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High speed train noise emission: Latest investigation of the aerodynamic/rolling noise contribution

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Abstract

The aim of this paper is to discuss the quantification of aeroacoustic and rolling noise sources emitted by high-speed trains externally. This work relies on the comparison of experimental data obtained in the DEUFRAKO Annex K and K2 projects and those produced more recently. These are firstly measurements obtained within the NOEMIE project dedicated to the High Speed Technical Specifications for Interoperability involving the measurement of the acoustic emission of different rolling stock travelling at 250, 300 and 320 km/h (TGV-Duplex, ICE3, Thalys). Additionally, measurements are considered that are obtained in the framework of an SNCF acoustic test campaign performed on a TGV-Duplex at speeds up to 350 km/h. These comprise source localisation using two-dimensional acoustic array measurements and assessment of the wayside noise increase as a function of the speed. The conclusions drawn in the DEUFRAKO K project are compared with the new set of data. A detailed analysis of the results is also provided, supported by complementary measurements (wheel and rail measurements) and simulations (TWINS calculations).

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1. Introduction

The wayside noise emitted by the railway system at high speed is known to be the combination of two main families of sources:

- The radiation of the vehicle and the track due to the excitation at the wheel/rail contact patch. This noise is generally called "rolling noise".
- The aeroacoustic sources generated by the turbulence around the vehicle structure (flow-obstacles interaction) so-called aerodynamic noise.

The traction noise is considered to be of less importance.

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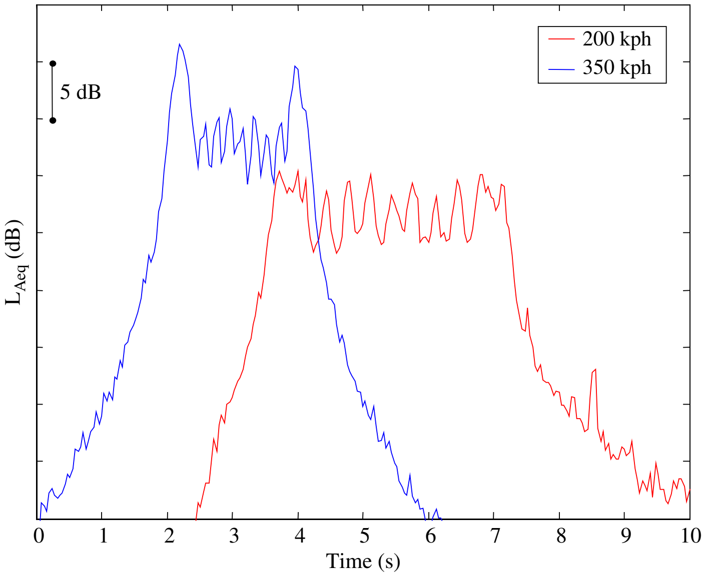

Fig. 1. Time history of TGV-duplex pass-bys.

There is a need for a good knowledge and an accurate description of the main characteristics (position, strength, directivity, governing parameters, etc.) of these different sources as they are used as inputs in simulation tools (noise propagation codes) and guide the studies on mitigation measures.

For conventional speeds (up to 160–200 km/h), the phenomenon responsible for the wayside noise is mainly produced by only one kind of source, the rolling noise, which is correctly modelled by TWINS. But for speeds above 200 km/h, the contribution of the aeroacoustic sources makes more complex the understanding of the pass-by noise mechanism. For these speeds, the quantification of each kind of source becomes a real problem.

Some clues have been obtained thanks to the investigations carried out in the DEUFRAKO K project [1] in the early 1990s. The conclusions were derived both from a single microphone and acoustic array measurements and are still a reference in the domain.

The aim of this paper is to discuss this topic, using updated experimental data and tools, and propose to go further in the separation of the contributions of the different sources as a function of speed.

First, the analysis of results obtained using a single microphone and a two-dimensional star-shaped acoustic array allows one to identify the main sources generated on a TGV-Duplex (double deck) on trial at speeds between 200 and 350 km/h [2,3]. The comparison of the different noise maps allows the dependence of various sources as a function of the speed to be determined. In a second part, the conclusions drawn in the DEUFRAKO K project concerning the noise evolution as a function of speed are checked using the noise measurements on high-speed trains performed in the NOEMIE project [4].

2. Sources identification

2.1. Single microphone measurements

Using the time history data recorded by using a single microphone located near the track (here at a distance of 7.5 and 1.2 m above the rail), a rough estimate of the main source locations can be made. When looking at the time history of TGV-Duplex pass-bys (see Fig. 1), it is obvious that the relative contribution of power cars and trailing coaches highly depends on the train speed.[1]

This is confirmed by the data provided in Fig. 2 which show the A-weighted equivalent sound pressure level ($L_{A\mathrm{eq}}$) of the pass-bys and also quantify the energy coming from the different vehicles of the trainset. At low speeds

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[1] TGV-Duplex is composed of 1 front power car + 8 coaches + 1 rear power car.

