Parameters used for acoustic qualification/ quantification of automotive vehicles

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Abstract: The article presents, in a chronological way, the main parameters used for automotive vehicles concerning acoustic qualification/quantification. We start with the loudness concept, pass by the 'A' weighting philosophy and arrive to the sound level reduction including sound quality. We show a lot of parameters, each trying better to match the correlation between objective results and subjective evaluations. We mention several aspects of the human ear that make it difficult to describe sound sensations through a single parameter. We emphasise also the absence of exposure time in the parameters used to evaluate acoustic comfort. We show the large gap between the parameters used in the laboratory and those applied in legislation through standards. Some conclusions are presented and the future, related to acoustic parameters, discussed.

Keywords: acoustic qualification/quantification; noise evaluation; vehicle acoustic.

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1 Introduction

Acoustics, besides to be a classical science, can be considered a complete science, if we only look at the physical phenomena. We can be assured that the existing models describe the physical phenomena we see in nature very well. We would not be mistaken if we include in this situation other sciences such as optics, electromagnetism, thermal sciences, all in the classical sense. We are not associating the quantum aspects with this idea. Unfortunately when we investigate the interaction of these sciences with human being, this question changes very much.

The responses of the human with regard, for instance, to many sensations such as: sonorous, thermal, electromagnetic, visible radiation, colours, vibrations, infrasound, are very complicated (Azoulay, 1996; Broch, 1980; Morel et al., 1995; Onusic and Douglas, 1981; Onusic and Mandic, 1989; Onusic and Mizutani, 1993). The existing psychophysical models trying to qualify/quantify these sensations in an objective way are far enough to be complete and to be used in a trivial way.

The interaction man/machine/environment takes several forms with different boundary conditions. This also applies in the specific case of the automotive industry. We look at the field of sound sensations, describing and analysing the parameters used to quantify the subjective aspects of the man/vehicle interaction, with airborne sound propagation as the main target.

The new concepts of vehicle safety associated with mass reduction provoke the design/production of more flexible cars, increasing the vibration amplitude and needing more and more creative refined acoustic solutions. This also means that an evolution is required of the parameters used in the acoustic qualification/ quantification of the automotive vehicles.

2 Weber–Fechner law

Considering the increase of particle pressure in the medium – called sound or acoustic pressure – is a stimulus for the sense organs of living beings, it becomes important to know the relationship between the stimulus and the reaction produced in the nervous system of humans, called *sensation*. It is undoubtedly the fact that, when the stimulus varies, the sensation will vary accordingly.

Two neurologists, in independent work, proposed some conclusions regarding the above subject at the end of the 20th century, as listed below, and called the Weber–Fechner Law (Alexandry, 1978).

> "To increase the sensation, it is necessary the stimulus intensity grows in the same proportion."

> "The sensation grows according to the logarithm of the stimulus."

The first part of the Law says the stimulus E and the sensation S represent a biunivoc function:

$$E = \phi(S) \Leftrightarrow S = f(E)$$

The second part of the Law makes the quantification of the function of

$$S = \log KE$$

where K represents an individual sensibility constant.

Nowadays we bear in mind that K is not a constant. It depends on the individual subjective conditions, on the proper stimulus and other multiple variables, so complex as we want.

In this way, we can write

$$S = K(E, x_i) \log E$$

where x_i represents other multiple variables, some of them random.

Several studies effected, mainly by von Bekesy, show that the above expression is a reasonable representation of the auditory relation.

An important point in the above expression is the logarithmic dependence of the sound sensations, usual for the acoustic people but that provoke distinct reasoning when compared to the linear dependence.

3 Loudness concept

With the purpose of establishing quantitative relations according to Weber- Fechner Law, Fletcher and Munson presented a family of curves making the correlation between sound pressure (objective) and sound sensations (subjective), taking into consideration the audible frequency range and the extreme levels: threshold of audibility and threshold of feeling.

At that time, the basic reference tone was 1000 Hz, due to the following reasons:

- easy to define
- sometimes employed as a pitch standard
- makes easy the application of mathematical expressions
- audible sensibility was the same or bigger than the other frequencies
- considered to be in the middle (average) of audible frequencies.

Today we have some modifications concerning these affirmatives:

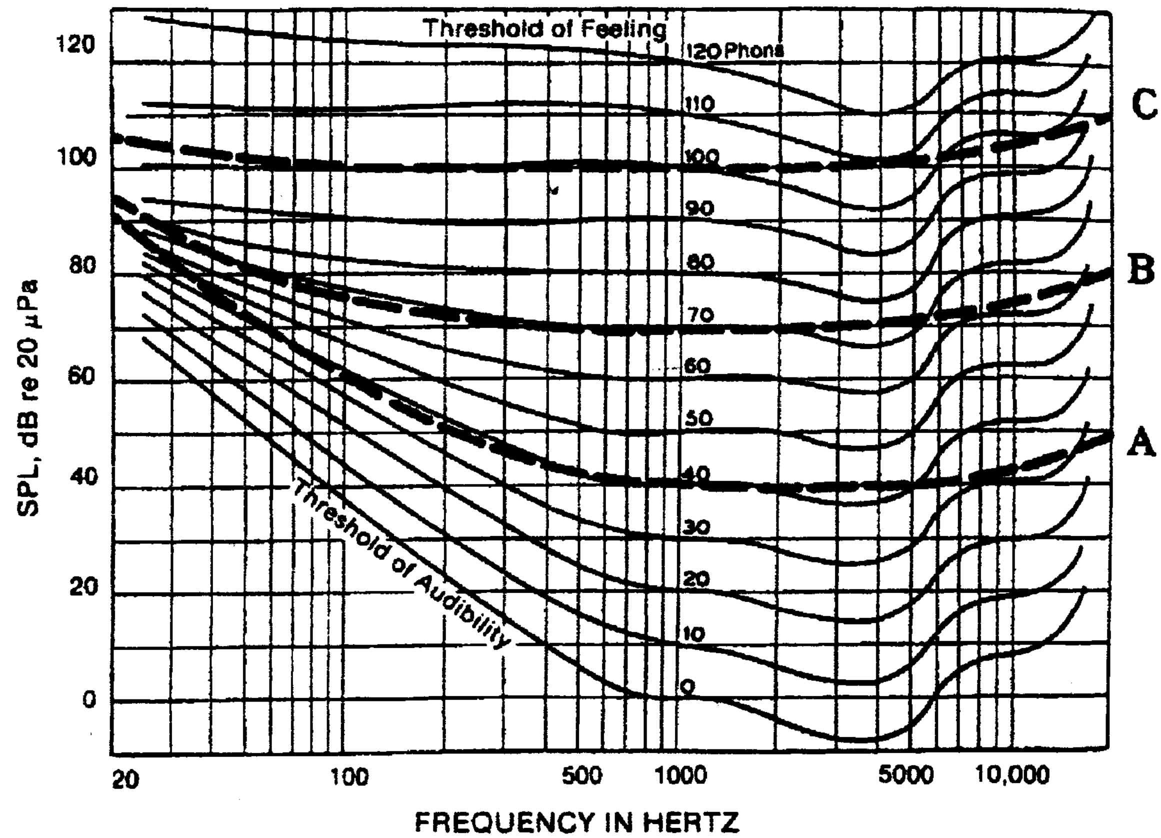
- the maximum sensibility oscillates between 3100 and 3200 Hz for pure tones
- the middle (average) of the audible frequencies is around 680 Hz.

