DIFFICULTIES AND SUCCESSES OF THE INTRODUCTION OF PSYCHOACOUSTIC INDICATORS IN THE INDUSTRIAL WORLD

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ABSTRACT

Laboratory of Mechanics and Acoustics (LMA) worked for several years with the French railway company (SNCF) and the telecommunication operator Orange. These collaborations had different consequences in terms of applications. LMA and SNCF worked together on annoyance, loudness, and on detection of emerging signals in noise. The aim was to find more suitable indicators than dB(A) alone to quantify annoyance. In telecommunication, the LMA and Orange Labs worked together to study how it would be possible to use loudness models to evaluate loudness at sending and receiving terminals instead of the Loudness Rating (LR) used until now. In this paper, we summarize the studies realized between LMA and SNCF and LMA and Orange Labs and we present their impact on both companies, in terms of specification and standardization.

1. INTRODUCTION

To quantify sounds, we can use physical metrics such as decibel, signal/noise ratio, spectral center of gravity, etc. The problem is that these metrics are not always representative of how sounds are perceived by humans. And, in general, industrials are interested by the impact (positive or negative) of sounds on their customers or more largely on the population. For many years, industry have sought to characterize sounds by taking perception into account. The aim is generally to improve the sound comfort of users.

Loudness is very important for comfort. Loudness can be roughly estimated using the sound pressure level with a weighting that takes into account the sensitivity of the ear with frequency [1]; dB(A) is widely used for this purpose. But loudness depends on features, such as the variation of loudness with spectral bandwidth, the effect of level on equal-loudness-level contours, which are not taken into account by using only a measure of sound pressure even with frequency weighting. Loudness models have been proposed and standards are available ([2], [3]). They result from the work of Zwicker's and Moore's teams ([4]–[10]).

In this paper we will present two cases where the use of loudness models greatly improves the characterization of acoustic comfort. These two applications are very different: one concerns annoyance of background noise inside train (collaboration between LMA and SNCF), the second the listening quality of phone terminals (collaboration between LMA and Orange Labs).

Another sound characteristic that is important for comfort is the presence of tonal components. In a study between LMA and SNCF, we have explored the relationship between annoyance and these tonal components in the case of noise inside railway coaches. We have also worked on a model of detection of multicomponent signal.

2. LOUDNESS AS A FACTOR OF COMFORT AND QUALITY

2.1 Loudness and annoyance of background noise inside railroad coaches

In a work presented at ICA 2007 [11] we measured annoyance and loudness of background noises recorded inside railway coaches. The sounds were recorded at different positions in TGV (high-speed train) coaches (one single floor TGV and one Duplex-TGV), in the lower floor and the upper floor of the Duplex-TGV, at different heights and for different speeds of the trains (from 150 up to 320 km/h). An absolute magnitude estimation procedure [12] was used to measure both annoyance and loudness. Annoyance (actually the logarithm of annoyance) was better correlated with loudness (actually the logarithm of loudness) than with dB(A), as shown in Figure 1 (R^2 = 0,97 and 0.86 respectively). The correlation was as high when loudness was calculated by Zwicker's model [6] (R^2 = 0.96). Looking at Figure 1, we can observe that a constant A-weighted sound pressure level might induce very different values of annoyance and a constant annoyance value might correspond to different A-weighted sound pressure levels. For example, a constant value of 60 dB(A) induces annoyance values from 16 to 31, which means a doubling of annoyance; a constant value of annoyance around 40 correspond to levels varying from 67 to 71 dB (A).

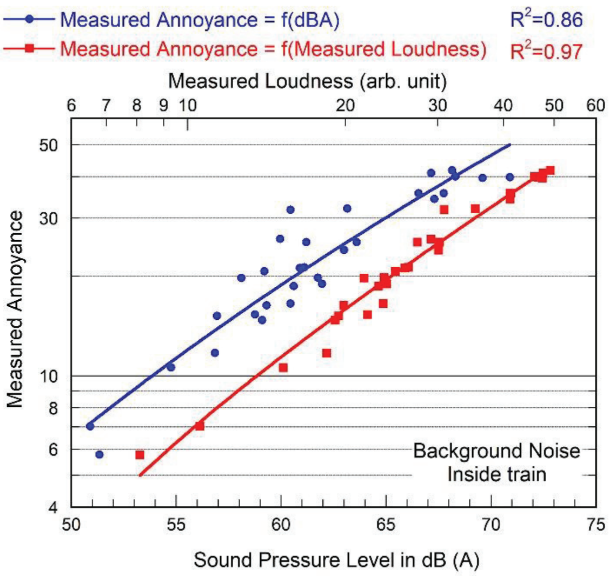

Figure 1. Annoyance as a function of dB(A) and measured loudness.