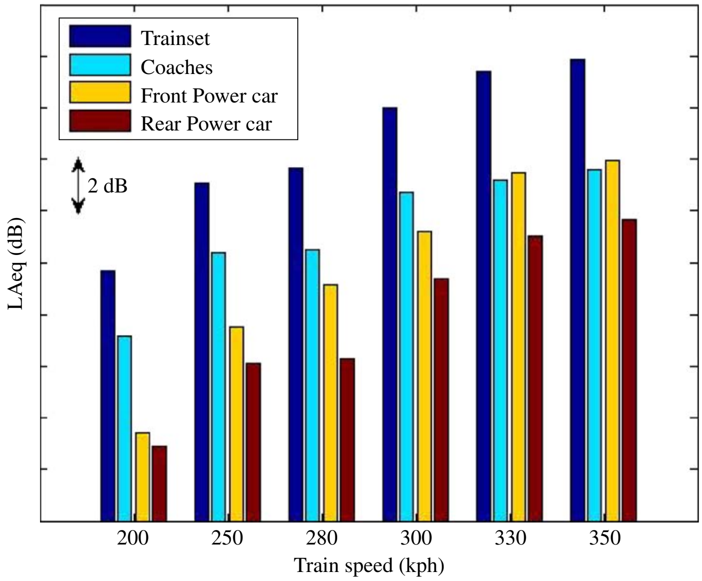

Fig. 2. Acoustic contribution of power cars and coaches.

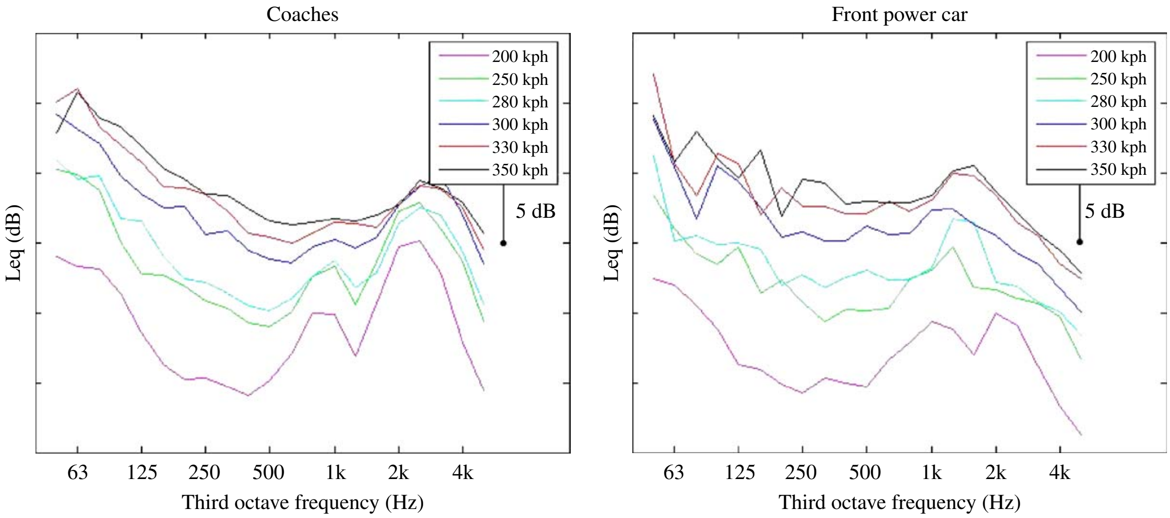

Fig. 3. One-third octave band spectra of the power car and trailing coaches.

(200–250 km/h), the noise radiated by the eight coaches is slightly predominant, but the contribution of power cars increases significantly with the train speed to become the main source of the noise emitted by the train. In fact, above 330 km/h, the noise emitted by both power cars dominates by at least 2 dB(A) the level induced by the eight coaches. It can also be observed that the front power car is significantly noisier than the rear one.

Considering that the maintenance state is quite equivalent on the wheelsets of the whole train, this typical behaviour cannot be generated by the wheel-rail contact excitation, and is then expected to be the result of an aerodynamic effect.

The analysis of the one-third octave band spectra (see Fig. 3) corroborates this hypothesis. For all the coaches, the acoustic level in dB(A) is mainly governed by two peaks, which could be assigned to the rolling noise:

- the first one at 800–1000 Hz which is characteristic of the track radiation, and
- the second one around 2000–2500 Hz which is typical of the wheels radiation.