In spite of this, the acoustic contribution was of great value, because they are responsible by today's accepted concept of Loudness Level.

> "Loudness Level is the sound pressure level necessary for a young and sound ear to hear any tone with the same 'magnitude' (subjective sensation) as one tone of 1000 Hz."
>
> "The Loudness Level unit is the phon, and is equivalent to the decibel at 1000 Hz."

These curves of the same Loudness Level are called isophonics (Berger et al., 1991). In the beginning they were established for pure tones, but studies carried out by Robinson and White determined isophonic curves for sound pressure levels in octave bands (Figure 1).

Figure 1 Isophonic curves



In 1955, Stevens presented an analogue concept, but tried to introduce a *linear variation* instead of a logarithmic one, i.e. Loudness.

> "The Loudness scale unit, called sone is the same as a pure tone of 1000 Hz and 40 dB sound pressure level, is such way that another sound producing two sones, will be heard with a Loudness two tones bigger."

It is important to emphasise that the basic assumptions considered for the above subjects were:

- sound pressure is the physical parameter that excites the ear
- the sound pressure unit is N/m^2
- the accepted concept is the sound pressure level, and the considered unit is the decibel, taking $P_0 = 2 \times 10^{-5}\,N/m^2$ (rms) as the reference pressure.

So, it was defined Sound Pressure Level:

$$SPL = 20 \log \frac{P}{P_0}\ dB$$

The relation between Loudness (S in sones) and Loudness Level (P in phons) for pure tones can be written:

$$\log S = 0.031(P - 40).$$

4 Loudness for complex sounds

Figure 1 represents the isophonic curves in octave bands. The calculation of Loudness or Loudness Level for complex sounds cannot be obtained by the above simple expression.

Stevens made a proposition, in 1957, concerning a method to determine the Loudness of a complex sound. After using the method, we are able to calculate the Loudness Level through the above simple expression. Besides, another researcher, Zwicker, during the same period, elaborated a graphic method to get the Loudness for a complex sound. ISO Standard R-532 describes the two procedures. In Stevens' method, which we judge to be simpler, the calculation is as follows:

$$S = S_m + \alpha\left(\sum S - S_m\right)$$

where:

$\sum S \rightarrow$ addition of sones values relative to all frequency bands

$S_m \rightarrow$ maximum sone value in any bandwidth

$\alpha \rightarrow 0.3$ for octave bands

$\alpha \rightarrow 0.15$ for third octave bands.

The appropriate values in sones corresponding to the sound pressure levels in dB for each bandwidth are given in tables or graphs.