Following this study, which confirmed the literature ([13]–[16]), the SNCF wanted to introduce loudness as an annoyance criterion for background noise inside railway coaches. First, SNCF tried to integrate loudness in the standard used in the railway domain for the measurement of noise inside railway vehicles (ISO-EN-3381 [17]). But it was not accepted for various reasons: suppliers are used to use 1/3 octave bands and dB(A) in their models for interior prediction, all calculation procedures use the 1/3 octave band as input data. So according to the manufacturer, the change from 1/3 octave to loudness seems too complicated. However, SNCF included in its own specification loudness density and loudness for the acoustic comfort inside trains, including a target in loudness to not exceed. At the moment, the manufacturer rejected the target for the main reason that the ISO-EN 3381 [17] does not refer to any loudness indicator. From now, the decision of SNCF Engineering is requesting to provide the value of the loudness inside the new launch train, at different speed, in order to feed a database. From this database, the objective is to define loudness criteria that are realistic and therefore applicable for suppliers.

2.2 Loudness model in telecom

2.2.1 Introduction: the loudness rating (LR)

In telecommunications, loudness of speech is one of the main parameters for a good listening quality [18]. For 30 years, the Loudness Rating (LR) [19] has been used to evaluate loudness at sending and receiving terminals. This indicator was first developed for narrow-band (300-3400Hz) handset terminals, then extended to wideband (50-7000Hz). It works well for narrow-band, but it failed in predicting loudness for wideband and has not been extended to larger bandwidths. Orange Labs highlighted the problem several years ago and proposed a collaboration with the LMA to study how it would be possible to use loudness instead of LR.

2.2.2 Loudness of speech signal: perceptual measurements and loudness model

Loudness of different speech signals was evaluated using a 100-point scale [20]. The loudness function measured for each signal allowed us to convert the loudness expressed on the 100-point scale to loudness level expressed in phons. The signals were speech in different contexts and languages, music or a mixture of speech and music. They were processed to simulate realistic telephone system paths. First, they were limited in bandwidths: Full Band (FB, 50Hz-20kHz), Super-Wideband (SWB, 50Hz-14kHz), Wideband (WB) or Narrowband (NB). Then each filtered sample was coded/decoded using a specific codec from two different families (FB with G.719 and OPUS, SWB with G.722.1.C and G.729.1, WB with G.722 and AMR-WB, NB with G.711 and AMR). The signals directly obtained after filtering or "filtering + coding/decoding" led to the "Nominal" level (Gain at 0 dB). These signals were also amplified by 5 dB, which led to the "Nominal+5 dB" level, or attenuated by 10 dB, which led to the "Nominal-10 dB" level

The loudness of these signals evaluated by listeners was compared to the loudness calculated by models. The results, for a free field listening (corresponding to handsfree telephone systems) are shown in Figure 2 and Figure 3. Surprisingly, the models for non-stationary sounds (Figure 3) are not the best for predicting loudness of the tested stimuli which were mainly non-stationary. Among the models built for stationary sounds, it can be observed that DIN 45631 [21] predicts the best the evaluated loudness (Figure 2). But it fails in predicting the data for the lower levels. A correction was made to this model and published in [22]. The correction consisted in adjusting the value of the exponent of the loudness function used to calculate specific loudness from excitation. Explanations are given in [22].

Figure 4 shows the loudness calculated by the modified Zwicker's model compared to the experimental data, we can observe that model and experience agree very well.