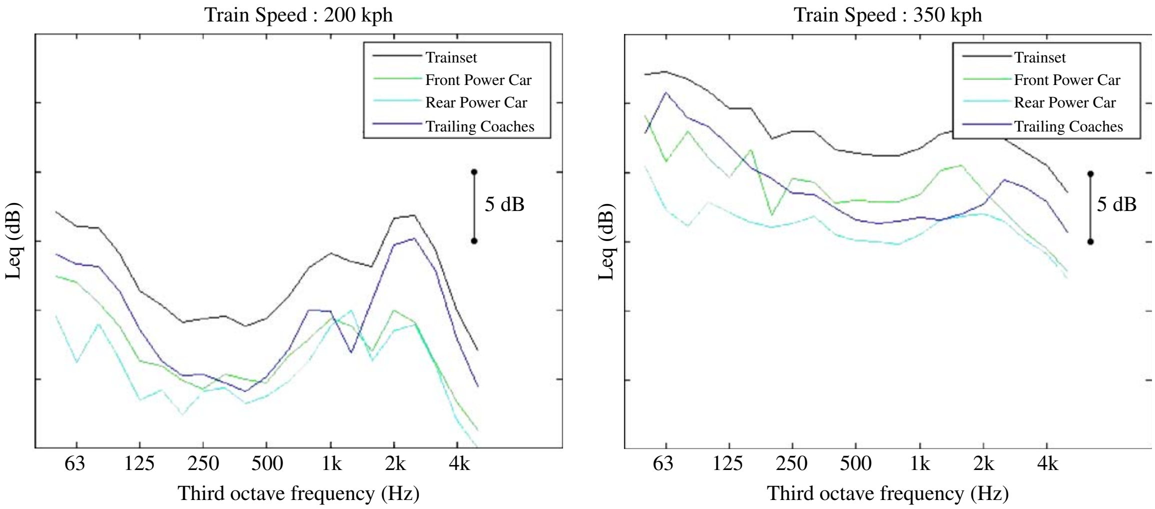

Fig. 4. One-third octave band spectra of the relative contributions of the different vehicles.

In addition to them, a broad-band component appears as the speed increases, which is likely to be due to the aerodynamic effect.

On the front power cars two peaks also exist for the speed 200 km/h but are completely hidden by the broad-band aerodynamic noise for speeds above this. Furthermore, at such speeds a contribution of aerodynamic source appears at 1250–1600 Hz. The contributions of these sources on the overall noise are shown on the graphs in Fig. 4.

This shows that the processing of single microphone measurements can lead to a first approximate identification of the main sources on a high-speed train. However, it leads to a weak discrimination of the sources in the travelling direction and fails to position them in the vertical direction. A more precise characterization requires a two-dimensional focusing which allows the movement of the train to be followed. These specifications are fulfilled by the two-dimensional array measurement technique which has been carried out.

2.2. *Acoustic array measurements*

A two-dimensional star-shaped acoustic array of 29 microphones (see Fig. 5) is used which allow investigation in the frequency range (200–4000) Hz. This is adequate for the identification of the principal aeroacoustic and rolling noise sources.

The processing of array data consists of beamforming and dedopplerisation. An example of results obtained using the acoustic array is presented in Fig. 6. This figure presents two colour maps of the sound pressure level as a function of the position on the forward power car and intermediate coaches of the TGV-Duplex.

From the visualization of the different maps, the main sources present on the TGV-Duplex are identified. These sources are recapitulated in Table 1. The following conclusions arise:

- The aeroacoustic source highlighted in Section 2.1 on the forward power car at 1250–1600 Hz seems to be due to the air flow over the first bogie (see Fig. 6 top).
- The wheels remain the main sources on middle coaches.
- An acoustic source exists in the intercoach gap.

All the sources presented in the table have been identified previously on the TGV-A and ICE trains from the measurements realised in the project DEUFRAKO. Only one source has not been identified on the ICE: the intercoach gap.

Moreover, a discrimination between aeroacoustic and mechanical sources is proposed, mainly based on criteria that point out their speed dependence (speed threshold, rate of level increase, frequency shift). This

