4500 m
Gain	-6.3 ± 2.4 dB(A)	-6.2 ± 1.9 dB(A)	-7.1 ± 2.3 dB(A)
Censored gain(percentiles)	-7.4 ± 1.5 dB(A) (5–90%)	-6.2 ± 1.5 dB(A) (5–100%)	-8.0 ± 1.0 dB(A) (5–85%)

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 Fig. 6. The two wheels are only 16 m apart, requiring no correction of the sample position.

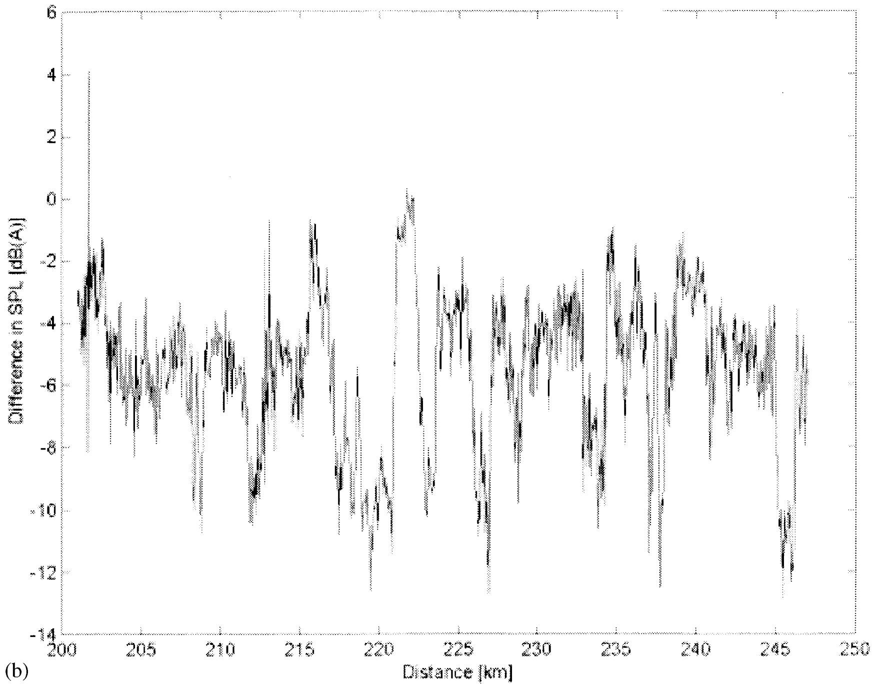
From all the data collected it is possible to make the following observations:

- The noise level is extremely high (up to 130 dB(A) and above) and the dynamic range of the instrumentation was almost entirely used. Only a few records (5 samples in a total of 14 test runs) resulted in an overload and they have been removed from the analysis.
- The noise levels are variable (up to 5 dB(A); see also Fig. 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, etc.). The implications of this evidence are discussed later.
- The benefit offered by the *Syope*® wheel shows a large variability. Fig. 6 shows that for considerable lengths of line the reduction is around −10 dB(A) (km 217 to 221) while in other sections the change can even be positive (km 221 to 223) showing that the damped wheel is noisier than the standard wheel.

The latter observation shows a pattern in that in almost all the test runs similar behaviour was observed. A correlation was found between the curvature of the line and the noise emitted. Fig. 7 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-hand curves while it is higher in right-hand curves. The noise emitted by the standard wheel remains constant or even increases in the right-hand curves, while the noise emitted by the *Syope*® wheel decreases. This shows that the actual position of the contact point

