Acoustic comfort inside trains: research to develop indicators of background noise and temporal and spectral emergences

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Summary

The acoustic comfort inside trains is a major issue for SNCF who is working in collaboration with research institutes to specify the comfort according to the passenger feelings. The objective is to define criteria of specification highly correlated to the passenger point of view.

For many years, the acoustic comfort has been specified to the train manufacturers by using classical indicators like the sound pressure level. To avoid pure tones emerging from the background noise, some criteria comparing the energy in a third octave band to the energy in the neighbours have been also used. These criteria should be later discussed because they are not quite well correlated with passengers’ perception.

Further researches have then been carried out, starting by studies on background noise. First results have been validated 3 years ago for the “background noise” [Poi2008]. Laboratory tests have shown that the loudness (ISO532B) is much more correlated to the people comfort than the A weighted sound pressure level. Comparison of passenger perception with physical data collected on the same time on board commercial train has furthermore confirmed that loudness is relevant to specify the acoustic comfort within coaches. This work also showed that temporal effects and tonal components are a source of discomfort perceived by passengers and that dynamic and acoustic components are correlated in passenger’s perception. Then, research study has been extended to deal with short stimuli emerging from the background and for a better understanding of dynamic-acoustic correlation.

This paper presents the loudness indicator used to specify the background noise. The studies carried out to deal with temporal effects and tonal components are also described. Results of the laboratory tests are discussed and perceptual criteria are proposed.

1. Introduction

For several years now, SNCF has engaged a research program on comfort in order to better understand passengers’ expectations about comfort and to improve specifications for new trains and renovations. This work is mainly based on inquiries and physical measurements carried out in the same time on board different commercial TGV. Concerning the acoustic components of comfort, this work has shown that passengers are sensitive to acoustic sources of the train in correlation with the perception of the train movements and that passengers are sensible to acoustic emergences during the travel. These emergences can be due to noise from other passengers, from unsteady train sources or equipment sources (like door slams). In addition to evaluation of global comfort of a journey, twenty co-operative passengers were question about the type of discomfort they perceived during the journey and the time they perceived these discomfort events. Physical measurements of acoustic, dynamic and thermal quantities have been carried out simultaneously. Correlations were made afterward between passengers’ speech and several physical indicators. The Figure 1 shows that loudness explains more sources of discomfort pointed by passengers than L_{Aeq}.

<table>
<thead>
<tr>
<th>Exemple of passenger speech to describe discomfort events</th>
<th>Emergence in sones</th>
<th>Emergence in L_{Aeq} (dB(A))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muffled sound, rail, wheel (T+25)</td>
<td>+8.2</td>
<td>+4.2</td>
</tr>
<tr>
<td>Sound of door slam (T+32)</td>
<td>+7.2</td>
<td>+8.2</td>
</tr>
<tr>
<td>Sudden crossing (T+55)</td>
<td>+8.3 No emergence</td>
<td>No emergence</td>
</tr>
<tr>
<td>Higher sound in tunnel (T+76)</td>
<td>-3</td>
<td>No emergence</td>
</tr>
<tr>
<td>Very unpleasant sound (T+76)</td>
<td>+2</td>
<td>No emergence</td>
</tr>
</tbody>
</table>

Figure 1: Correlations between passenger’s identification of discomfort events and acoustic indicators
The first step of correlation between passenger’s perception and acoustic indicators from investigations on board commercial trains leads to investigate furthermore three areas of researches which are presented in this paper. This work involved experiments on board experimental trains as well as in laboratories, both with people evaluations.

The main sources and transfer paths responsible of the “background noise” inside a TGV coach is introduced in section 2. The “background noise” corresponds to the noise inside a coach running at constant speed, without tunnels, crossings and bridges.

Development of an interface which allow to measure instantaneous discomfort of passenger is presented in section 3. Temporal effects which mainly correspond to some changes of the spectrum of the background noise during a short period have been investigated using correlation between instantaneous discomfort and physical indicators. This study also addressed the correlation between acoustic and dynamic components.

