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# Tram noise emission : spectral analysis of the noise source contributions

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In France we can see a wide development of tram networks for public transportation in main cities. At the same time questioning arises on the noise emission of trams and possible consequences for resident exposure. A French research project has been conducted for studying noise and vibration emission of trams : this paper concerns the description of the noise emission of passing-by trams. A measurement campaign was achieved on the city of Nantes network, involving two kinds of trams with distinct technologies and equipment, and tested on two types of tracks with different surface materials. Acoustic measurement included both a 2D-array for noise source identification and a microphone set for vertical directivity analysis. The dominant noise sources are mainly the bogie areas (powered bogies, unpowered bogies) and an extended noise source along the track and the lower part of the tram, all of them involving rolling noise. This paper focuses on the spectral description of the main sources. It presents and points out the effect of speed, tram type and track type on the frequency distribution of the emitted noise.

# 1 Introduction

After withdrawing most tram networks from the urban landscape in the 50's, many main cities in France are rediscovering this public transportation mode through new modern tram facilities. The tram is often seen as environmentally friendly, namely non polluting and silent. However complaints from residents living along the lines prove that it may sometimes lead to annoyance. A French research project has been conducted to identify situations perceived as annoying, and to relate physical data concerning noise and vibration to resident perception. The acoustical part of the project considered the noise emission characteristics in relation with several parameters : running speed, type of tram and type of track. It relied on an experimental study conducted on the tram network of the city of Nantes (France). This led to the development of a free-field noise emission model, involving equivalent noise sources associated with actual noise source locations. Details on the measurement campaign, the global noise emission and the main noise sources, as well as the noise emission model characteristics were reported in [1] and [2].

A social survey achieved in parallel [3] pointed out a connection with the noise frequency content, between the perception of tram noise and annoyance. An acute investigation on spectral aspects of noise emission has thus been conducted. The present paper focuses on this topic for a tram at pass-by, and describes the effect of speed, tram type and track type on the frequency distribution of the main noise sources. It should be noted that the typical case of squeal noise in curves, otherwise widely studied [4], is beyond the scope of this paper.

The next section (§2) describes the experimental approach of the noise emitted by trams ; it recalls the various aspects of the measurement campaign and gives an overview of the main noise sources which have been identified. Then a spectral description of the acoustic power is given in §3. Finally the effect of the main parameters (i.e. the running speed, the types of track laying and tram) is considered more deeply, with regard to spectral analysis of the main sources (§4).

# 2 Experimental approach

## 2.1 Measurement sites and configurations

The measurement campaign formed the foundation of the acoustical study, among other things as a means of stating the actual noise emission for various common configurations of French tram networks.

Two measurement sites were chosen as representative of usual track laying (Fig.1) : the first one is a standard laying of rails (without specific vibration absorbing device) with a grass surfacing, the other one involves absorbing pads (DPHI) and is covered by a paved surface. Thus the former offers an acoustically partly absorbant surface, whereas the latter is reflective. In each case, laying of rails and type of surface converge to the same trend, either quieter or noisier. For each site, the rail condition can be considered as satisfactory. The roughness could only be measured at large wavelengths (0.1m - 1.25m), which fit the vibration frequency domain but concern the sole lower part of acoustic frequencies. In this range, the roughness was lower than the limit curves of the reference rail of EN ISO 3095:2005 [5].

Two types of trams were measured on both measurement sites (Fig.1). The first tram (TFS, Alstom), here named *tram A*, is representative of rolling stock from the beginning of tram renewal, that is 1985-1995. It is composed of three modules, the middle one with a low floor, and has two powered and two unpowered bogies. Its total length is 39.15 m. It is equipped with DC motors, and has no Heating, Ventilation and Air Conditioning system (HVAC). The second tram (Incentro, Bombardier), named *tram B*, is representative of the more recent tram generation (after 1995). It has a full low floor and three bogies, among which two are powered with independent wheels (one motor for each wheel, asynchronous motors). Its length is 36.14 m. The HVAC, as well as much auxiliary equipment, is roof-mounted. One tramset was available for each tram type, the same for every measurement site. For both trams, the wheels were in good maintenance state, except maybe for a light flat on one wheel of TFS.

Figure 1: Trams and measurement sites
*left* : tram A - DPHI track + paving
*right* : tram B - standard track + grass

During the measurement period, the trams were running in both directions on the same track line. Records concern pass-bys at constant speeds, from 20 to 50 km/h, in a straight line. Complementary measures were also made at stop, for studying auxiliary equipment noise.