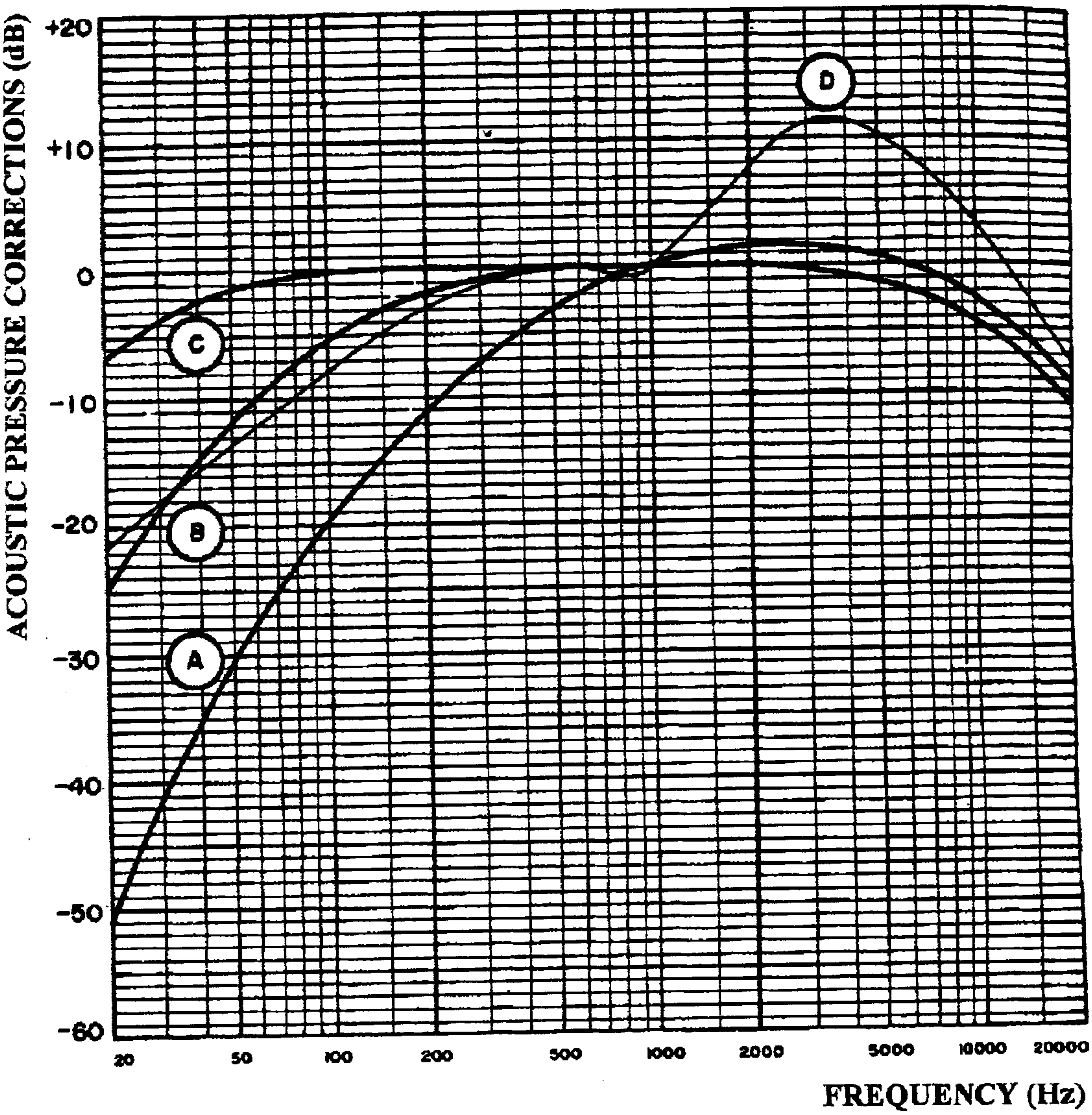
5 Brief historical approach

In the 1950s, there were several hybrid methods to measure noise. Besides the use of Loudness, there were some simplified methods but any kind of normalisation.

These simplifications are shown in Figure 2, and are still known as weighting curves for 40, 70 and 100 phons levels. In some countries the measurement in dB was used through a flat frequency response. In some situations, the use of the weighting curve D was established, created for noise measurements in airports and aircrafts. In Germany, the DIN-phon was used for measurements associated to the A, B and C weighting curves, depending on the dB-level considered.

The lack of uniformity affected the economic aspects of import and export and also brought several problems in the development of acoustic equipment. The international community asked for ISO (International Standardization Organization) to elucidate the situation. ISO had in mind to standardise a practical method, but in such a way that the results could be correct and adequate, taking into consideration the state of the art at that time. It could take some years to develop a good method and it needed to be approved by members of several countries. The market would not accept this deadline and ISO was compelled to adopt a rapid solution (Zwicker, 1987).

Figure 2 Weighting curves



ISO looked for the solution of the noise measurements in two stages. The first step could be a simple method, easy to introduced with the available techniques and that could be used everywhere without expense and investment. The sound pressure level weighted by the A curve was chosen, originating the dB(A). It would be a preliminary method that could provoke inadequate and misinterpreted results concerning noise control. However, it had the advantage of satisfying the international market because it was a uniform method.

The second step proposed by ISO, was not so simple as dB(A), but with values having better correlation between sound pressure and sound sensation. Two methods were put in the market through ISO 532, a few years after dB(A) proposition.

The first method dB(A), was rapidly incorporated into several regulations. The second step, Loudness calculations, received no attention, because the market was satisfied with dB(A), due to uniform use rather than results.

6 Automotive industry application

Application of the weighting curve 'A' in the automotive industry is traditional. It is present in the external noise standards and legislation as well as in internal noise evaluations. dB(A) is used to quantify the overall noise. Sometimes, to emphasise the low frequency portion of the spectrum, dB(B) is used, mainly in internal noise. Utilisation of other weighing curves created to improve performance of evaluation was always ignored. A typical example is the dB(CTC) – Car Test Computer as shown in Figure 3. Besides, some comparisons including distinct *parameters* are always accomplished (Figure 4).

Non-acoustic people *are* excluded from the noise reduction targets and keeps 'outside'. On the other side, the discussion results of the 'inside' acoustic experts are divulged to the public but are not correctly understood. Several times, the non-acoustic people imagines 40 dB(A) is 50% subjectively intense than 80 dB(A). Sometimes, a noise reduction from 80 to 72 dB(A) means a success of only 10%!

Figure 3 Weighting curves: 'A' and 'CTC'

