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Chapter 5

Tyre/Road Noise Annoyance Assessment Through Virtual Sounds

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Abstract

Road-traffic noise is the most significant source of environmental noise. Among the several different sources of noise emission from vehicles, tyre/road noise at speeds above 40 km/h is the most prevalent. Its negative impact on health is now better known and may be mitigated by optimising road surface characteristics. Experimental data linking the characteristics of the road surface to levels of annoyance regarding noise remain scarce. Moreover, assessing annoyance by experimental means using real sounds is complex and could impede study interactions with a wide set of variables. In this chapter, we describe, discuss and present the results of a straightforward method to assess tyre/road noise and related annoyance, based on the virtual sounds made by vehicles, with no interferences.

Keywords: traffic noise, annoyance, virtual noise, tyre/road noise

1. Introduction

Road-traffic noise is the most significant source of environmental noise. Among the several different sources of vehicle noise emission, tyre/road noise is predominant at a wide range of speeds, from low to high, but more so above 40 km/h. Its negative impact on health is now better known [1] and may be mitigated by optimising road pavement surface characteristics. Even though a lot of research and effort has been made in the last few years to develop and construct low-noise road pavement, annoyance remains a problem. Studies linking the road surface characteristics involved in tyre/road noise generation mechanisms with levels of annoyance are scarce.

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Moreover, the field recordings in urban or rural environments are susceptible to contamination by other noise sources, thus limiting considerably the number and type of factors, which can be controlled and manipulated, or even the feasibility of the studies. Therefore, to avoid these drawbacks, a more straightforward procedure that combines noise acquisition close to the tyre (close proximity measurements) with auralisation of these acquisitions in a virtual scenario, tested and validated, would be useful. In addition, by manipulating the sounds measured in the source (the tyre), it will be possible to manipulate and analyse a wider set of traffic parameters and other road environment features.

This chapter aims to briefly introduce tyre/road noise generation mechanisms and analyse pavement surface characteristics and factors involved, and then to present and discuss the results of an innovative and straightforward method to assess tyre/road noise annoyance based on vehicles' virtual sounds generated from continuous close proximity tyre/road measurements.

2. Background

2.1. Road-traffic annoyance studies

The health impact of noise and of road-traffic noise, in particular, is commonly studied through annoyance assessments, either by surveys and questionnaires directed to large populations or by laboratory experiments with selected samples [2, 3].

Some of the most recent annoyance studies have been concerned with the health-related quality of life as, for example, studies on the annoyance caused by exposure to different noise sources, including road-traffic noise exposure [4], or studies on noise annoyance related to residential transportation and its impact on the physical activity of residents, change over time [5].

Taking into account the impact of the pavement surface on noise generation mechanisms, from low to high traffic speeds, it seems wise to comprehensively study the influence of road surfaces and their interaction with traffic characteristics on annoyance. From a practical perspective, the outcomes of these kinds of studies could be useful for highway engineers and decision makers. Nevertheless, previous studies have treated these annoyance factors separately. Some authors have been more concerned with road-traffic noise generation and addressed the impact of pavement type on annoyance [6, 7], while other authors addressed annoyance taking into account traffic parameters [8, 9], powered two wheelers and heavy vehicles and other factors such as industrial noise [10, 11].

In the scope of road-traffic noise generation, the most recent studies have analysed annoyance by taking into consideration the interactions of several types of pavements with relevant traffic parameters such as speed, type of vehicle and vehicle composition [12]. However, the main issue is that the experimental procedure to measure tyre/road noise is very complex and time consuming.

In an attempt to simplify the experimental procedure, the suitability of tyre/road noise close proximity measurements to assess annoyance through psychoacoustic parameters was

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examined [13, 14]. Furthermore, relations between subjective annoyance ratings and the traffic noise levels described by acoustic and psychoacoustic indicators (LA_{max}, LA_{eq} and Loudness) as a function of speed were established [14].

Despite the good results, the experiment conditions do not yet fully replicate those occurring near the road. However, the use of virtual sounds, built from close proximity records, to assess traffic annoyance is an almost unexplored solution, insufficiently documented in the literature.

2.2. Tyre/road noise and pavement surface characteristics

The noise emitted by a single vehicle is generated by three main sources: the engine, exhaust and transmission noise; the aerodynamic noise; and the noise generated by the interaction of the tyre with the road surface. The predominance of each one depends on vehicle operation conditions. It is recognised that tyre/road noise becomes predominant above 40 km/h [6]. Nonetheless, this limit has had a tendency to become lower due to the technological improvements in vehicles which have taken place over the last few years, such as the use of electrical engines.