### 2.2 Acoustic quantities

The acoustic measures involved several different aspects. Besides standard microphone position at 7.5 m of the track centre (height 1.2 m), two additional devices were used. The first one consisted of a set of 5 microphones distributed on an arc of circle of radius 5.1 m centered at the track axis ; it aimed at studying the vertical directivity of noise emission and at estimating the total acoustic power radiated by the trams. The second device was a microphone array, designed for locating and analyzing the noise sources on the tram. Composed of 41 microphones, this cross-array consisted of two overlapping line arrays (microphone spacing resp. 5 cm and 15 cm) for each arm. Both arms were perpendicular, in a vertical plane parallel to the rails (2.32 m away from the nearest rail), and could be oriented either horizontally-vertically or rotated 45° from the vertical. The array centre was located either at 1 meter high for focussing on sources in the lower part of trams, or at 3 meters high for roof-mounted sources. The array signal processing involved near-field beamforming (*focussing*), with source tracking during pass-by (*dedopplerisation*). More details may be found in [1].

Kinematic data were provided by infrared cells, detecting the pass-by of bogies and estimating the vehicle speed for each bogie.

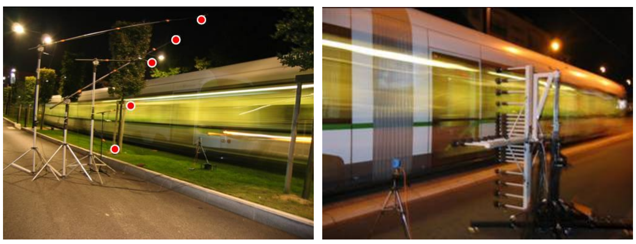

Figure 2: Vertical directivity measurement set (*left*) and microphone array (*right*)

### 2.3 Main noise sources

The noise source analysis indicated that most sources are located on the lower part of the vehicles [2]. Predominant as compact sources are the wheel areas, and more widely the bogie areas, with differences between powered and unpowered bogies since in the former case the wheel area (resp. bogie area) may include motor contribution. This additional contribution gives rise to the presence of tonal and narrowband components in the spectra. Otherwise the bogie area is dominated by rolling noise, linked to the radiation of the wheels, the rails and the platform. The dominant effect of the type of platform and laying of rails on the global noise levels could be pointed out.

Another important source extends along the lower part of the trams, from the front to the rear. Although locally not too strong, its total contribution for the whole tramset may make it as the dominant source during the pass-by. It is composed of the noise radiation from the rails and the platform due to rolling noise, and of the contribution from the underframe of the tram, with possible multiple reflections between the ground and tram frame. The type of track and surface is a dominant parameter for the global noise levels and acoustic power radiated by this extended source.

Other secondary sources could be detected, with a lower contribution to the total emitted noise. Among these is the HVAC, located on the roof of tram B, which may firstly affect residents living in the building storeys. The other auxiliary equipments do not have a significant contribution to the global noise emitted.

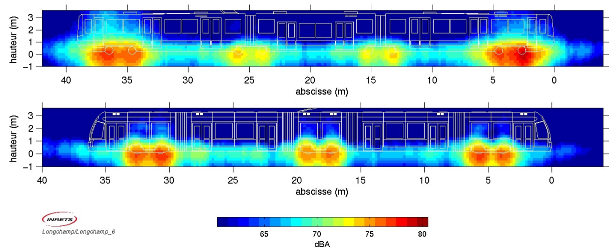


Figure 3: Noise source cartographies of both tram types at 30 km/h (site DPHI + paved surface) (*up* : tram A - *down* : tram B)

## 3 Spectral analysis of the acoustic power

As specified in § 2.2, the acoustic power has been estimated by using the five microphones distributed on a vertical arc of circle (Fig.2), in third octave bands. Figure 4 shows power spectra, as developed by tram type / track type / speed. The differences which occur according to the types of tram and track are quite obvious. One noticeable feature relates to the powerful contribution of third-octave 4000 Hz and those neighbouring, which is specific to tram B. Noise source analysis associated this narrowband spectrum component with the location of the motors, just next to every powered wheel. It is no pure tonal contribution, and it does not depend on vehicle speed, neither in frequency nor in power level.

Power spectra frequency distribution differs notably from one site to the other : rather uniformly spread on the largest part of the frequency range for the site with standard track, it concentrates around the middle-frequency range for the DPHI site with paving.

Deeper insight will be given in the next paragraph to the behaviour of each main source contributing to the noise emission.