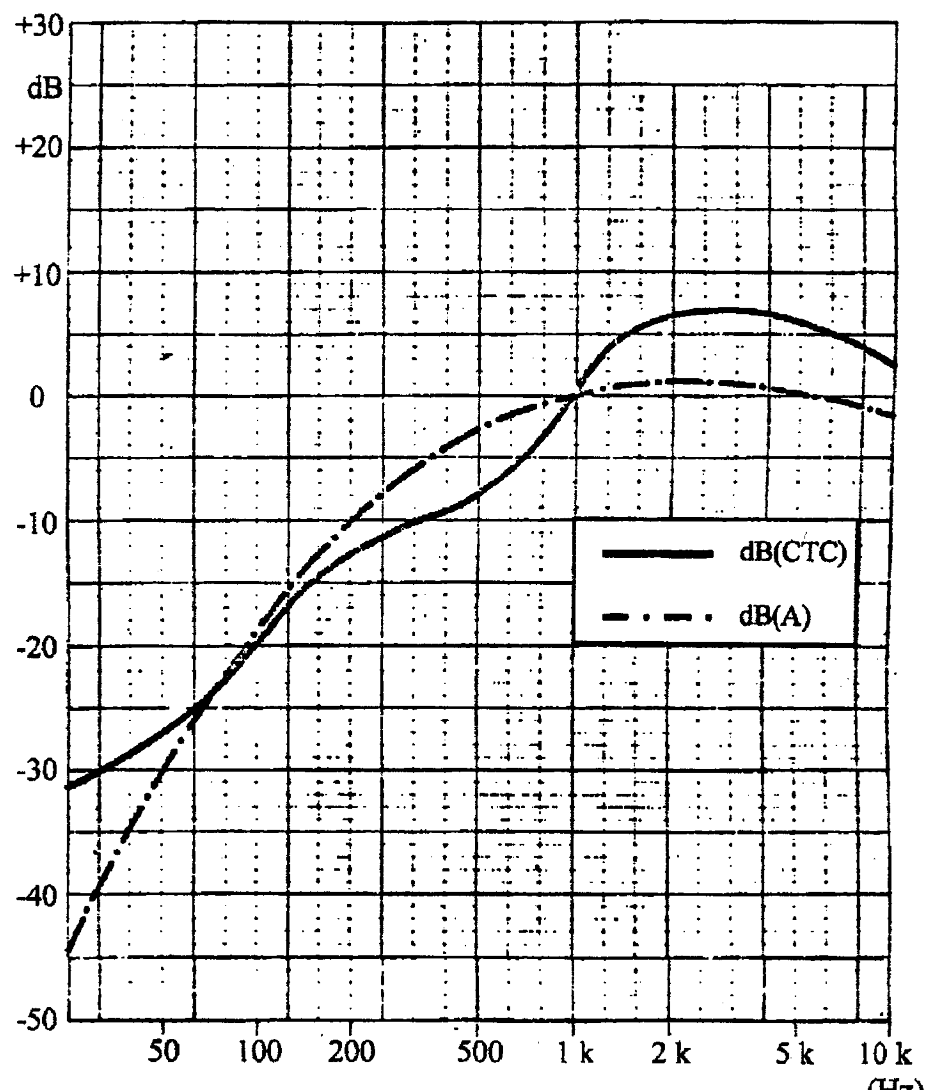
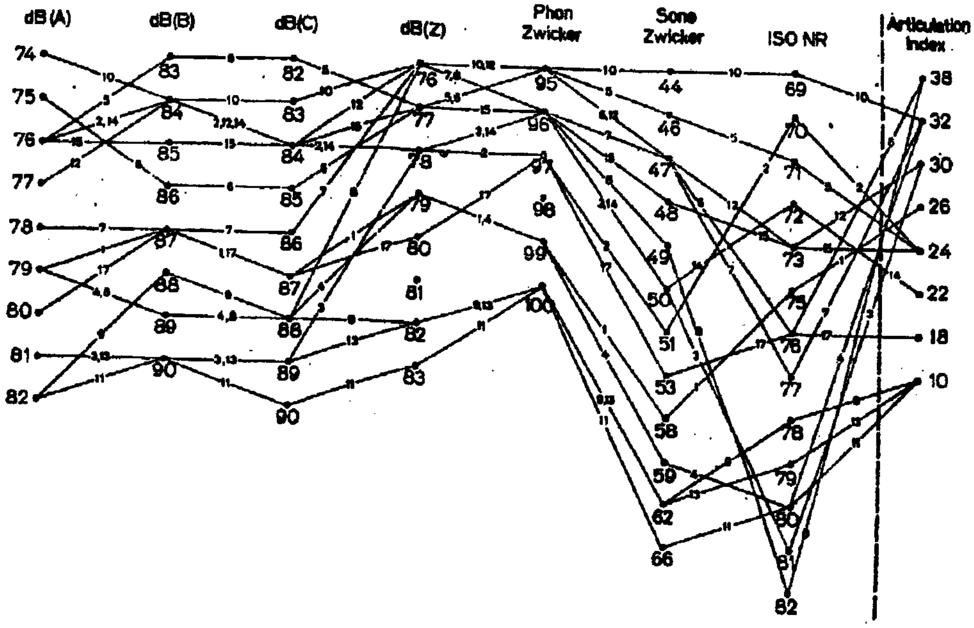


Figure 4 Results according to different weightings and parameters

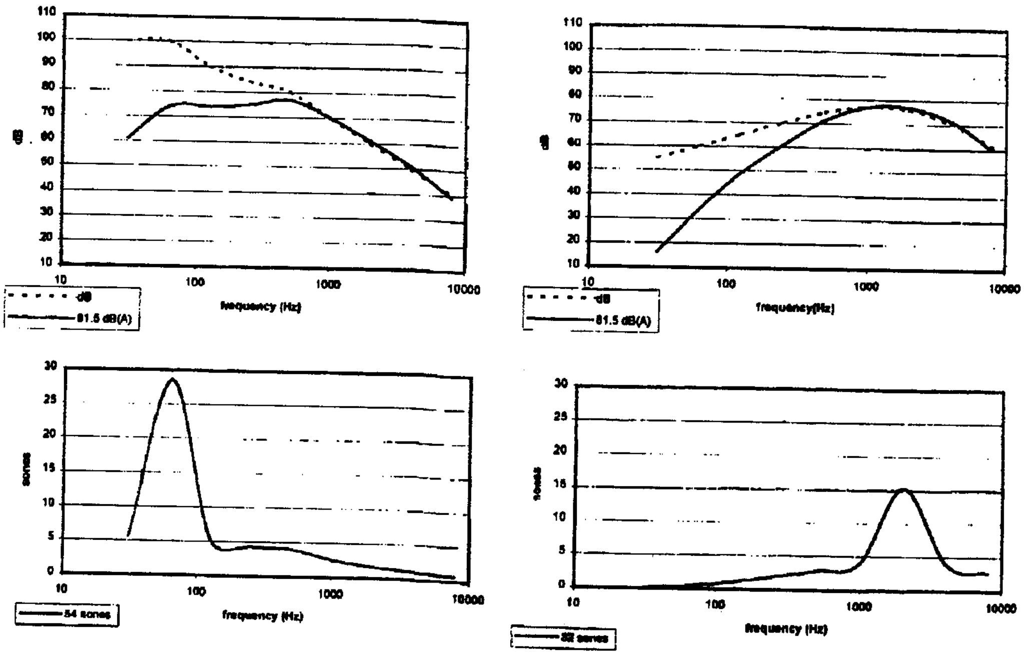


The above questions could be solved if the Loudness in sones was further explored in society. Although some attempts were carried out, it was lost in time.

We can say that concerning product development and research, the acoustic experts use and abuse the available parameters, but when they need to present the results, they divulge them in dB(A), as the information receivers are not sensible to other parameters. Besides, the international technical standards still ask for the overall noise in dB(A).

We can see some differences regarding these parameters through an interesting example, as shown in Figure 5.