Tyre characteristics and pavement surface characteristics play a crucial role in noise generation. The energy created by the interaction of the tyre with the pavement surface is radiated as sound. The tyre/road surface noise generation mechanisms are both vibrational, resulting from the impact and the adhesion of tyre treads on the surface, and aerodynamical, resulting from air vibrations around the tyre and in pavement and tyre surface cavities. There are also noise-related amplification or reduction mechanisms such as the horn effect, the acoustical and mechanical impedance of the surface and the tyre resonance [6].

The main characteristics of the tyre that affect noise are the tyre structure, the geometry, the tread pattern, the hardness of the rubber and the overall condition (wear and ageing) [6].

The noise generated by the contact of tyres on pavement surfaces is also influenced by a set of factors. There are three main road pavement surfaces: cement concrete, asphalt concrete and modular pavement. In general, they are made of mineral aggregates and a cementitious or asphaltic binder. Modular pavements may be made solely of natural stone. Despite their obvious differences, factors such as texture, porosity, aggregate gradation, type of bitumen and stiffness/damping [15] affect the interaction noise.

High macro-texture [16] and low mega-texture, negative texture, high porosity [17], small and regular mineral aggregates and low stiffness [17] or high damping [14, 18] are the main characteristics of a low noise surface. Asphaltic surfaces with bitumen modified with rubber [19] or with elastic aggregate substitute materials [20] also contribute to tyre/road noise reduction.

Therefore, dense asphalt concrete, stone mastic asphalt and surface dressings are the ones that generate more noise in contrast with double and single porous asphalt, thin layers and poroelastic surfaces [21–24].

Changes in pavement surface characteristics occur with time due to traffic wearing and weather exposition, generating more noise [19]. Weather-related factors such as the temperature of the surface and water on the surface also affect tyre/road noise. As the temperature increases, the tyre/road noise decreases [25, 26], while wet road surfaces always generate more noise than dry surfaces [27].

2.3. Tyre/road noise measurement methods

2.3.1. The statistical pass-by method

The statistical pass-by (SPB) measurement procedure, as described in IS0 11819-l: 1997, was designed to evaluate vehicle and traffic noise generated on different sections of road surface under specific traffic conditions.

In the SPB method, the maximum A-weighted sound pressure levels (SPLs) of a statistically significant number of individual vehicle pass-bys are measured at a specified roadside location together with the vehicle speeds (**Figure 1**). Each measured vehicle is classified into one of the three vehicle categories: 'cars', 'dual-axle heavy vehicles' and 'multi-axle heavy vehicles'. For each of the three speed ranges defined (low, medium and high speed categories) as well as for each of the three vehicle categories, a nominated reference speed is given. Each individual pass-by level, together with its vehicle speed, is recorded. This data is then analysed to determine the statistical pass-by index (SPBI).