## 4 Effect of parameters on noise source spectra

### 4.1 Bogie area

Classical array processing, based on delay-and-sum beamforming [6], is characterized by its spatial resolution [1],

[1] ability to separate neighbouring sources

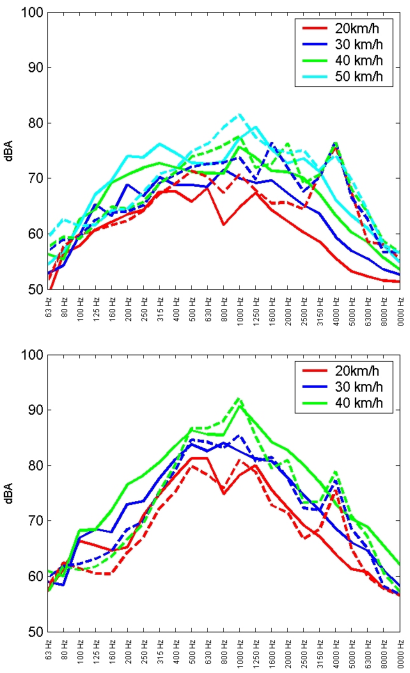


Figure 4: Acoustic power spectra of tram noise emission
(*full line* : tram A - *dashed line* : tram B)
(*up* : standard track + grass - *down* : DPHI + paving)

which depends on the ratio between the wavelength of the incident wave and the length of the array. Thus for a given array, lower frequency implies lower resolution. The search for processing offering uniform resolution over a wide frequency range would involve the use of a specific processing (or even a specific array geometry) [7] which was not implemented here. Since both wheels of a bogie cannot be separated at the lowest frequencies, it is preferable here to gather the contribution of all the bogie sources and to consider one unique source for each bogie on the whole frequency range, called *bogie area*.

The signals analysed are the pressure levels as measured at the array centre (2.32 m away from the nearest rail) associated to the side noise emission of the bogies. The description hereafter reports the average behaviour of each type of bogie (powered and unpowered respectively).

The spectra associated with the bogie area differ with the tram type, the track type and the tram speed. However some characteristic behaviour may be emphasized, as follows.

**Powered *vs* unpowered bogie** Powered and unpowered bogies differ mainly through the presence (resp. the absence) of motor components. The comparison of their spectra points out level differences which are specific to each type of tram (Fig. 5). For tram A, powered bogies are noisier on a wide part of the spectra (mostly 125-4000 Hz) ; this also includes tonal components whose frequency increases with speed (530 Hz at 20km/h and its first harmonic, and 120 Hz at 20km/h), directly linked to the working of the motor and the neighbouring auxiliaries. For tram B, noise pressure levels received from powered and unpowered bogies are similar, from low frequencies up to 1250 Hz ; they differ clearly at high frequencies, greater than 1600 Hz. Additional components on powered bogies include a speed dependent tone (1545 Hz at 30km/h), and a wider contribution (2500-4000 Hz, mainly 4000 Hz) already mentioned in §3.

The level differences between powered and unpowered bogies are globally higher for tram A, which may be noticed for instance on Fig.3.

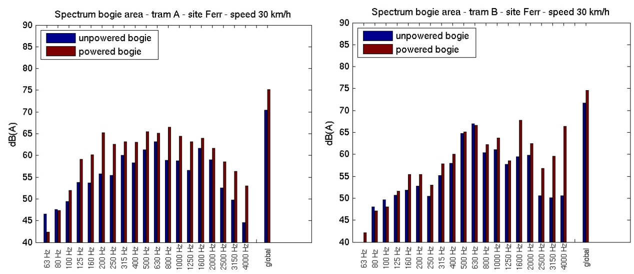


Figure 5: Pressure spectra for powered (resp. unpowered) bogie area at 30 km/h - standard track
(*abscissa* : third-octaves 63 Hz to 4000 Hz)
(*left* : tram A - *right* : tram B)

**Type of tram** Both tramsets are representative of different tram generations, with distinct technological options. This results in spectra with various frequency distribution, predominating at low frequencies for tram A and at high frequencies for tram B (Fig.6). However their global pressure levels have similar values.