Figure 5 Spectrum profile: dB(A) versus sones/phons



Stevens expression can be written (Onusic and Hage, 1994):

$$S = \frac{3}{10}\sum_{i \neq m} S_i + S_m$$

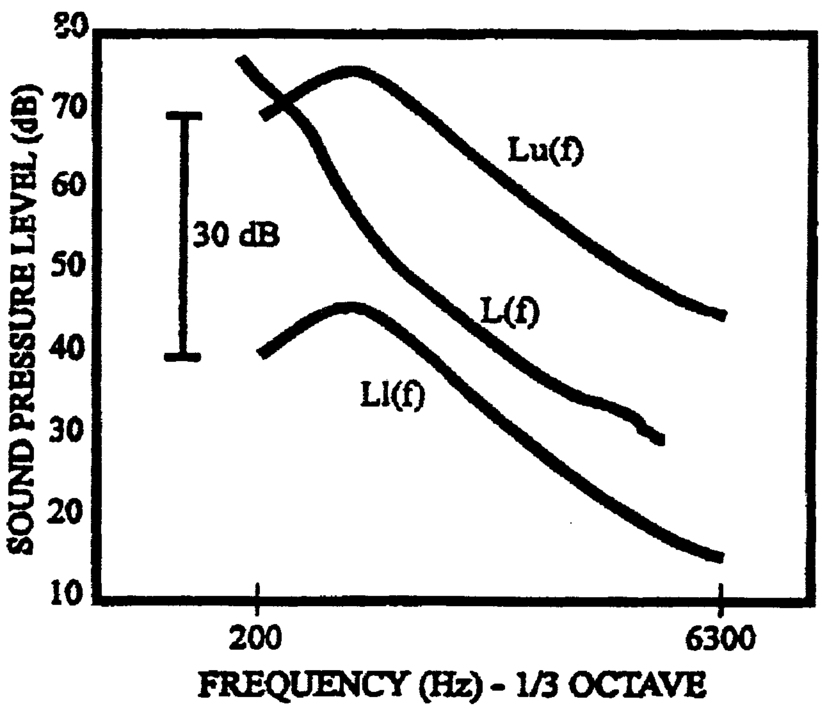
Two spectra are plotted in octave bands, including phons, sones and dB(A). The overall noise in dB(A) is the same, but when sones are considered, the difference is around 60%!

When we describe the overall noise in dB(A), in many situations, fluctuations due to modifications in the product in the high frequency portion of the spectrum, are not enough to change dB(A), since the spectrum composition is mainly of low frequencies coming from the transmission through the structure (structure-borne sound).

So, the high frequencies level may be synthesised by another parameter. Two of them, SIL (Speech Interference Level) and PSIL (Preferred Speech Interference Level), are not commonly applied. In the past, the parameter AI (Articulation Index) has been used, mainly in Europe. It was developed for the telecommunication industry in USA and adapted for vehicles, with the purpose of evaluating intelligibility inside passenger compartments.

It is calculated from the sound pressure levels in third octave bands, in the frequency range 200–6300 Hz, the speech region, as shown in Figure 6. The values for each band are weighted, and the maximum values are contained inside the range 1000–4000 Hz (Hage and Onusic, 1992).

Figure 6 Articulation index definition



In the investigation of the parameters' correlation, we found strong linear dependence between them. As they are representative of different portions of the spectrum (low and high frequencies), we suggested the introduction of the H-index, trying to take advantage of their correlation properties to evaluate internal noise, using the two parameters simultaneously. See Figures 7–9 (Onusic and Hage, 1992; Onusic et al., 1989).