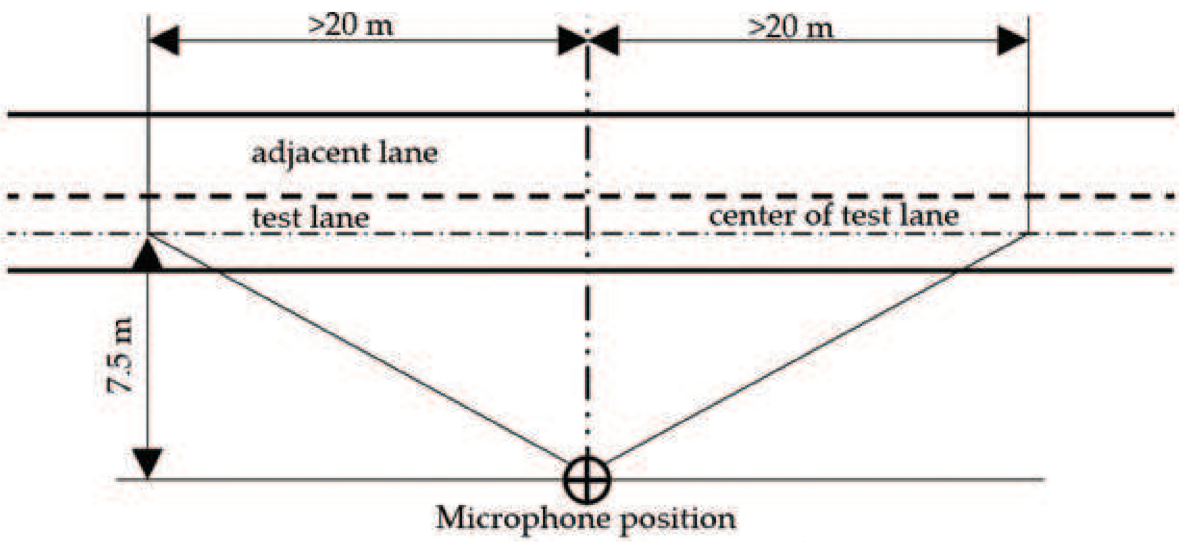

Figure 1. SPB testing geometry.

2.3.2. The controlled pass-by method

The controlled pass-by (CPB) method is a modified version of the statistical pass-by method that can be carried out using either a single vehicle or selected vehicles. In this method, the noise generated from a single car or light truck is measured when the vehicle approaches the test site at a specified speed in a specified gear.

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2.3.3. The statistical pass-by method using a backing board

The statistical pass-by method using a backing board, ISO 11819-4:2013, specifies a modified version of the statistical pass-by method and uses a microphone mounted on a backing board instead of a microphone in normal, free-field conditions. It is suitable for measurements taken in an urban, built-up, environment or in the presence of safety barriers, noise barriers, embankments or road cuttings.

2.3.4. The close proximity method

In the 'close proximity (CPX) method', the average A-weighted SPLs emitted by specified tyres are measured over an arbitrary or a specified road distance, together with the vehicle testing speed, by at least two microphones located close to the tyres. For this purpose, a special test vehicle, which is either self-powered or towed behind another vehicle, is used (**Figure 2**). Reference tyres are mounted on the test vehicle.

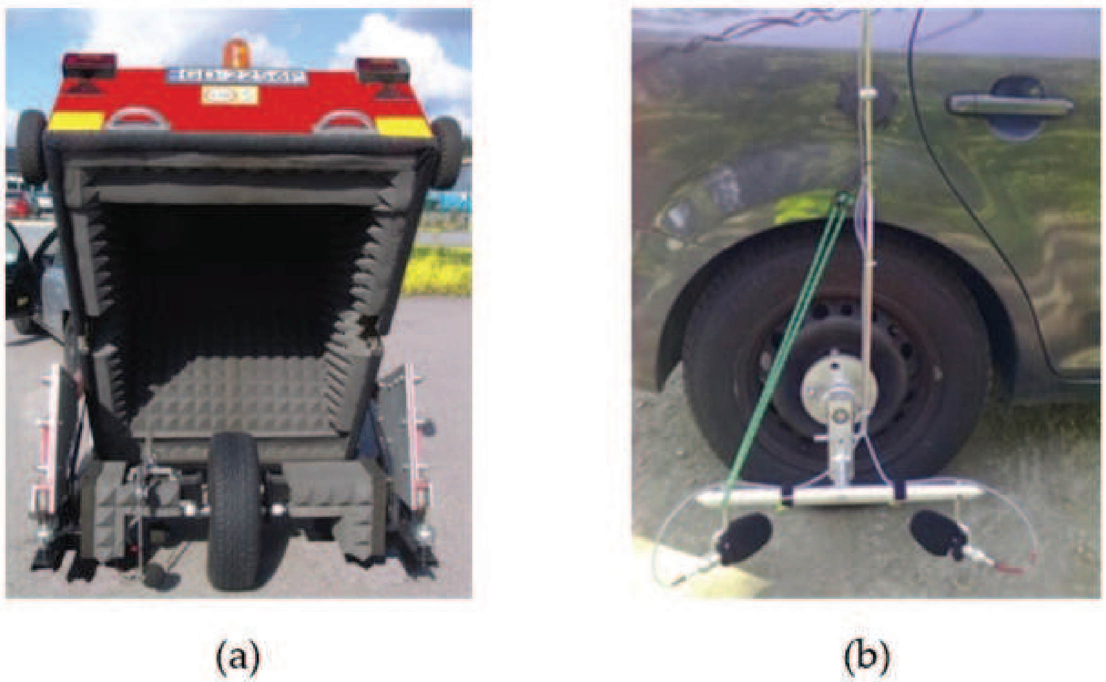

Figure 2. Examples of CPX devices: at left (a) the interior of the TUG Tiresonic Mk4 CPX trailer [28]; at right (b) the University of Minho device [14].