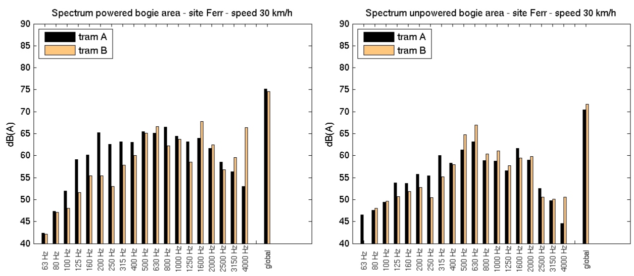


Figure 6: Pressure spectra for bogie area of tramsets A and B at 30 km/h - standard track
(*abscissa* : third-octaves 63 Hz to 4000 Hz)
(*left* : powered - *right* : unpowered)

**Speed** Pass-by speed is an essential parameter for the bogie area pressure levels, which globally increase around 7.5 to 9 dB(A) between 20 and 40 km/h, depending on tram, site and bogie type. However this increase differs a lot with frequency. For tram A, the effect of speed is high on the whole frequency range, whereas it is restricted to high frequencies for tram B (Fig.7). This property holds for powered and unpowered bogies as well, whatever the track type. Thus speed does not change spectrum distribution of tram A, whereas it reinforces high frequency range on tram B.

**Type of track and platform** The track is a key parameter for noise emission, concerning both the generation of rolling noise (rail roughness, laying of rails) and noise absorption (surface). As mentioned above (§2.1), although the quality of rail surface could not be

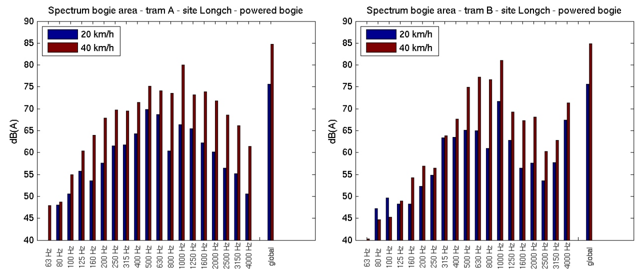


Figure 7: Effect of the speed on the pressure spectra for powered bogie area - (DPHI track + paving) (*abscissa* : third-octaves 63 Hz to 4000 Hz) (*left* : tram A - *right* : tram B)

measured throughout the meaningful wavelength range, it can however be considered as satisfactory for these sites. Measures estimate the site effect to reach globally 8 dB(A) for the powered bogie area and 9 dB(A) for the unpowered one, at the same speed. Differences between both sites mainly affect frequencies greater than 200 Hz, for both bogie areas. Fig.8 for instance points out large differences from 315 Hz to 1250 Hz for tram B. These cannot be attributed to the sole absorption ; it may be noticed that it coincides with the frequency range where rail radiation usually prevails.

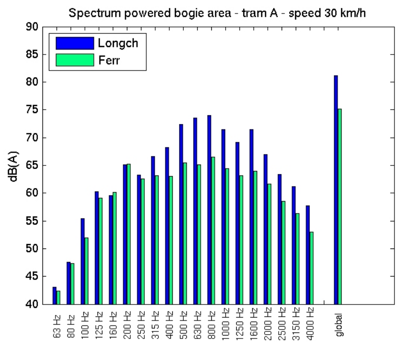


Figure 8: Effect of the type of track on the pressure spectra, for powered bogie area at 30 km/h - tram A (*abscissa* : third-octaves 63 Hz to 4000 Hz) (*blue* : DPHI+paving - *green* : standard track + grass)

## 4.2 Extended track source area

The extended track source spreads over the tram length, along the track. As a first approximation, we consider it as a uniform line source. Then the method of analysis differs from the one used for compact sources. The horizontal branch of the array in its low position (height : 1 m) is used when facing central sections of the tramset distant from the bogies. This is allowed as long as no other source is present at another height for the same abscissa range. The array is equivalent to a spatial filter, and a noise pressure contribution per unit length of track is estimated, taking into account a correction linked to the spatial response of the array [2].

The acoustic quantities delivered for this source are pressure levels brought to the array distance (2.34 m away from the nearest rail) at 1 m height, expressed per track unit length.

Global noise levels indicate that track type and speed are main parameters for this source [2]. The following developments describe differences on the frequency axis.

**Speed** Global levels for this source increase with 7 to 9.5 dB(A) from 20 to 40km/h, depending on site and tram, but quite unevenly in frequency. Speed affects spectrum of tram A with a similar trend on the whole frequency range ; thus the frequency distribution changes little with speed. But for tram B, the increase of speed strengthens the middle and high frequency components of spectrum (500 to 2500 Hz), while low frequency levels remain almost unchanged (Fig.9). We find here the same trends as for the bogie area (4.1), which may be due to the decisive contribution of rolling noise in both cases.