Figure 7 Linear correlation: dB(A) versus velocity

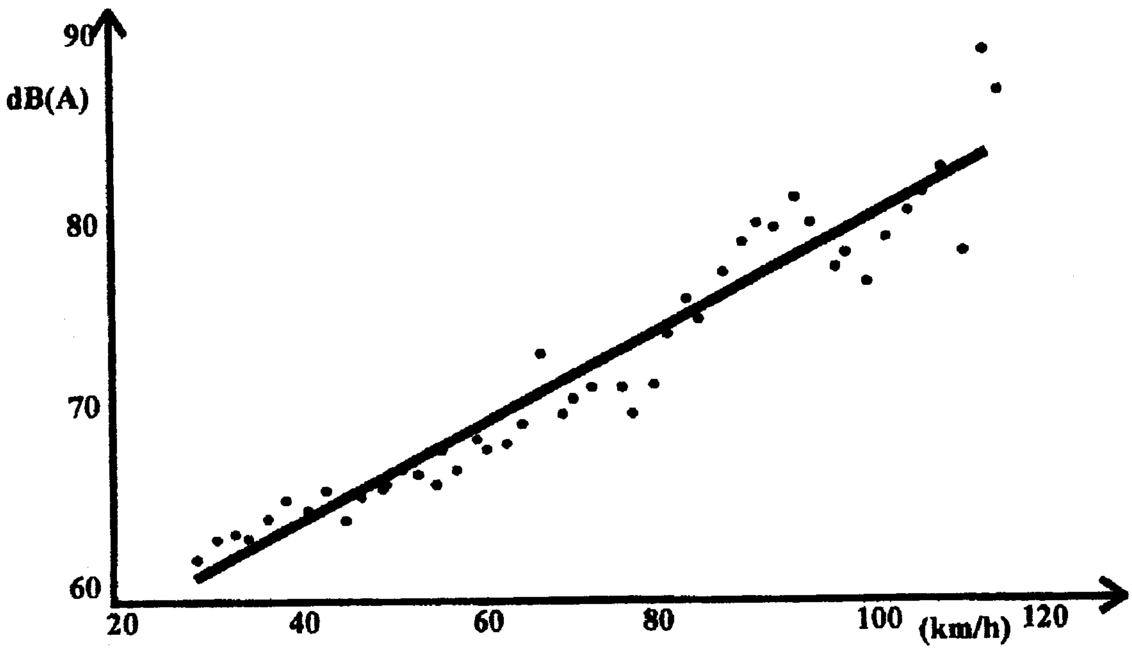


Figure 8 Linear correlation: dB(A) versus AI

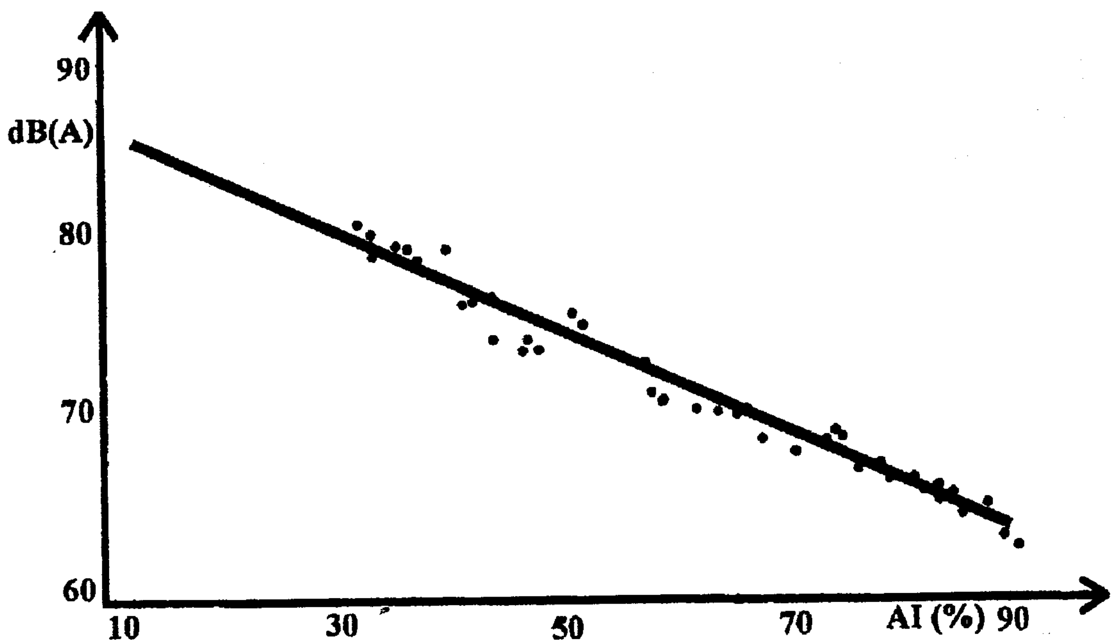
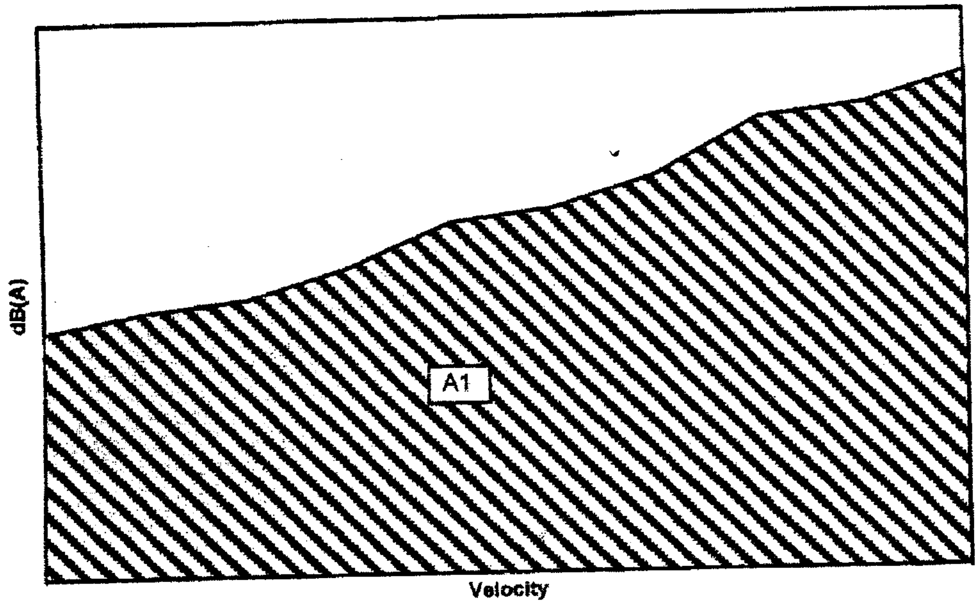
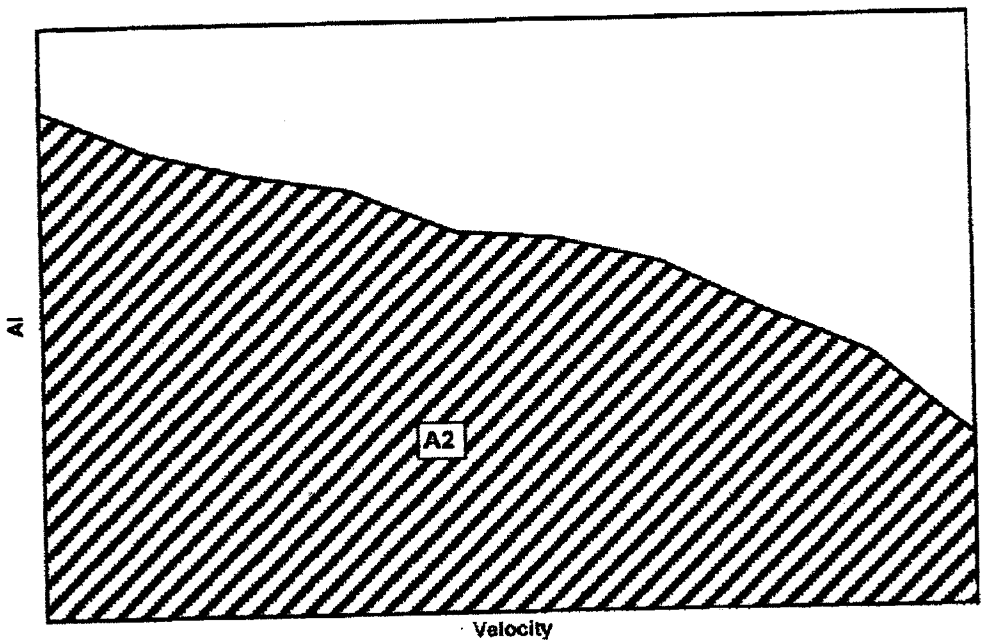


Figure 9 H-index definition



S(dB(A)) = A1; S(AI) = A2; => H = A1/A2



$$H = \frac{\int_{V_1}^{V_2} dBA(v)dv}{\int_{V_1}^{V_2} AI(v)dv}$$

A ranking can be produced when we compare different vehicles. Instead of dB(A), we can use other kinds of parameter representing the overall noise. See Table 1.