According to ISO/DIS 11819-2, the tests are performed with the intention of determining a tyre/road sound pressure level, L_{CPX}, at reference speeds.

For each reference tyre and each individual test run with that tyre, the average sound pressure levels over short measuring distances, together with the corresponding vehicle speeds, are recorded. The sound pressure level of each segment is normalised to a reference speed by a simple correction procedure.

The CPX level, $L_{CPXt,V}$, is the resulting average sound pressure level for the two mandatory microphones at the reference speed (*V*) for the reference tyre (*t*). If more than one reference tyre is used, the Close Proximity Sound Index is calculated.

2.4. Perceptual noise indicators

Currently, the impact of road-traffic noise and also tyre/road noise is represented by the A-weighted equivalent mean average sound level (LA_{eq}) or the A-weighted maximum sound Level (LA_{max}). These acoustic indicators do not account for sound perceptual base items used by the human auditory system, such as loudness, roughness, sharpness and others [29]. Therefore, a comprehensive tyre/road noise annoyance study should include not only the objective noise indicators but also the perceptual indicators (subjective).

There are many models used in psychoacoustics for predicting the subjective sensation of loudness, sharpness and roughness.

Loudness is the attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from soft to loud [29]. Loudness depends primarily upon the sound pressure of the stimulus, but also upon its frequency, waveform and duration. The 'loudness level' of a sound is defined as the sound pressure level of a 1 kHz tone in a plane wave and frontal incident that is as loud as the sound; its unit is 'phon' [29].

Loudness models can be divided into ones which use Bark auditory filters (or critical bands) and ones which use Erb auditory filters, and can also be divided into steady-state and dynamic models [30]. Steady-state models account for spectral effects on loudness, while dynamic models also account for the effect of auditory temporal integration on loudness, therefore they are better suited for time-varying signals.

Examples of steady-state models are Zwicker's model [29] and Moore, Glasberg and Baer's model (MGB) [31]. Glasberg and Moore (GM) [32], using Erbs, and Chalupper and Fastl (FC) [33], using Barks, are examples of dynamic loudness models.

Sharpness is a measure of the high frequency content of a sound (over 1100 Hz). The greater the proportion of high frequencies, the 'sharper' the sound [29]. A sound of sharpness 1 acum is defined as a narrow band-noise one critical band wide at a centre frequency of 1 kHz having a level of 60 dB [29].

There are several models to calculate sharpness, for example, Aures [34] or Zwicker and Fastl [29]. Zwicker and Fastl's model is a weighted centroid of specific loudness, while Aures's model is more sensitive to the positive influence of loudness on sharpness [30]. High frequencies generated by traffic are determined by aerodynamical noise generation mechanisms that make this indicator suitable to quantify their impact on annoyance.

Roughness is a complex effect that quantifies the subjective perception of rapid fluctuations (15–300 Hz) in the sound received by auditory filters [29]. The unit of measure is the asper. One asper is defined as the roughness produced by a 1000 Hz tone of 60 dB which is 100% amplitude modulated at 70 Hz [29].

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Models of roughness for simple stimuli are given by Zwicker and Fastl [29]. For arbitrary stimuli, the roughness model optimised by Daniel and Weber [35] is applicable.

3. Method to assess traffic noise annoyance

3.1. Description of the method

The method to assess traffic noise annoyance follows four main steps: (I) tyre/road noise measurement, including road surfaces selection; (II) running an auralisation process to the acquired sounds using head-related transfer functions (HRTFs); (III) determining objective and subjective acoustic indicators; and (IV) running annoyance rating experiments **(Figure 3)**.