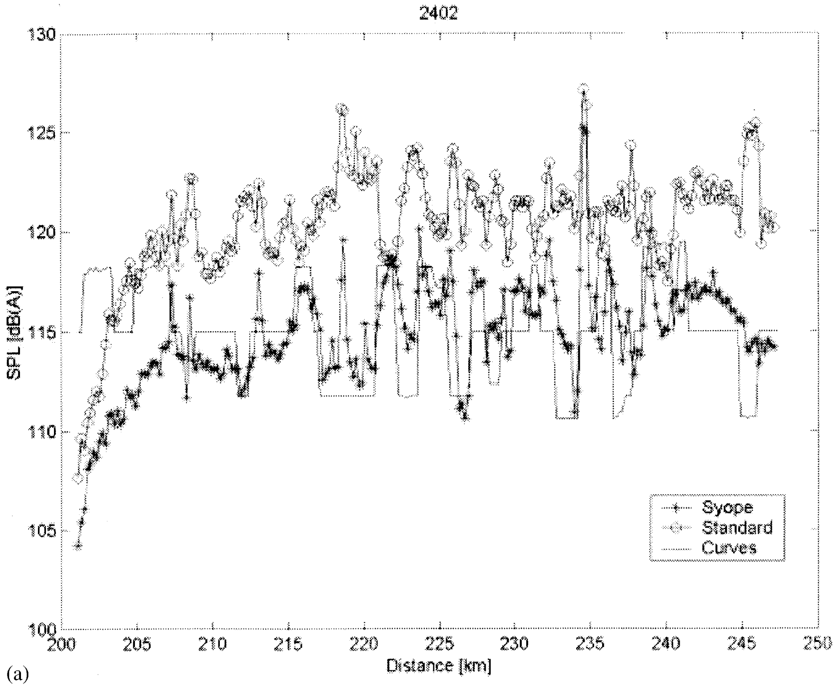


(a)

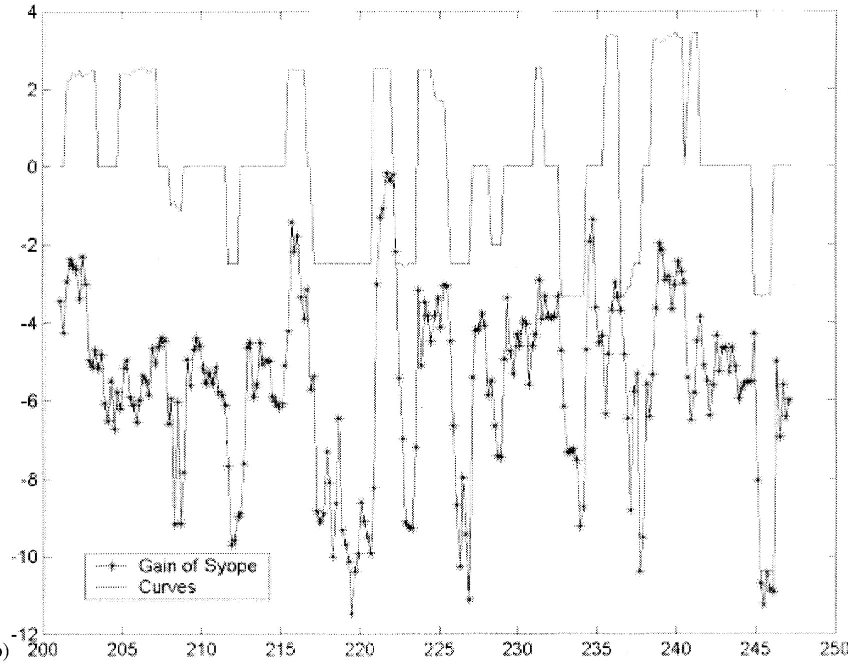


(b)

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).



(a)



(b)

Fig. 7. As Fig. 6 with data grouped following a distance-based criterion (1 sample = 200 m). The curvature in m^{-1} multiplied by 10^4 is also shown.

and the presence of driving forces have a large effect especially for the damped wheel; in general, the exact contact point location depends, once the rolling stock has been specified, primarily on the line curvature, the superelevation and the speed.

This behaviour has been verified in all the test runs. The data have been grouped into 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 the 10 and 90 percentiles have been retained (this procedure is correct as the average remains unchanged while only the standard deviation decreases). These results are shown in Fig. 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 over all the speed range. A more detailed analysis was performed on the single run for L_{pA} levels and spectra, depending on the attitude of the wheel, for the whole run, and in a section of the line where the speed is reasonably constant (Tables 4 and 5).

As a zone where the speed is almost constant can be recognized 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 analyze this zone in order to eliminate the influence of the speed.