Table 1 Ranking according to H results

	H	*Vehicle*
1°	1.059	13
2°	1.068	10
3°	1.081	14
4°	1.179	2
5°	1.24	11
6°	1251	1
7°	1.262	12
8°	1.444	8
9°	1.447	6
10°	1.638	7
11°	1.839	9
12°	2.027	4
13°	2.606	3
14°	2.817	5

7 Some considerations about the human ear

A vital point in the consideration of the above parameters is that they do not contemplate the *exposition time*, which is an important variable in acoustic daily work. This time is well developed when we consider Occupational Noise Exposure, with the purpose of avoiding injury instead of acoustic comfort. In this case, although we still use the 'A' weighting curve, we also consider an average time, and this new parameter is called Equivalent Continuous Sound Level (L_{eq}) (May, 1978).

A general expression can be written:

$$L_{eq}(Q) = q \log\left[\frac{1}{T}\int_0^T 10^{L_A/q}\,dt\right]$$

$$q = \frac{Q}{\log 2}$$

where Q is the exchange rate in decibels, and characterises the dose considered.

The most traditional is Q = 3 dB, the equal-energy approach on the 3-dB rule, and the above expression becomes:

$$L_{eq} = 10\log\left[\frac{1}{T}\int_0^T 10^{L_A/10}dt\right].$$

Other expressions and criteria are used with Q = 4, 5 or 6.

We want to emphasise that, although we recognise that exposition time is important, we do not have a standard procedure to apply it in vehicle acoustics. Maybe an alternative is to apply an adaptation of L_{eq}. As an exception, in the case of vibration exposure, we have an international standard procedure that contemplates the comfort of vibrations besides the injury due to vibrations (ISO 2631).

We describe below, some important data, that make clear the difficulties we have in obtaining acoustic parameters which take into consideration all the variables.

- Some typical numbers regarding eardrum displacements:
  - 60 dB $\rightarrow 10^{-8}$ m;
  - 120 dB $\rightarrow 10^{-5}$ m;
  - 0 dB $\rightarrow 10^{-11}$ m (atomic diameter fraction).
- The basilar membrane, where are located the hair cells which respond to audible frequencies, displaces around 10 to 100 times less.
- The different responses associated with age, sex, nationality, exposition time ...
- 'Just Noticeable Differences' (JND) for sound pressure levels and frequencies.
- The models direct related or crossed related to:
  - physical variables: intensity, frequency, waveform
  - psychophysical variables: loudness, pitch, timbre.
- Some other complicated phenomena:
  - masking
  - phase effect
  - infrasound
  - spatial perception/sound localisation
  - stationary waves/diffuse reflections
  - activity/boundary condition
  - nonlinear behaviour.
- Structure sound propagation (through bones).
- Simultaneous interaction of different sensations. For instance thermic/acoustic.

We could write another list of complicated phenomenon that makes difficult the way of developing parameters for acoustic qualification/quantification, but we think it is enough to show the limitations.

8 Level reduction plus sound quality

Although the legislation and also the standards did not improve concerning the use of more modern parameters instead of dB(A) to quantify the sound pressure levels, the same cannot be said about research and development in the laboratories.

In the past few years, the unique concept of Level Reduction has not been enough. The addition of Sound Quality has become a constant interest.

This means that besides Loudness, other complementary parameters are incorporated, and joined together, harmoniously to try to describe the subjective impression in a better way.

In the automotive industry case, a classic example is the work done by AVL on engines (Schiffbänker et al., 1991; Stuecklschwaiger, 1993).

Besides Loudness, other complementary parameters are introduced such as:

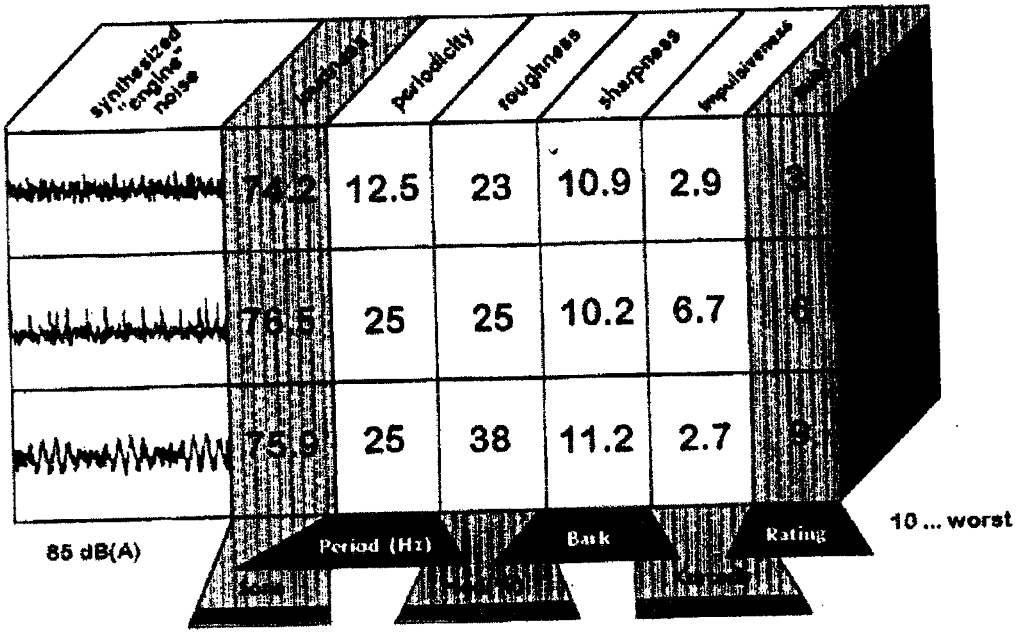
- periodicity
- roughness
- sharpness
- impulsiveness

We give below, the main purpose of each one.

- *Loudness*: a contribution of ≈ 80% in the final result; calculated following ISO 532 B.
- *Periodicity*: a contribution up to 10%. Associated with the result of the combustion and mechanical process of the engines. The sound varies between cylinders and is due to cyclical fluctuations in the combustion. The analysis is effected using Cepstrum.
- *Roughness*: a contribution up to 8%. It is useful to guarantee improvements in the engine under the same operational conditions and it is a measurement of the signal modulation degree in six bandwidths between 125 and 4 kHz.
- *Sharpness*: a contribution up to 8%. It is obtained from Loudness graphs according to Zwicker. It measures the high frequency contributions.
- *Impulsiveness*: a contribution up to 6%. It measures the engine idle characteristics though the Kurtosis determination, in a amplitude probability chart.

The combination of the above parameters produces the Annoyance Index, a single number for engine comparison. See Figure 10.