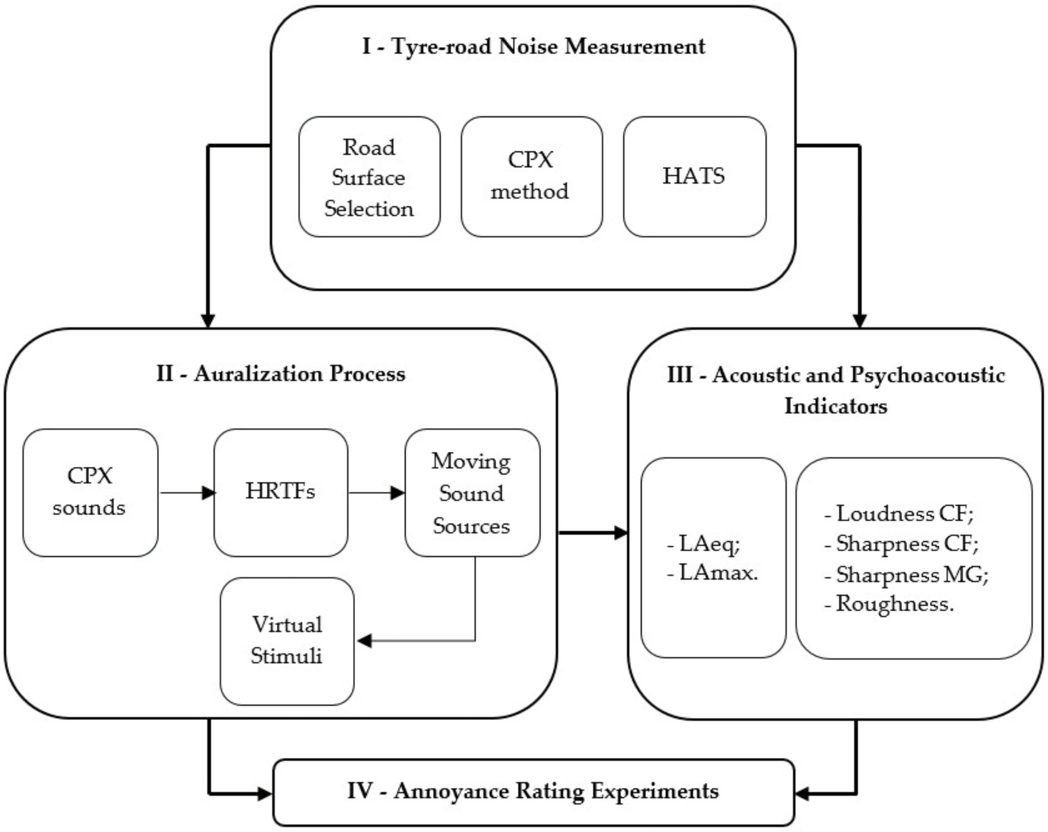

Figure 3. Organogram of the traffic noise annoyance method.

3.2. Noise measurement

Depending on the goal of the measurement, tyre/road noise measurement methods have advantages and disadvantages. SPB measurements include not only all vehicle noise sources and the effect of all propagation mechanisms, but also include other acoustic information near the measurement. For the evaluation of roadside noise through the SPB method, unreliable results due to the influence of surrounding conditions, even using a modified procedure, have been reported [36]. Records with head and torso simulator are in reality the SPB measurements, having precisely the same problems **(Figure 4)**. For annoyance or vehicle detection tasks, noise measurements contaminated with undesired sounds are an impediment to adequately accomplishing the task.

Figure 4. Measuring systems for SPB tests: microphone and HATS.

With the adoption of the CPX method, this important problem is eliminated. The influence of noise sources other than tyre/road is eliminated at most driving speeds. Also, this measurement method has been shown to be suitable for annoyance studies [37]. Moreover, since the source of tyre/road noise is in close proximity to the tyre/road interface, a substantial part of the propagation effect by acoustically absorptive surfaces is included in the microphone signal. In this way, the acoustic contribution of the pavement can be isolated and virtualised. Other effects, besides the pavement, can be added if desired.

3.3. Virtual noise construction

To create virtual noise, which is equivalent to the moving sound source obtained with the CPB measurements, an auralisation process was used. This technique enabled the virtual stimuli to be constructed using tyre/road CPX measurements as input sounds, resulting in the sound of a vehicle passing by the subject in a frontal-parallel plane.

All the stimuli were built with 5 seconds of length each. The vehicle passes the subject at the middle of the stimulus length. Like the CPB measurement, the position of the subject is located at 7.5 m away from the centre of the lane at 1.2 m height (see **Figure 5)**. The auralisation process was made using Head Related Transfer Functions, and a geometrical attenuation was calculated considering a previous study [38].