As the number of data recorded is different for tangent track, right- and left-hand curves, the statistical influence of each value is not the same. For example, only about half the data are available for left-hand curves compared to the other two conditions. In order to obtain data equally for the three conditions a specific test programme would have been needed, where different train speeds were observed over different line sections with the required mix of tangent

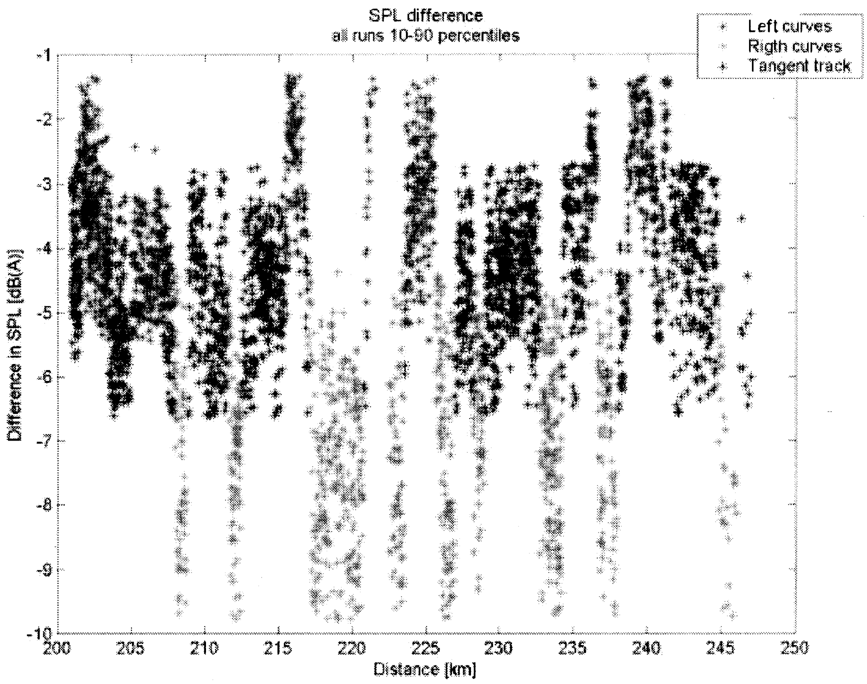


Fig. 8. Difference between the noise emitted from two wheels 10–90 percentiles for all test runs (independently from the speed).

Table 3
Average *Syope*® gain for all 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 4
Average *Syope*® gains for the whole run 2402 (all speeds)

	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 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)

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

track, left- and right-hand 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 attempted to isolate an array of values that can be considered to be unaffected by local factors (Fig. 9). The values are selected from consecutive stretches of the line in order to minimize the effects of 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).

Spectra derived from selected data are shown in Fig. 10. Two sets of results are illustrated; one for a run 2402 with a speed of 200 km/h, and one for a 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-hand curves with a radius of curvature of 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 inside of