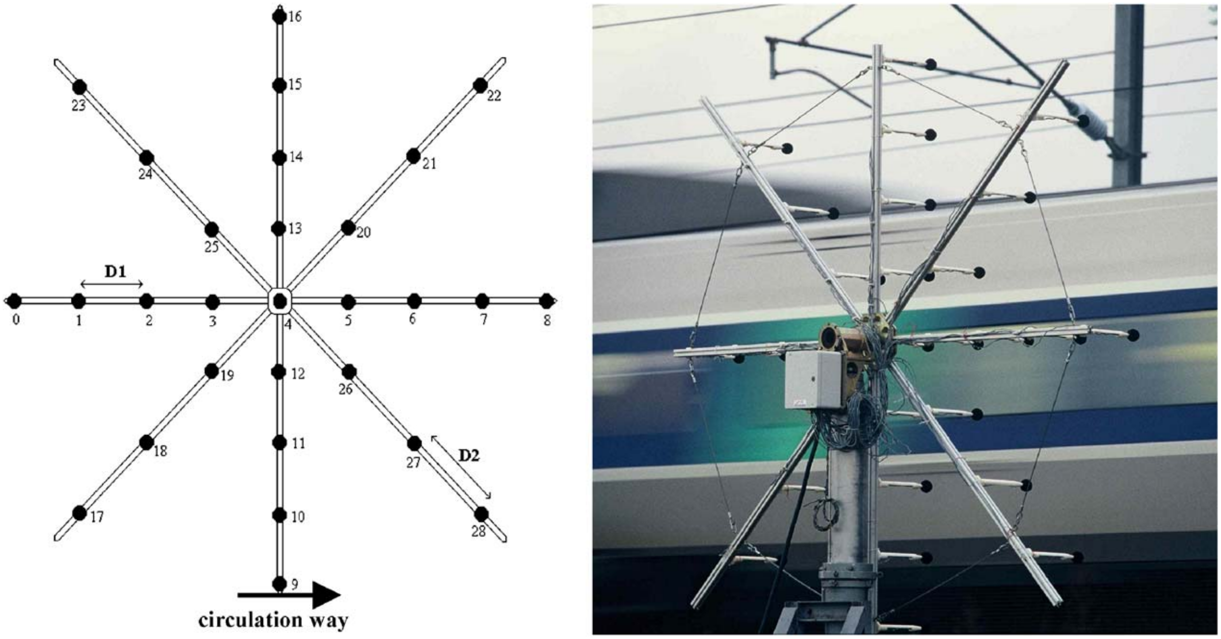

Fig. 5. Star-shaped acoustic array.

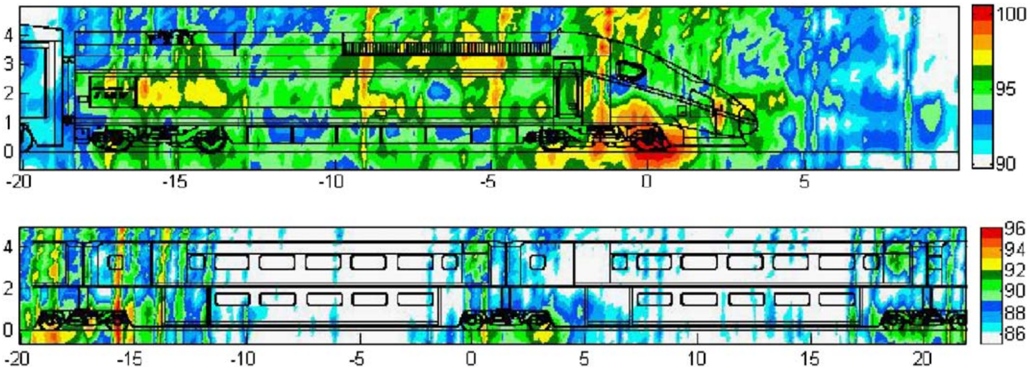

Fig. 6. Noise sources maps of the forward power car and second and third middle coaches at 300 km/h in the third octave band 1250 Hz.

classification has been made using the graphics presented in Fig. 7. Fig. 7 represents the one-third octave spectra of the maximum level for each source, extracted from the noise maps. It can be noticed that:

- All maximum sources levels increase with the train speed but not at the same rate (5 dB(A) for the first bogie, 1 dB(A) for louvres for instance).
- The spectral content of some sources changes with speed. This frequency shift is especially observed for the acoustic radiation of the first bogie. For instance, considering the frequency range below 800 Hz, the maximum level at 300 km/h occurs at 400 Hz but it is at 500/630 Hz for 350 km/h. Similar behaviour can be observed on the last bogie or the pantograph recess which are also typical aerodynamic sources. Conversely, this phenomenon is not observable on the two louvres.

The extension of such analyses to all speeds has enabled a classification of sources into three main families to be achieved:

- *Aeroacoustic sources* mainly composed of the bogies, pantograph and its accessories and the front windscreen (these sources have been shaded in Table 1).

Table 1
Identification of sources (coloured cases identify sources which are classified as aeroacoustic sources)

	High speed train Identified sources
Forward power car	First bogie Second bogie Front glass Pantograph recess Wheels Louvers air inlets Louvers air outlets
Middle coaches	Ventilation Wheels Intercoach gap[a]
Rear power car	Pantograph Last bogie Wheels First bogie Louvers air inlets

[a] This source has not been identified on the ICE.

- *Rolling noise source* composed of wheels.
- *Unclassified*, which have been added to put unclassifiable sources[2] such as the louvres. Insufficient information is available to discriminate if the noise emitted by these sources is generated by the flow over these louvres or from the cooling fan operation.

2.4. Conclusion

The classical acoustic measurements have permitted, on the one hand, to identify the main sources responsible for the noise radiated by high speed trains and on the other hand to highlight the importance of both the power cars in the overall train noise for speeds above 300 km/h. The power cars become the main contribution in the overall noise emitted by the train set at high speed. These measurements, strengthened by the use of a two-dimensional acoustic array, allowed these sources to be localised and their behaviour with increasing speed to be described.