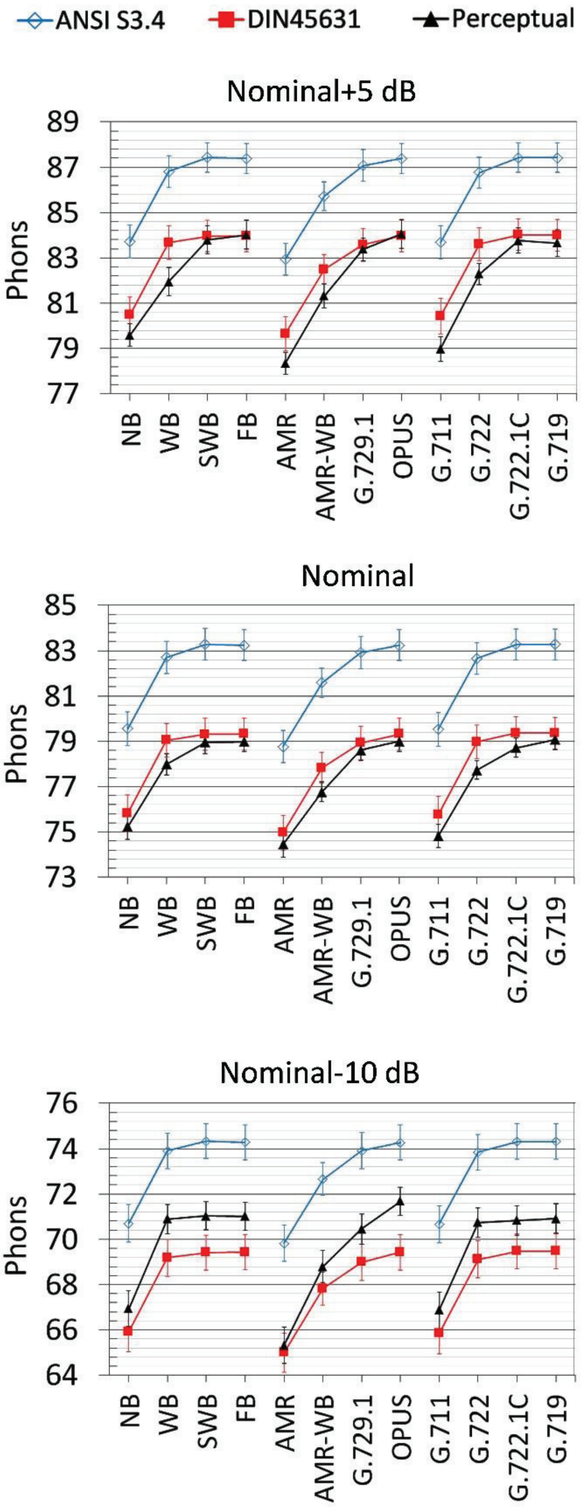

Figure 2. Loudness evaluated by listeners (Perceptual) compared to loudness calculated by models for stationary sounds (ANSI S3.4 [23] and DIN 45631 [21]), for different bandwidths and different codecs.