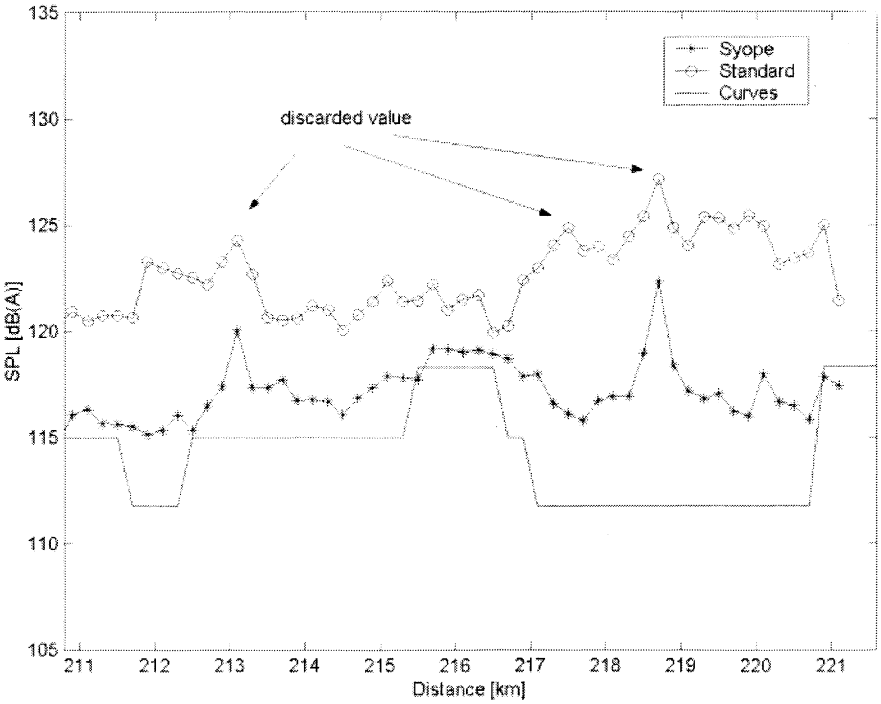


Fig. 9. Zoom view of run 2402 (200 km/h) between km 211 and 221.

the curve. At 250 km/h, $a_{nc} = 0.32\,\mathrm{m/s^2}$ (cant deficiency $h_d = 50\,\mathrm{mm}$) with lateral forces directed towards the outside of the curve.

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 prominent peak appears at approximately 650 Hz in the spectrum for the standard wheel when the train runs at 200 km/h, while this peak appears neither in the spectrum of *Syope*® wheel at 200 km/h, nor in the spectrum from both the wheels when the speed increases.

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

The influence of the peak at 650 Hz on the overall noise is about 1 dB(A) in tangent track and left-hand curves (the peak level is almost the same as that of the peaks at higher frequency) and 0.3 dB(A) in right-hand curves. This appears to contrast with the results shown in Table 6, where the greatest variation in gain is for right-hand curves. It should be pointed out however that the change in benefit is due to a change in the noise emitted by both wheels, and does not show that the *Syope*® and the standard wheel noise change with speed in the same way. Moreover, it should also be noted that when changing 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.