Section 4 is dedicated to the tonal components like the parametric excitation (pure tone corresponding to the sleeper passing frequency). This study focuses onto the detection of a single pure tone, like generated for example by the parametric excitation, in the background noise of a TGV coach. Recordings in normal operating conditions of overall coach sound environment have been used as stimuli in listening tests carried out in the laboratory. The influence of the reproduction mode, headphones or loudspeakers in anechoic chamber, has been also investigated.

Results are then summarised in the conclusion and perspective to improve acoustics in train specification are proposed.

2. Background noise

Noise within train is due to the sources all around the coach and the transfer from the sources to the room. The main sources are the rolling noise, the aerodynamic noise around the bogie and the inter car gap, the boundary layer noise on the coach panels and the equipment sources (HVAC…). The noise or the vibrations generated by the sources are transferred to the coach through the air or the connections between the train structures and the bogie. Then, acoustic transparency of the coach plays a major role in the transfer as the connections between the bogie and the coach. Using the transfer path analysis approach, the contribution of each source to the inside noise can be estimated.

As presented in [Poi2011] in the case of TGV Duplex, the background noise is a mixed between the rolling noise, the aerodynamic noise around the bogie and the boundary layer noise. In the lower and upper salons, the aerodynamic noise around the bogie is the predominant source.

The Innovative and Research Department from SNCF has carried out since 1999 a research program to investigate the acoustic comfort of passengers. The background noise was the first target. The main objective was to find an indicator highly correlated with passenger’s feelings to be used as criteria for specification of new rolling stocks. The work is continuing to focus the temporal and spectral emergences (see sections 3 and 4).

Method

Thirty sound samples of background noise were recorded in single floor TGV and Duplex TGV running between 150km/h and 300km/h. A listening test has been organised in the soundproof room of the Laboratoire de Mécanique et d’Acoustique (LMA, Marseille). The level at the ears of the listener (free field equivalent) was the same than the level of the sound during the recording. The total signal duration was 4s and had rise-fall times of 100ms shaped linearly. Twenty-four listeners, 20 to 50 years old, participated in the experiments. They listen to the sound samples in stereo with a Sennheiser HD 650 headphone. The magnitude estimation without reference protocol was used to measure loudness and annoyance of the sound samples and directly establish a ratio of the two parameters. The average is directly computed with the measurement results without normalisation (see the red points in Figure 2).

Results

The logarithm of the measured annoyance according to the sound pressure level in dB(A) is also presented in Figure 2 (blue points).
The solid lines show the linear regression of the data with the corresponding relationship on the upper-left part of the figure 1. Annoyance is highly correlated with loudness and the correlation is lower when considering sound pressure level in dB (A).

The Zwicker’s model of loudness [Zwi1984] has been tested as an indicator of annoyance. The same kind of listening test has been carried out to measure the correlation between the annoyance and the calculated loudness. The correlation is high (0.98) and the following relation ship can be achieved with a linear regression:

\[
\text{Log(Annoyance)} = -2.15 + 0.044\text{Lphons}
\] (1)

where Annoyance is the measured annoyance and Lphons is the loudness level in phons calculated using Zwicker’s model.

3. Temporal effect

The previous section shows that loudness is correlated with the annoyance and can be used as a criterion to specify the background noise. Train’s passengers can also be greatly affected by short stimuli emerging from the background. This section presents briefly how temporal noise emergences may be evaluated and also how noise and vibration stimuli are correlated in the instantaneous subjective perception of discomfort.

Method

Subjective and sound and vibration data have been acquired during a test campaign [Gau2010] investigating the effects of increasing the speed of high speed train on various aspect of railway transport (eg: specification of braking to maintain the headway, external and inside noise, ballast projection risk, passenger dynamic comfort as a function of track quality…). Results, shortly presented bellow, are focused on determining and specifying the objective causes (noise and vibration) of the observed instantaneous discomfort. This section investigates two hypotheses: 1- instantaneous discomfort can be predicted by emergences of noise and vibration from the background; 2- noise and vibration are correlated in the passenger perception of discomfort.