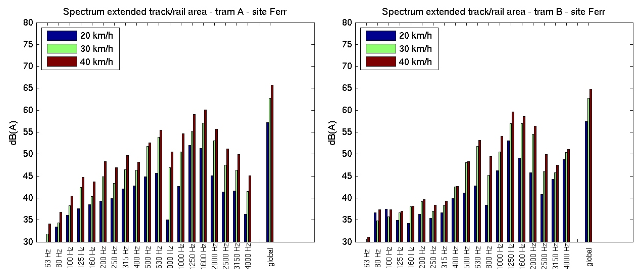


Figure 9: Effect of the speed on the pressure spectra for the extended track source - (standard track + grass) (*abscissa* : third-octaves 63 Hz to 4000 Hz) (*left* : tram A - *right* : tram B)

**Type of track and platform** The site with vibration absorbing pads and a paved surface always produces a noise pressure level for the extended track source which is definitely higher than for the standard track with grass, at middle and high frequencies (400-4000 Hz). However the standard track is slightly noisier at low frequencies (80-200 Hz) for both types of tramsets (Fig.10).

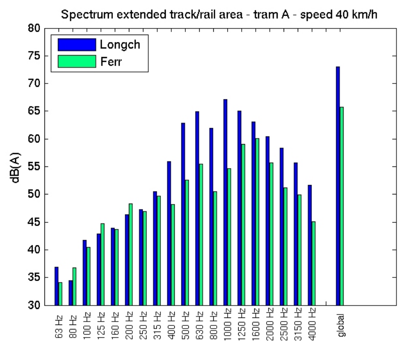


Figure 10: Effect of track type on the pressure spectra for the extended track source at 40 km/h (*abscissa* : third-octaves 63 Hz to 4000 Hz) (*blue* : DPHI+paving - *green* : standard track + grass)

## 4.3 HVAC unit

Only tram B is equipped with a HVAC unit, located on the roof. During pass-by measures, the cooling system was stopped ; only the basic ventilation was working. In this case, the array identified a weak noise source associated with it. The noise emission of the HVAC system in full working condition was investigated with the tram at stop. Its spectrum is composed of several peaks, including one powerful peak (290 Hz) and its first harmonics (Fig.11). Of course the characteristics of this noise source do not depend directly on the environment running condition. Vertical directivity measures showed the upward preponderant emission, indicating that is likely to affect noise levels at upper storeys. It could be shown that in conditions where rolling noise contribution is high (high speed, unfavourable track conditions [2]), HVAC noise is insignificant. However in case of low rolling noise (low speed, favourable track conditions), HVAC tones may emerge in the upwards radiated noise spectrum.

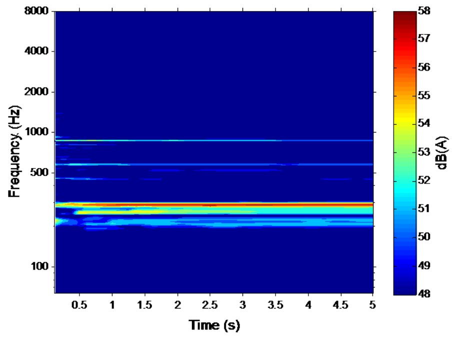


Figure 11: Spectrogram of the upper microphone - tram at stop - full working HVAC

# 5 Conclusion

This paper, part of a project studying noise and vibrations of trams, examines the noise spectrum of trams during pass-by, and the effects of parameters on the individual noise source spectra. Similar trends could be observed from bogie areas and from the extended track source insofar as rolling noise is involved in both source areas. Generally speaking, the tram B spectrum is richer in high frequency components than tram A, and speed tends to further reinforce them. On the other hand, speed does not change the relative frequency distribution of the tram A spectrum. As for the type of track, the site with vibration absorbing pads and a reflective surface gives higher noise levels, with a greater contribution of middle-range frequencies, than the standard site with grass. It was not possible to separate the contribution of the type of laying of rails from that of the type of surface. The frequency characteristics of the HVAC system have also been estimated, and issues on their contribution to total noise, mainly towards upper storeys, have been given.

Briefly summarized, the type of platform (track + surface) and speed have a great effect on the noise levels of sources, whereas the global effect of the type of tram is secondary. But the distribution of these effects in frequency is greatly influenced by the type of tram.

[2]Favourable or unfavourable track conditions are determined by roughness, track laying stiffness and surface material.

# 6 Acknowledgments

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