These measurements have been used to classify these sources according to their behaviour and the speed-dependence of their contribution. Three main families have been identified with the aeroacoustic sources, the rolling noise and a last class called "unclassified" in this paper which is probably due to traction noise but cannot be confirmed in the present study.

3. Sources behaviour as a function of speed

3.1. DEUFRAKO K results

Within the framework of the German–French cooperation project DEUFRAKO, annex K (see Ref. [1]), aimed at investigating the noise radiated by high-speed trains. One of the main topics addressed was to establish regression laws of the sound pressure level as a function of speed. The conclusions were then derived from measurements performed on different rolling stock and from a phenomenological model of the main aeroacoustic sources.

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[2] By the measurement method used.

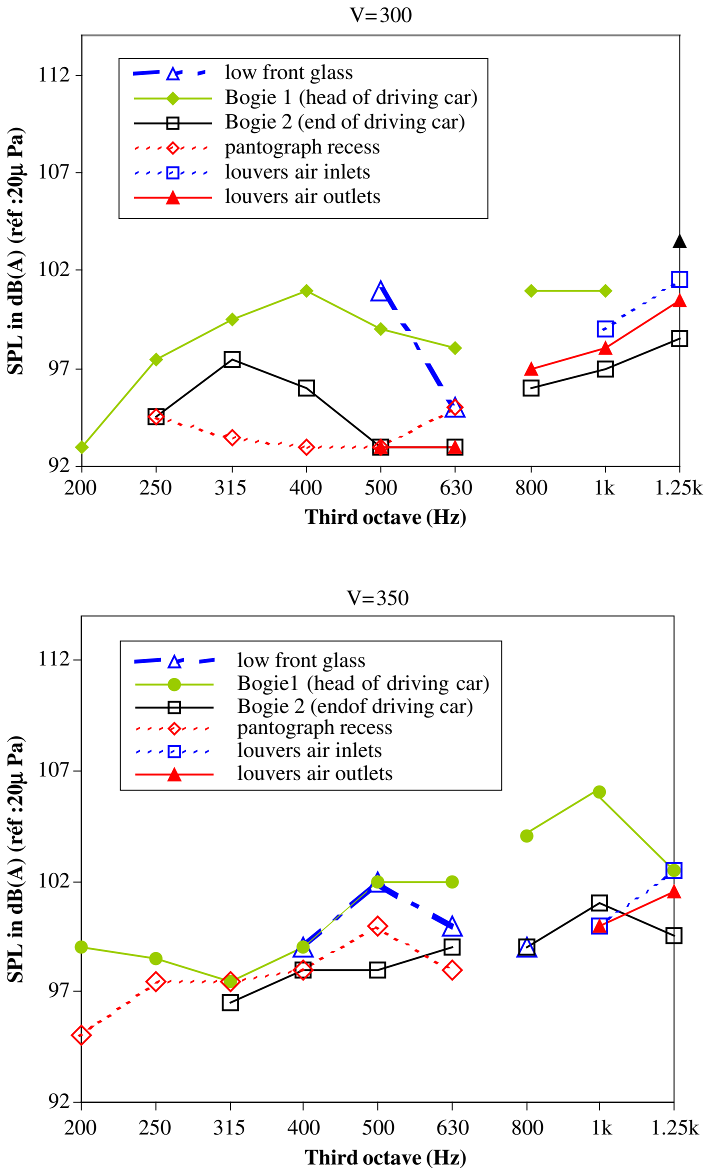

Fig. 7. Level of the main sources observed on the forward power car at two speeds.

3.1.1. Aeroacoustic development

The main aeroacoustic sources identified above were investigated in detail in the DEUFRAKO project:

Bogie area

The bogie area of a TGV-Atlantique has been investigated in detail through DEUFRAKO K. This source is due to complex turbulent recirculations in the bogie area. Investigation both in wind tunnel and through on-board and trackside measurements lead to the following conclusions:

- The first bogies of the trainset contributes more than the following bogies of the coaches to the overall noise.
- The aeroacoustic source in the bogie area is relatively broadband and has a significant contribution between 315 and 2 kHz.

The measurements carried out in DEUFRAKO have also permitted a speed exponent of 4.8 to be determined for the aeroacoustic source of the bogie area.

Pantograph area

Two sources can be identified in the area of the pantograph: the pantograph itself and the cavity on which the pantograph is mounted on the train.

- Pantograph noise generation is mainly due to vortex shedding around cylinders of the pantograph. An overall speed exponent of 7 is generally taken in the models.
- The cavity of the pantograph is a complex area where turbulent background noise is superposed with specific frequencies representative of vortex shedding around electrical equipment in the cavity, like isolators.

An overall speed exponent of 6 could be taken.