Instantaneous discomfort of 15 passengers (defined later as subjects), located on the top level of a double deck high speed train, was acquired using specifically designed ‘force handles’ (see Figure 3).
Subjects were asked to press the handle proportionally to the discomfort experienced. The boundary given as references were: - no force applied means no discomfort felt; - the maximum force they could applied means maximum discomfort. The data collected corresponds to the force measured by the load sensor inside the handle. The data were normalized and the offset cancelled to consider the different physical forces observed between subjects and the variation of the static force observed between handles. Sound pressure was acquired with a microphone located at the ear height of a seated passenger. Vibrations were measured on the floor below the seat and between the seat and the passenger (see Figure 4).

Results
Figure 5 shows four sets of data (from the top to the bottom) obtained during a journey at 350 km/h with subjects standing parallel to the train’s direction:
- Level of instantaneous vibration calculated from the measured floor acceleration using the following formula:

\[ N_{vi} = \sqrt{\frac{1}{T} \int awx(t)^2 dt}^2 + \frac{1}{T} \intawy(t)^2 dt}^2 + \frac{1}{T} \int awz(t)^2 dt}^2 \]

with awx the weighted acceleration measured on the floor in the x direction and T the integration period (3 s in this case). This estimator showed better correlation than other standardized estimators such as RMQ or VDV (ISO 2631, 1997) with the subjective data collected during various SNCF test campaigns (data not published yet);
- Median subjective instantaneous discomfort calculated for the 12 subjects;
- The Loudness calculated over a period of 0.3s (later defined as instantaneous loudness);
- The $L_{Aeq,1s}$.
Rectangles drawn on the figure show possible correlations between the 3 types of data presented (dynamic, subjective and acoustic). There are three noticeable results:

- Concerning temporal emergences, the instantaneous loudness and the LAeq,1s show similar trends;
- Emergences in noise are very often correlated with emergences in vibration;
- Dynamic and acoustic estimators seem to show good correlation with the subjective data. More data analyses with the seated subjects (less sensitive to vibration than standing passengers) should be conducted to confirm the trend.

The correlation between the instantaneous acoustic and dynamic estimators has some effects on the subjective perception of discomfort. Passengers expect to hear the corresponding sound when they feel a type of vibration. A study conducted in this campaign tends to show that when train’s passengers wear headphones producing a white noise or another train’s sound (recorded during another journey), the instantaneous discomfort seems to increase (see Figure 6). The case of passengers wearing headphones that attenuate the train noise (Hellberg headphones used for reducing noise for workers) didn’t allow concluding about a significant effect of passengers’ discomfort.

Figure 6: Median instantaneous discomfort acquired during three separated periods of a journey where subjects were exposed to three types of sound stimuli (white noise, uncorrelated train’s noise, attenuated noise) divided by the median instantaneous discomfort measured with normal acoustic (subjects wore no headphone) conditions during the same three periods of a similar journey (same tracks, same train’s speed).
To conclude on the temporal emergences, although more analyses should be performed, it seems that the instantaneous loudness (or the $L_{eq,1s}$) can be used to specify the acoustic temporal emergences. We also need to consider that acoustics emergences should be considered with the dynamic emergences in passengers’ perception. It means that a noise reduction of an emergence should be associated with a reduction of the corresponding vibration, whereas a reduction in discomfort might not be achieved.

4. Tonal components

Methods

As mentioned before in the paper, emergences generated by various acoustic sources can create annoyance for passengers. These signals may be totally masked by the background noise (the masker). So, masking plays a very important role in railroad acoustic comfort. In the study, we have investigated the influence of sound reproduction comparing results for a tone masked by broadband noise. Detection thresholds were measured for seven frequencies (80 Hz, 160 Hz, 320 Hz, 640 Hz, 1280 Hz, 2560 Hz, 5120 Hz) and two different maskers without harmonics (white noise and train noise). The signal had a total duration of 500 ms, including a 20-ms raised-cosine ramps. The masker, when present, was gated synchronously with the target.