Figure 10 Different sound quality for equal overall levels



Other parameters could be used, as for instance (Zwicker and Fastl, 1990):

- pitch and pitch strength
- sensory pleasantness
- fluctuation strength
- subjective duration
- non-linear distortion.

The above descriptions show how non trivial are the interaction between subjective and objective concepts.

9 Conclusions

Based in our exposition we can make some considerations:

- Having the variation in time of the sound pressure, p(t), passing through filters with different bandwidths, we manipulated these signals in several imaginative ways, establishing many parameters for acoustic evaluation. See Figure 11.
- The ISO standards will continue to specify dB(A). They are straightforward and well known, in spite of their limitations. People want a single number. The legislation follows these standards (Schumacker, 1998).
- An exception is, for instance, the evaluation of the level of noise of an aircraft. Besides the A-weighted sound level, the PNL – *Perceived Noise Level* – is used to monitor the peak noise level of an aircraft passby (or flyover or flyby). It is a step ahead, if we compare with Loudness.

- In addition, EPNL – *Effective Perceived Noise Level* – is used, taking into account duration and noise level by integrating the PNL over the duration of the event (May, 1978).

- The sophisticated parameters, although more precise, will remain inside research groups. They are non-trivial, need greater acoustic knowledge and are multidisciplinary. We do not see them as a popular use in the short term.

- We observe that the 'time exposition' is not considered in the parameters when dealing with comfort. An exception is the standard concerning vibrations applied to people (ISO 2631).

- The subjective evaluations are very important. They are complementary to the objective measurements.

- The time exposition or the evaluation duration must be considered in the subjective tests, because short times and long times can produce different sensations.

- An attempt to incorporate the time factor in the objective measurements could be exercised by the ISO Committees. Perhaps the parameter L_{eq} could be the initial reference.

- In the case of internal noise, as we do not have legislation, the parameters are used for researchers but not divulged to society. When necessary, dB(A) is still used (ISO 5128).

- In the case of external noise, as the legislations call for ISO 362, the associated number is in dB(A), yet. The boundary conditions for measurement procedure have become ever more rigorous, but the parameter used for evaluation has not changed.

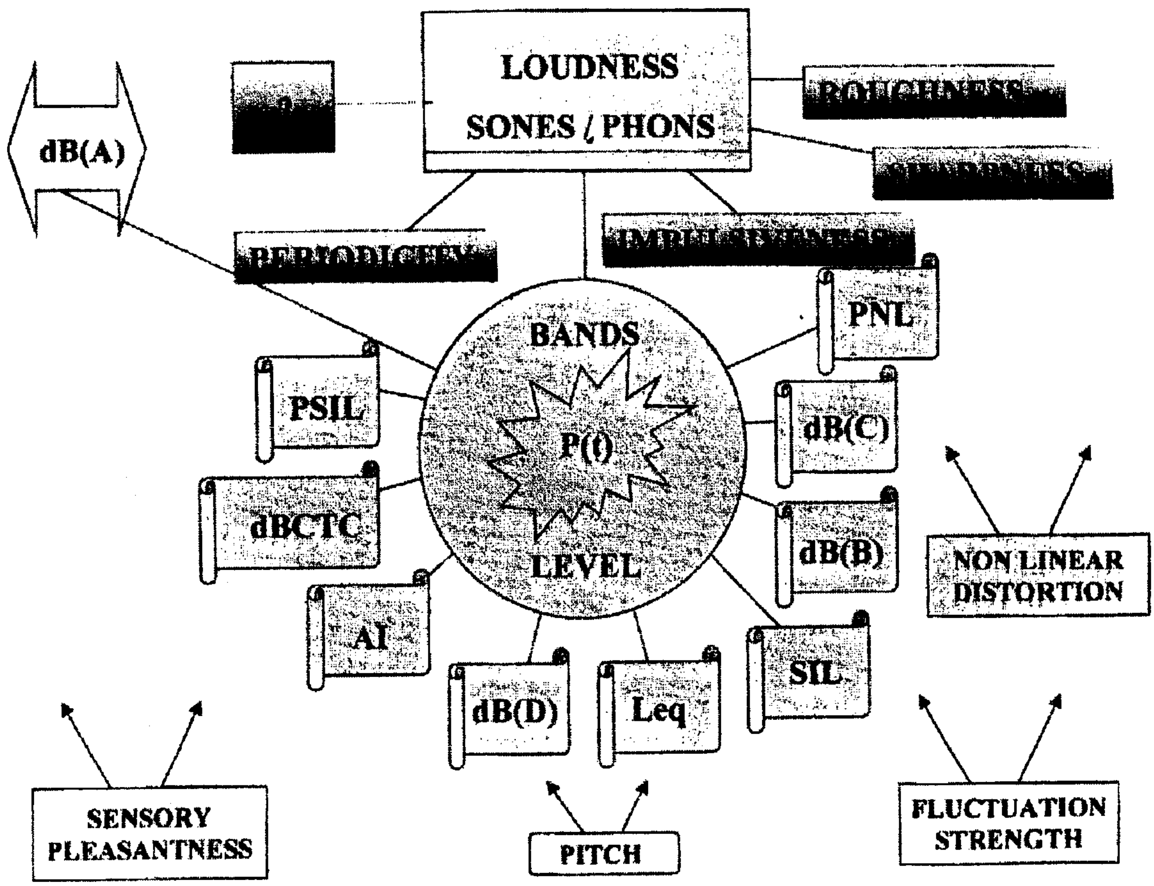
- As a suggestion, the ISO Committees could elaborate more advanced standards incorporating other parameters, as '*Recommended Standards*' to increase the knowledge of people for future implementation. In Brazil there is a specific standard concerning Articulation Index for automotive vehicle, elaborated by ABNT (Brazilian Technical Standards Association).

- A good beginning would be the simultaneous adoption by ISO 362 and ISO 5128, of the Loudness in sones for the overall noise, together with dB(A). This parameter, because of its linear behaviour, is easier for people to understand.

- An internal noise evaluation through measurements would have at least the following data:

  - a weighting curve ↔ overall noise
  - Articulation Index ↔ medium/high frequencies
  - sound pressure level associated to the engine explosion order.

Figure 11 A partial today vision concerning acoustic evaluation parameters



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