3.1.2. Noise level evolution as a function of speed

From the measurements carried out by the different partners of the DEUFRAKO project, a synthesis has shown that the evolution of the pass-by sound pressure level as a function of speed could be approximated by a second-order polynomial of the variable log V (where V is the train speed) to take account of the rolling noise source energy which is proportional to the speed to the power of around 3 and the aeroacoustic source energy which is proportional to the speed to the power of around 6. This difference in the speed exponent induces a break in the linear regressions corresponding to the low speeds on the one hand and the high speeds on the other hand. The regression law has been expressed as

$$L_{A\mathrm{eq},tp} = A + B\,\log(V/V_0) + C[\log(V/V_0)]^2, \tag{1}$$

with $L_{A\mathrm{eq},tp}$ the A-weighted equivalent sound pressure level integrated over the pass-by period, V the train speed, V_0 the reference speed, equal to 200 km/h in the DEUFRAKO project; and A, B, C the regression coefficients.

Fig. 8 shows the regression curves obtained from the model for the different types of high speed train tested: TGV-A, ICE, and also the magnetic train Trans-Rapid 07 (TR-07). The regression curves corresponding to the “classical” rolling stock (ICE, TGV-A) are quite similar and very close to a straight line, while the TR-07 noise curve exhibits more clearly the shape of a second-order polynomial with a significantly greater slope at high speeds. This can be understood from the intrinsic characteristic of this rolling stock: the TR-07 is a guided magnetic train on which the mechanical noise due to vehicle/infrastructure interaction is negligible.

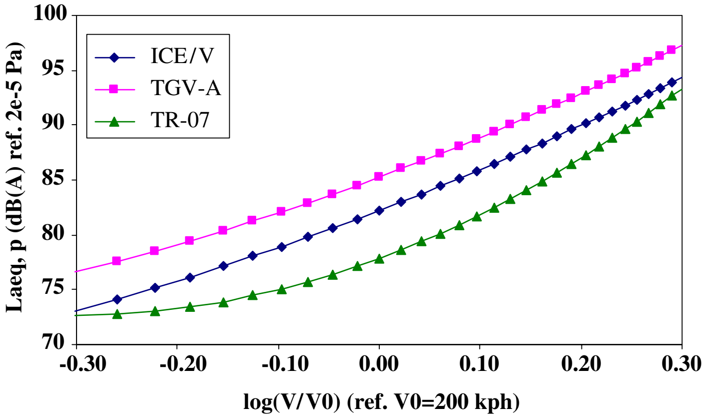

Fig. 8. Regression curves of the SPL vs. speed (from DEUFRAKO annex K).

3.2. Analysis of the DEUFRAKO's regression law

3.2.1. Reprocessing of the DEUFRAKO data

The data from the measurements obtained in the DEUFRAKO project have been reprocessed. The results provided in Fig. 9 shows that a linear regression is enough to fit accurately the DEUFRAKO data for the TGV-A and ICE/V with a good correlation coefficient R even at speeds up to 350 km/h.

It is also noteworthy that their slopes are about 33 (which corresponds to a speed exponent 3.3). This is close to the value of 30 commonly used in the prediction formula for rolling noise, which is widely employed to extrapolate noise emission of trains:

$$L_{A\mathrm{eq},tp}(V) = 30\,\log(V/V_0) + L_{A\mathrm{eq},tp}(V_0), \tag{2}$$

where V_0 is the reference speed for which the noise emission of the train is known.

From these measurements, it could then be expected that this linear law is valid up to 350 km/h. The transition speed, where aerodynamic noise becomes as important as rolling noise, which is generally considered to be around 300 km/h [5,6] does not occur clearly.

The objective of the following part is to check if this simplified formula is in accordance with the data resulting from recent high-speed train measurement campaigns in France.

3.2.2. Application of the regression law to the Noemie data

The investigations are carried out from the results of two different field test campaigns organised in France by the SNCF test department:

- NOEMIE 1 Phase 1 measurement campaign, which took place mid 2003 on the North High Speed Line (between Lille and Calais). It involved an ICE3, a Thalys PBKA (Paris-Brussels-Köln-Amsterdam) and a TGV-Duplex (hereafter called TGV-D1) running at three different speeds (250, 300 and 320 km/h).
- A specific SNCF campaign dedicated to the research on high speed train acoustic emission. The test has been performed on a TGV-Duplex (hereafter called TGV-D2) running at speeds between 200 and 350 km/h on the Mediterranean high-speed line.

All the data presented in Fig. 10 were obtained from a single microphone located at a standard position, 25 m from the centreline of the track and 3.5 m above the railhead.

As in the DEUFRAKO project, the speed dependence of all the trainsets is correctly approximated by a linear regression but here with a large spread of slopes (from 36 for the ICE-3, and up to 56 for the PBKA).