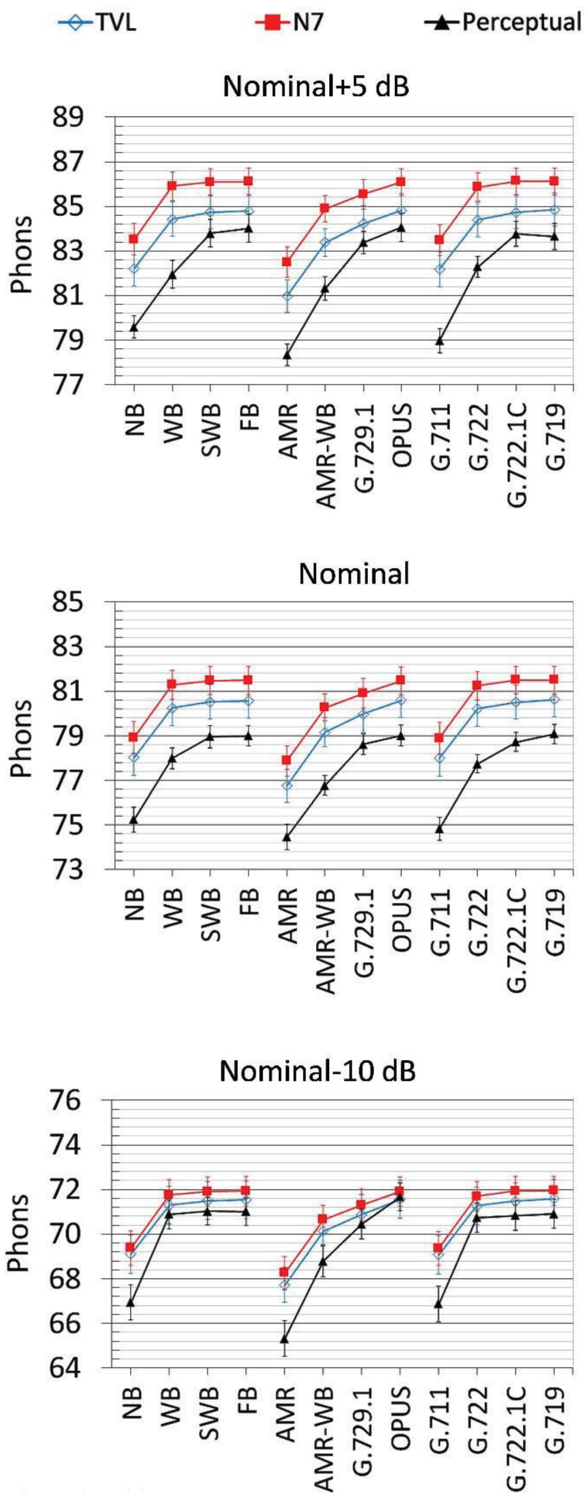

Figure 3. Loudness evaluated by listeners (Perceptual) compared to loudness calculated by models for non-stationary sounds, for different bandwidths and different codecs. TVL: averaged Long-Term Loudness [24], N7: loudness values reached and exceeded during 7 percent of the time [7].

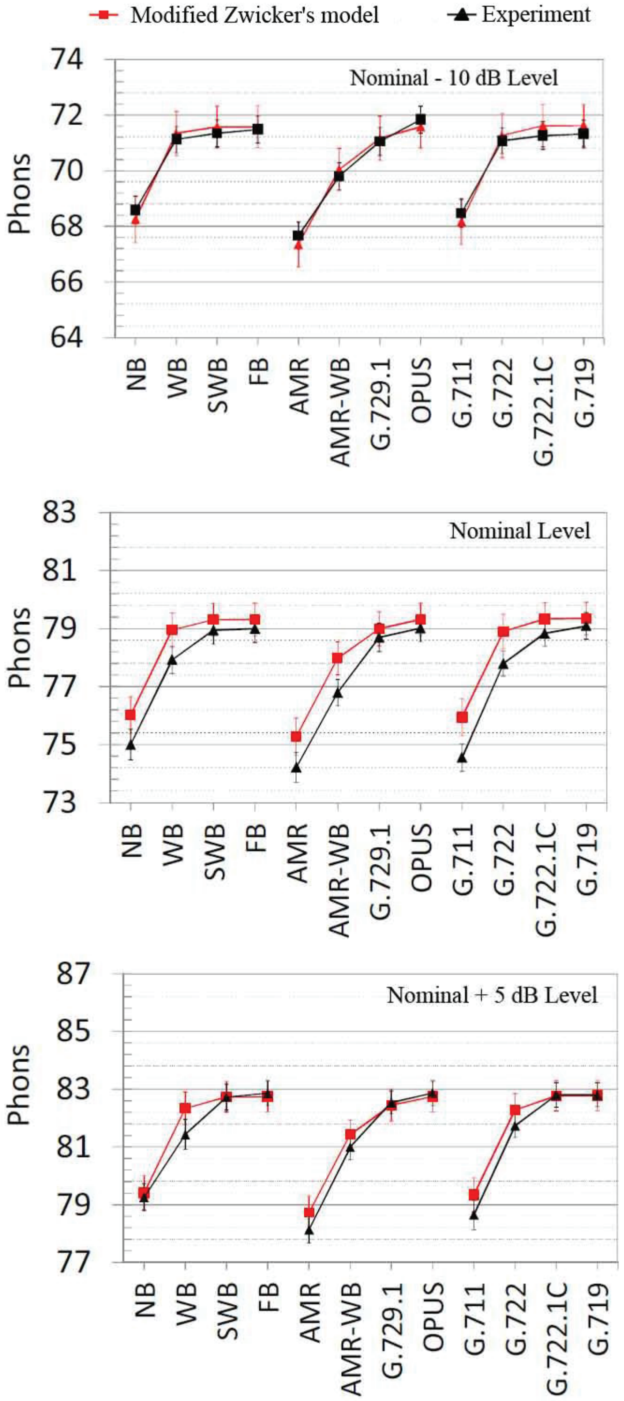

Figure 4. Loudness evaluated by listeners (Perceptual) compared to loudness calculated by the modified Zwicker's model.