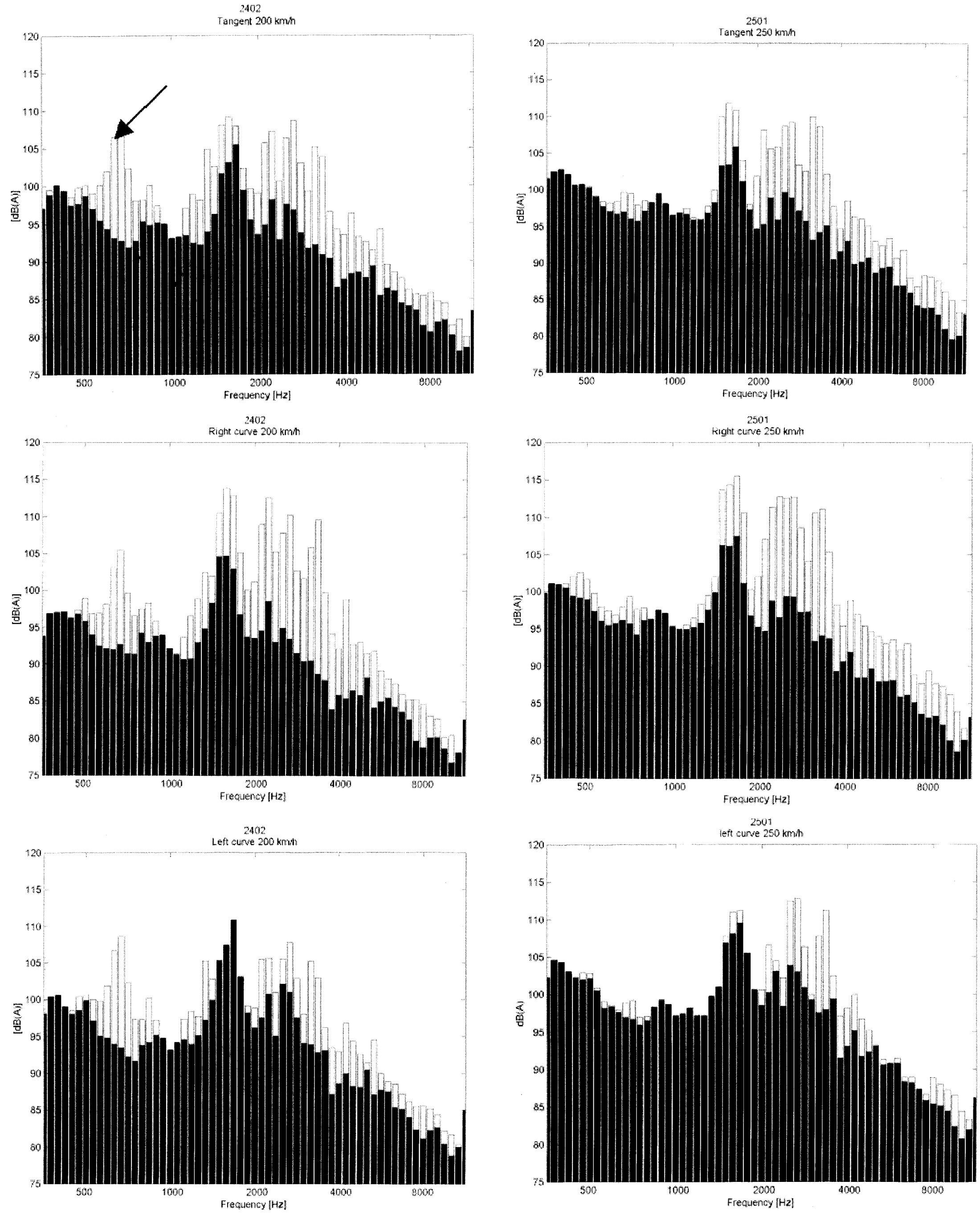


Fig. 10. Spectra for *Syope*® (black) and standard (white) for different line curvatures at 200 km/h (left) and at 250 km/h (right).

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

	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

In contrast with earlier studies, it has proved 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.

4. Conclusions and further developments

During a test programme, the behaviour of a new type of damped wheel (*Syope*® manufactured by Lucchini CRS) has been compared to standard ETR500 wheels and to different noise reduction solutions (fairings applied to bogie area). Simultaneous measurements performed at the trackside and on-board confirm that a combination of both damped wheels and fairings give the highest noise reduction. Whether it would prove impossible or un-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 as replacements on any disc braked vehicle, while fairings can limit the visual inspection of some vital parts of the bogie.

Due to different data recording procedures, on-board measurements under the axle boxes showed previously unobserved noise emission behaviour depending on the line curvature. Unfortunately, due to the limitations in the test programme, it was not possible to carry out a more detailed 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, and abnormal tyre wear. It is intended to perform an experimental modal analysis of the entire wheelset to verify the correspondence of the individual frequency (around 650 Hz) and some wheel/axle eigenmodes.

It is hoped, with the agreement of *FS Trenitalia* (the rolling stock owner), to repeat some measurements under more controlled conditions.

Acknowledgements

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References

[1] A. Bracciali, Lucchini CRS *Syope*® damped wheels noise qualification, *Proceedings of the 13th International Wheelset Congress*, Rome, Italy, September 2001, pp. 17–21.

[2] prEN ISO 3095, Railway applications-acoustics-measurement of noise emitted by railbound vehicles, 1999.

[3] S.L. Grassie, M.J. Saxon, J.D. Smith, Measurement of longitudinal rail irregularities and criteria for acceptable grinding, *Journal of Sound and Vibration* 227 (5) (1999) 949–964.

[4] AEA Technology Rail BV, Roughness Analysis Software RAS v1.7.

[5] A. Bracciali, L. Ciuffi, R. Ciuffi, P. Rissone, Continuous external train noise measurements through an on-board device, *Journal of Rail and Rapid Transit* 208 (1994) 23–31.

[6] A. Bracciali, L. Ciuffi, R. Ciuffi, Metodo innovativo per la misura della rumorosità esterna dei convogli ferroviari, *Ingegneria Ferroviaria* 6 (1994) 317–332.

[7] A. Bracciali, L. Ciuffi, R. Ciuffi, Calibration of an on-board noise measuring device by simultaneous measurement of trackside noise of three different wheelsets for the ETR500 F.S. Train, *Journal of Rail and Rapid Transit* 211 (1997) 41–49.

[8] J.-F. Cordier, P. Fodiman, Experimental characterization of wheel and rail surface roughness, *Journal of Sound and Vibration* 231 (3) (2000) 667–672.