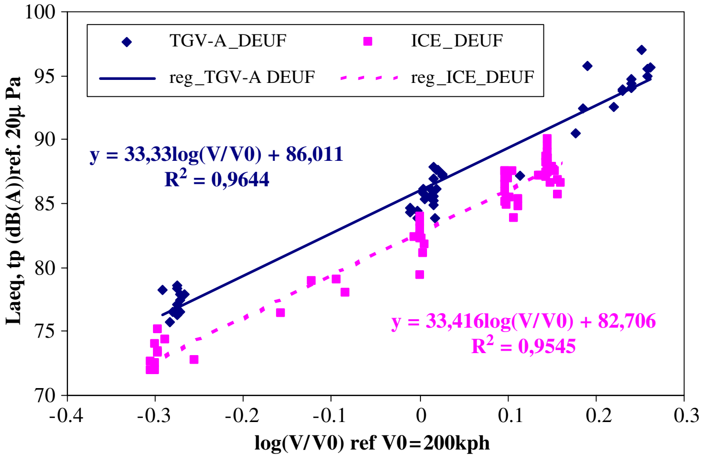

Fig. 9. Linear curve fitting of data measured in the DEUFRAKO project.

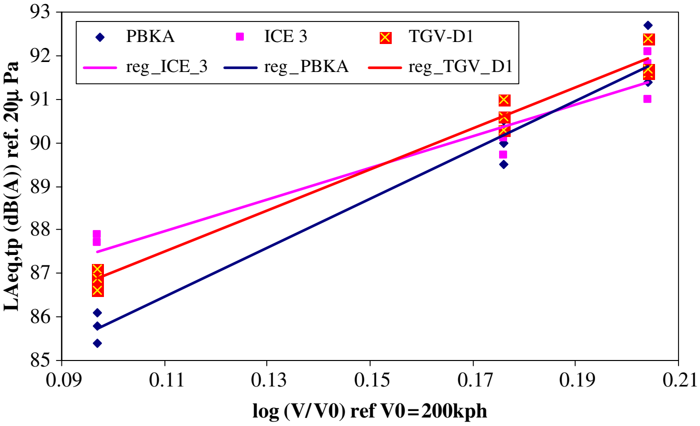

Fig. 10. Linear curve fitting of NOEMIE.

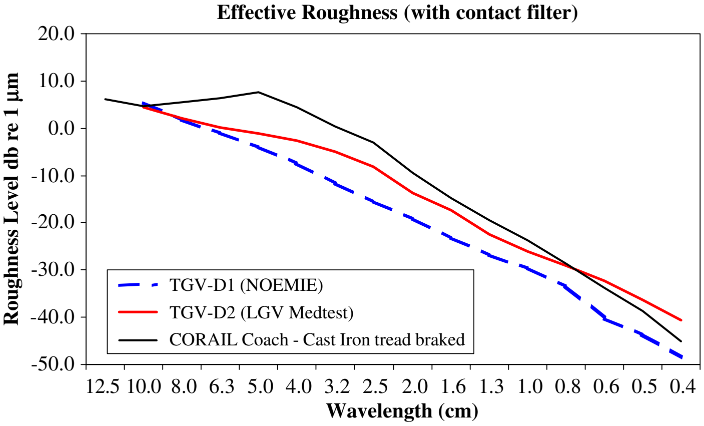

Fig. 11. Effective roughness of both TGV-duplex on trial and of a typical cast iron tread braked vehicle (Corail coach).

3.2.3. Analysis of the dispersion on the speed exponents

The differences observed in the slope of linear regression can be explained by differences between the effective roughness. The way the effective roughness may cause variations in the speed dependence of the high-speed train acoustic emission is twofold:

- Firstly, smooth wheel and rail surfaces induce weaker mechanical noise and then the aerodynamic noise (which has a steeper slope) will become predominant at lower speeds. This is particularly the case for the PBKA trainset which has very smooth wheels and also the lowest emission level at 250 km/h where the rolling noise should have more influence.
- Second, depending on the spectral content of the effective roughness some deviations from the common $30\log(V)$ law, characteristic of rolling noise, may occur.

The effect of the effective roughness on the linear regression coefficient is illustrated by Figs. 11 and 12. It can be underlined that two trainsets of the same kind (TGV-Duplex) may also produce noticeably different values of slope (cf. Fig. 12). This difference is, in this present case, mainly induced by the difference of effective roughness between the two TGV-Duplex. The effective roughness of the TGV-D1 is lower by 5 or 7 dB overall compared with the TGV-D2 (cf. Fig. 11). This variation could be induced by the NOEMIE protocol which imposed that the measurements had to be taken on a reference track [11] with recently reprofiled rolling stock wheels and, on the other hand, by the difference of braking system between the two TGVs. The TGV-D2 was equipped with disc brakes on all wheel sets while the TGV-D1 was equipped with disc brakes except on the wheels of the power cars, which have composite brake blocks.

One can then raise the hypothesis that this slope strongly depends on the mechanical contact interaction force which is directly proportional to the roughness of the wheel treads and rail running band.