From this work, Orange Labs proposed to start the standardization of a new model for loudness at ITU-T (International Telecommunication Union), where Study Group 12 (SG12) eventually adopted a new standard (P.700) based on the Zwicker's model described in ISO-532-1:2017 [2], the modified version was not retained. This standard is valid for all bandwidths and all conditions (handset, handsfree, teleconference). It had been tested on signals different from the ones used to build the model. Now Orange Lab uses ITU-T P. 700 [25] and ask their suppliers to characterize their products using loudness.

3. TONAL COMPONENTS INSIDE RAILWAY COACHES

The noises inside trains have tonal components generated by various acoustic sources. For example, the parametric excitation, which is due to the passing-by of the sleepers under the coach, produces a tonal component at 139 Hz for a speed of 300 km/h (Figure 5). These tonal components can create annoyance for passengers.

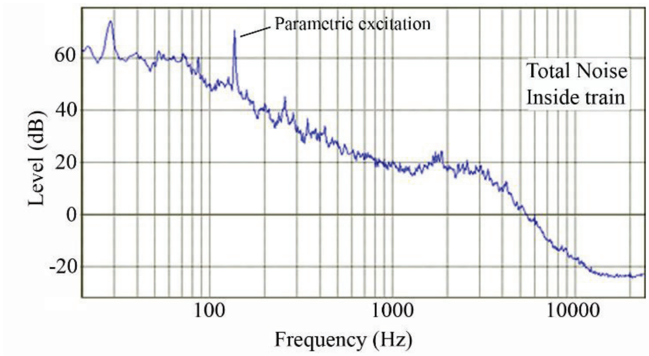

Figure 5: Spectrum of the noise measured in the lower floor of a railroad coach of a duplex TGV traveling at 300 km/h

3.1.1 Annoyance and tonal components

We measured annoyance of a background noise inside a train with a tonal component at 139, 155 or 167 Hz corresponding to the parametric excitation of TGV at speeds of 300, 320 and 360 km/h. The partial loudness of these tonal components was also measured. Annoyance was evaluated on a 7-point scale with verbal anchors (not annoying at all, moderately annoying and extremely annoying). Partial loudness was evaluated using an absolute magnitude estimation procedure [12]. Figure 6 shows that annoyance is well correlated with partial loudness, showing the importance of the tonal component on annoyance. In this case, the sound pressure level of the whole signal (background noise + parametric excitation) remained almost constant, because the levels of the parametric excitation were much lower (from 65 to 79 dB, all above the detection threshold of the tonality in the background noise) than the level of the background noise (82 dB SPL). Thus, a purely physical metric, applied to the whole signal, as dB(A), is not a good predictor of annoyance of tonal components in noise. The best indicator would be partial loudness. We have tested a model of partial loudness [8]. Figure 7 shows the relationship between annoyance and partial loudness calculated by the model. The model worked very well for loud partial loudness, but it fails in predicting partial loudness and annoyance for low partial loudness.
Following this study, SNCF integrated tonality in their specifications to suppliers. But as no standard exists for partial loudness, they follow the recommendations of the DIN 45681 standard [26].

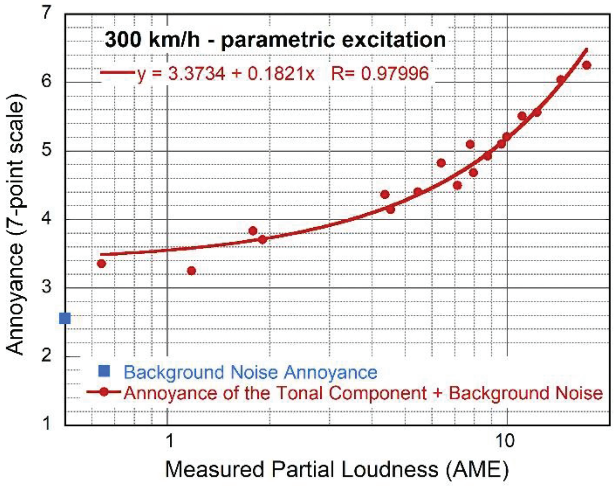

Figure 6: Annoyance as a function of measured partial loudness of the parametric excitation