The masker and the signal were generated in a RPvds (TDT) circuit, including 20ms cosine-squared rise/fall ramps. Listening intervals were 500ms in duration. The stimuli were played out by a real-time processor (TDT RP2), passed through programmable attenuators (TDT PA5) and headphone driver (TDT HB7) before being presented to the listener via a Sennheiser HD650 headset. The masker was presented at a level of 55 dB SL. Listeners in an anechoic chamber had to detect tones in broadband noise, presented via headphones, in diotic conditions or via a loudspeaker in front of them.

Thresholds were measured using an adaptive, three-interval, forced choice (3 IFC) procedure incorporating a three down-one up stepping rule. Feedback was provided after each observer response. Level was initially adjusted in steps of 5dB, and reduced to 2dB after the second track reversal. The track continued for a total of twelve reversals, and the associated threshold estimate was computed as the average signal level at the last eight track reversals. For each observer, the signal conditions were assigned a random order, and thresholds were collected in blocks. Two threshold estimates were collected in each condition. All estimates were averaged to generate a final threshold estimate. If the standard deviation of that average was greater than 3dB, an additional estimate was obtained and included in the average.

Twelve subjects (4 females, 8 males) ranged in age from 22 to 51 years (mean=29 years) participated. They had thresholds at or below 15 dB HL at audiometric test frequencies from 125 to 8000 Hz.

Results

According to the power spectrum model of masking, the detection threshold for a tone masked by broadband noise is defined by a relation [Uno2006]:

$$ P_s = K + N_0 + 10 \log_{10} \left\{ \int_{f_{ms}}^{f_{max}} W(f)df + \int_{f_{min}}^{f_{max}} W(f)df \right\}. $$

(2)

$P_s$ is the signal level at threshold (dB SPL); $N_0$ is the noise level at the output of auditory filter of the auditory filter centred at the signal frequency; $W(f)$ is the weighting function corresponding to the filter, asymmetrically defined at the right and left sides of the signal frequency; $K$ is a constant which is related to the efficiency of the signal detection. The asymmetric rounded exponential (Roex) filter has been successfully used to represent the experimental data. In the Figure 7, the $K$ values corresponding to the different experimental conditions are plotted. The $K$ factor is the difference between the signal threshold and the noise level at the output of the auditory filter (Roex filter). A repeated-measures ANOVA failed to indicate a significant effect of masker type ($F(N=12, d=2)=2.4$; $p=0.01137$) and sound reproduction ($F(N=12,d=1)=0.81$; $p=0.3874$). The results obtained via headphones reproduction, with an eardrum calibration, are in good agreement with those obtained via a loudspeaker in an anechoic chamber. This conclusion gives credit to the headphones reproduction for masking experiments, particularly at low frequencies (around 100 Hz).
The findings of this experiment validate headphones reproduction, with ear-drum calibration, corroborate established results concerning the detection of pure tones in broadband noise, but extend them to specific configurations of train coach noises.

5. Conclusion
The acoustic comfort has been investigated, taking into account the passenger feelings to define some criteria of specification. For the background noise, Zwicker’s loudness seems to be relevant. Results have been validated by listening tests and thresholds have been defined. For temporal effects, new methods of passengers’ instantaneous discomfort collection have been developed and allowed correlation between subjective perception and physical indicators. First results confirmed relevance of loudness as acoustic indicator and confirmed as well correlation between acoustics and dynamics which should be addressed together in further researches. For tonal components, a detection threshold has been validated. Some experimental studies are still necessary to define the annoyance threshold based on the detection threshold. These new indicators and associated thresholds will be introduced in the specification of the future trains. In a first step, old criteria can be preserved in parallel to make easier the discussion with the rolling stock manufacturers.

The next step of the research program will focus onto the design of the soundscape within trains.

References


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