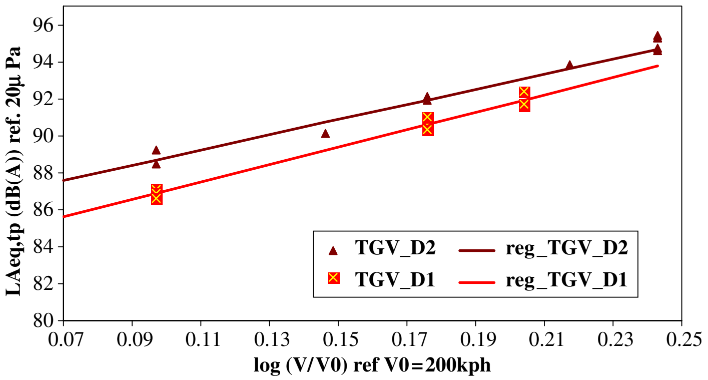

Fig. 12. Linear curve fitting of TGV-D1 (LGV North) and TGV-D2 (LGV South).

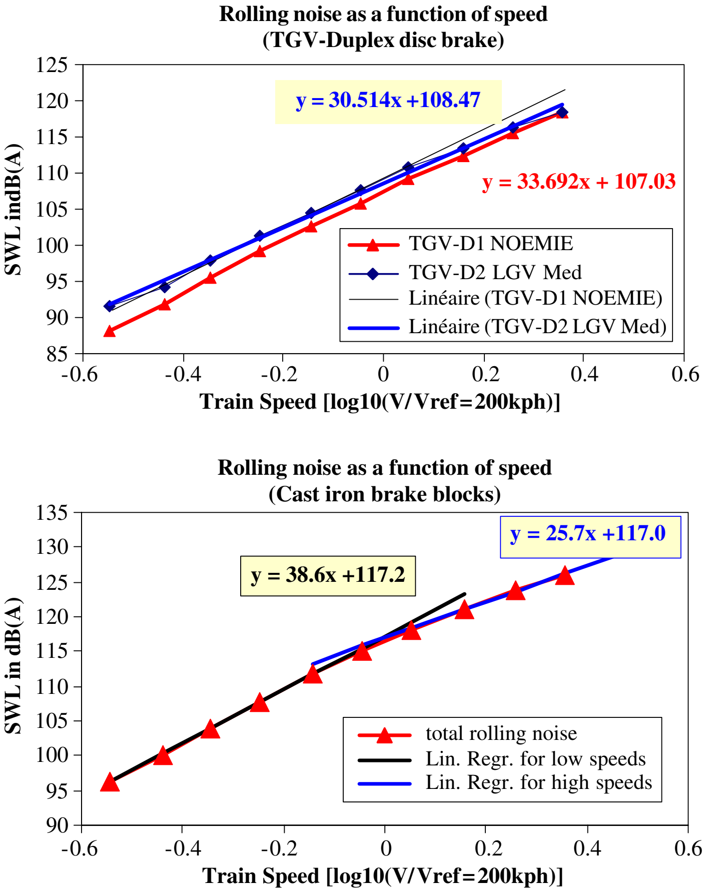

Fig. 13. Numerical investigation of the rolling noise speed dependence.

The second effect has been carefully analysed numerically, based on computations performed with TWINS. The results, in Fig. 13, give the Sound Power Level (SWL) radiated by one wheel (920 mm diameter) rolling on a typical French track (ballast bed, UIC 60 continuously welded rail, biblock concrete sleepers, resilient rail pads of vertical stiffness 500 kN/mm). The three different roughness spectra are given in Fig. 11.

The computations demonstrate that the rolling noise speed dependence fits quite well a constant slope of about 30 which is mainly due to the shift of the excitation spectrum introduced by the wavelength to frequency transform $f = V/\lambda$. However, for a typical tread braked wheel roughness, some deviations can be highlighted: the slope is higher for low speeds than for high speeds. This phenomenon also exists for the TGV cases but to a lower extent.

All these analyses show that the general speed dependence law (Eq. (2)) has to be handled carefully when used to extrapolate the noise emission to a different speed. In fact, even if the rolling noise actually follows a $30\log(V)$ law, the total noise can reach significant variations in slopes (about 25%).

Moreover, on new rolling stock, the transition speed between rolling and aerodynamic noise turns out to be very low (under 300 km/h), due to braking systems which maintain good wheel surfaces. Therefore, far higher slopes may be reached.

4. Conclusion

The relative weight between aerodynamic and rolling noise emitted externally by trains travelling at high speeds has been investigated using experimental data acquired recently. Most of the conclusions drawn in the DEUFRAKO project, which are considered as a reference up to now, have been discussed.

At first, the positions of the main sources have been confirmed, and the importance of the aerodynamic source located on the power cars have been put forward. As a consequence of this level increasing, the power cars become the main source of noise for the trainset for speeds above 300 km/h.

Then the validity of the speed dependence law is questioned. It is shown that no general rule can be proposed even for speeds below 300 km/h, widely considered as a threshold for the aerodynamic source influence. Then, when using such simple laws for engineering purpose, one has to keep in mind the uncertainties attached to the results.

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