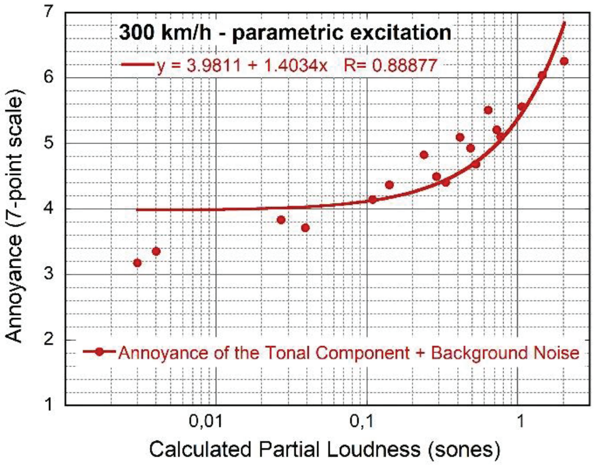

Figure 7. Annoyance as a function of partial loudness of the parametric excitation calculated with Moore et al. model [8].

3.1.2 Detection threshold of tonal components

One of the problems when looking at a spectrum like the one presented in Figure 5, is that we cannot know whether the tonal components are audible or not. When there is only one tonal component, the ratio between the level of the component and the level of the background noise at the output of the auditory filter surrounding the frequency of the component permit to predict the masked threshold ([27], [28]). Figure 8 shows the parameter K, defined as the difference between the signal threshold and the noise level at the output of the auditory filter (Roex filter), as a function of the frequency of a pure tone masked by different noises. It shows that the efficiency of detection varies with frequency and that the detection is better at mid frequency. More interestingly, the figure shows that K does not depend on the type of masker, thus, knowing K, it is possible to predict the auditory threshold of a pure tone in a broadband noise. However, when the masker contains itself tonal components, this rule does not work anymore. We have proposed a model of detection based on excitation pattern to predict threshold of pure tones masked by noises with tonal components [29].

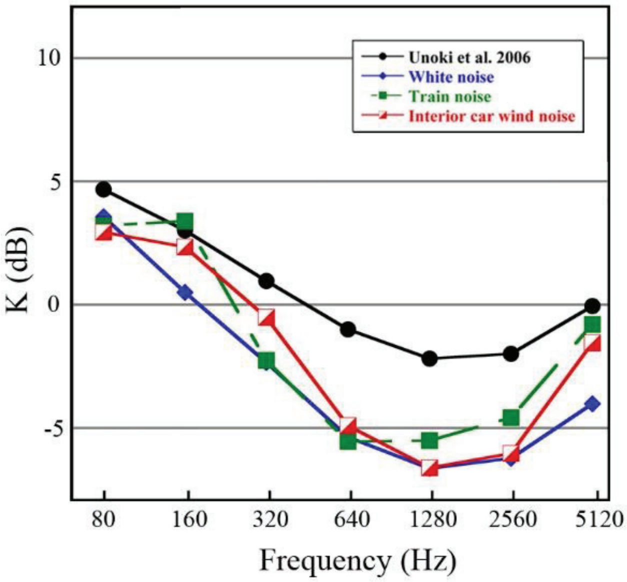

Figure 8: Parameter *K,* which represents the signal to masker ratio required at the output of the Roex auditory filter to reach masked threshold, as a function of the frequency of the masked pure tone, for different maskers. The maskers are: white noise (blue, diamonds), the background noise inside a train coach (green, full squares) and the aeroacoustic noise inside a car (red, semi-full squares). The black line and circles represent data adapted from Unoki et al., 2006 [27].

When several tonal components are present, the signal is better detected than its more detectable member [30]. We elaborated a model of detection of multicomponent signal in the case where components have different levels [31], and a patent was published [32]. This work was done in a collaboration between LMA, SNCF and the car manufacturer Renault.
As no standard exists nowadays for multicomponent signals, this case is not part of the specifications.

4. DISCUSSION

As loudness is one of the major attribute of comfort and annoyance, industry have been interested from many years in integrating loudness models in the acoustical specificities of their products. It has been known for several years that loudness models for stationary sounds fit well perceptual data ([33], [34]). The studies presented in this paper, a collaboration between a research laboratory (LMA) and two compagnies in different domains, railway (SNCF) and telecom (Orange Labs) have confirmed that.
The work with SNCF showed that loudness is a better indicator of annoyance than dB(A). The slope of the function relating the logarithm of annoyance and the logarithm of loudness was found to be larger than 1. This

means that annoyance varies more rapidly than loudness as was also found before by Berglund et al. [35].
Our work with Orange Labs showed that the models for stationary sounds predicted better the loudness of the tested sounds, mainly speech, than the models for non-stationary sounds, confirming that speech loudness would be largely determined by the long-term spectrum as found by Rennies et al. [36]. However, the results obtained with the DIN 45631 standard [21] diverge from measured data at low levels: the standard underestimates the loudness. In a previous study [33], the reverse was found, that is that the model of Zwicker [6] overestimated the measure at low levels for different environmental sounds. The discrepancy may be due to differences in the methods used to measure loudness (adjustment vs absolute magnitude estimation), or due to the different types of signals used (stationary environmental sounds vs speech), but there is no data to draw firm conclusions. Orange Labs oriented its work toward an adaptation of the model described in DIN 45631 [21] in order to propose a new standard for telecom [25]. An inspection of Figure 3 shows that models for non-stationary sounds follow well the variation of the measured loudness. TVL gives loudness less than 3 phons above the measure and tends to overestimate loudness mostly for high levels. This result is in agreement with [33], [34]. TVL is closer from the measure than ANSI S3.4 which suggests that the model of loudness applicable to time-varying sound proposed by Glasberg and Moore [24] is more adapted to speech than model for stationary sounds. DIN 45631 [21] and its most recent version ISO 532-1:2017 [2] was chosen by the telecom community because it is simpler and gives very good results. But, for research purpose and in order to broaden the domain of application, it would be interesting to investigate deeper the TVL model in order to adapt it to speech in telecom and other applications.

Our collaboration with SNCF led us to study the issues of detection of tones in a background noise. This work allowed us to confirm that the detection threshold of a pure tone in a noise can be predicted by the level of the noise in an auditory filter surrounding the frequency of the tone ([27]–[29]). When the noise contains tonal components, this simple rule does not hold, and we have proposed a model, based on the comparison of excitation patterns which predicted well the masked threshold of our signals (pure tones in coach train noises or inside car noises) [29]. We also proposed a model of detection in the case where the noise has no tonal component and the signal is made of several pure tones of different frequencies and different levels [31].

5. CONCLUSION AND PERSPECTIVES

The aim of this paper was to show the impacts of the researches done in collaboration between an university research laboratory (LMA) and two industries from different fields (SNCF and Orange Labs).
In the railway domain, following our collaboration concerning the annoyance of tonal components, specifications to the suppliers have included tonality based on DIN 45681 standard [26]. With regard to loudness, it was not possible to include it in ISO EN 3381 [17], the standard used in railway. Nowadays, SNCF works on a database in order to define realistic targets for their suppliers. SNCF is also working on a multicriteria indicator of comfort, based on dB(A) or loudness, and on tonality (DIN 45681 [26]). Another objective is to define acceptability thresholds depending on activity.
Collaboration between LMA and Orange labs explicitly targeted the adoption of new standards for the telecommunications and therefore results were submitted to the relevant standardization organization (ITU-T SG12), where the concept of a universal loudness metric has convinced all main players (in particular vendors of artificial heads, ears and mouths like HEAD Acoustics and Bruel & Kjaer). The finalization and validation of the model in ITU-T P.700 [25] has only been possible thanks to their contribution.
The telecommunication field adopted very quickly the use of loudness models whereas it is not the case in the railway domain. The reason may be that, in telecom, all stakeholders were applicants. In addition, they were already using Loudness Rating, which is a form of loudness model dedicated to narrowband signals. This has certainly made it easier to adopt a more complete loudness model. Whereas in the railway sector, suppliers are reluctant to use loudness models because they are used to analysis in dB(A) and 1/3 octave. The evolution of noise standards might make train suppliers changing in the future. But nowadays, they are not demanding of changes and are very representative in standard committees, which makes evolution difficult.

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