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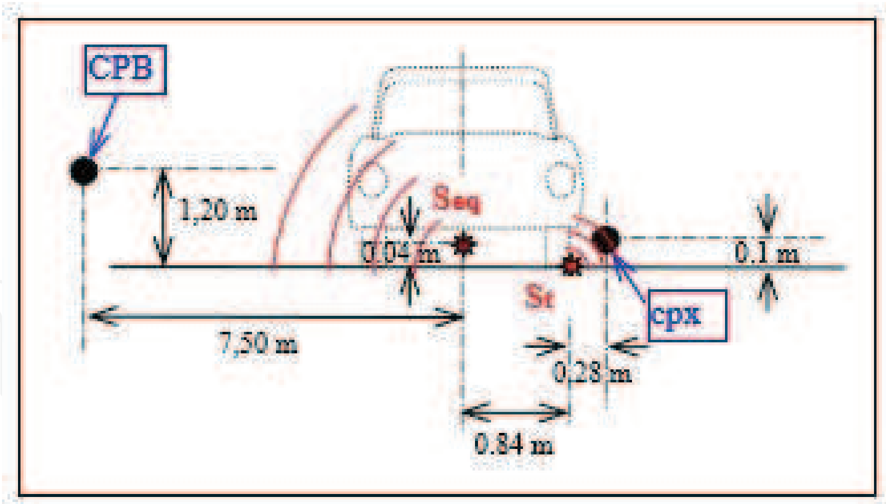

Figure 5. Noise sources location [38].

The original input sound, the CPX measurement sound, was partitioned into small samples; and for each sample, the correct attenuation level and the correspondent HRTF filter according to the azimuth angle between the subject and the vehicle position were applied. To apply the filter, head-related impulse responses (HRIRs) were used, convolved with the small samples in the time domain.

Depending on the vehicle speed during each trial, the vehicle's sound source position and azimuth were calculated for each consecutive small sample. For example, if the vehicle was travelling at 50 km/h, the initial position was at 69.45 m from the passing point, 69.85 m from the subject and the azimuth angle variation in this trial would be between −83.86 and +83.86 degrees. A Doppler effect was also applied since the stimuli consist of sound sources moving along a well-defined trajectory.

To calculate the geometrical sound attenuation, a sound pressure level difference between the CPX and the CPB measurement was defined:

$$\Delta L = L_{\mathrm{CPX}} - L_{\mathrm{CPB}} \tag{1}$$

Figure 5 represents a simplification of this model in which an equivalent point source is defined as S_{eq}, and this point was used in the virtual noise construction as the point moving along the previously defined trajectory.

The following equation represents the complete geometrical model:

$$\Delta L = Att_{\mathrm{CPX}} - Att_{\mathrm{ct}} - 20\log_{10}\left(\frac{r_{\mathrm{CPX}}}{r_{\mathrm{ct}}}\right) - 10\log_{10}\left(1 + \left(\frac{r_{\mathrm{ct}}}{r_{\mathrm{ft}}}\right)^{2} 10^{\frac{Att_{\mathrm{ft}} - Att_{\mathrm{ct}}}{10}}\right) - 10\log_{10} \tag{2}$$

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where Att_{CPX} is the sound pressure attenuation between the CPB measurement position and the S_{eq} position relative to the free field; Att_{ct} is the sound attenuation relative to free field between the closer tyres and the CPB measurement position; Att_{ft} is the sound attenuation relative to free field between the farther tyres and the CPB measurement position; r_{CPX} is the distance between the CPX measurement position and the tyre source position; r_{ct} is the distance between the closer tyres and the CPB measurement; and r_{ft} is the distance between the farther tyres and the CPB measurement.

Some noise contributions were not taken into consideration, such as the exhaust, engine and transmission noise as well as the sound reflections in the car body. The road surface attenuation was not simulated. Consequently, the stimuli reproduce a pure reflective road surface, and taking this into account, the Att_{ct}, Att_{ft} and Att_{CPX} have a value of 6 dB for all frequencies. The final equation of attenuation is defined as:

$$\Delta L = 10\log_{10}\left(\frac{{r_{ct}}^2 {r_{ft}}^2}{2{r_{CPX}}^2\left({r_{ct}}^2 + {r_{ft}}^2\right)}\right) \tag{3}$$

Since this equation represents the geometrical difference between L_{CPX} and L_{CPB}, a distance compensation was also used between the listener and the sound source for all the consecutive small samples in each sound.

3.4. Experimental method to measure traffic noise annoyance

Road traffic is an important source of noise annoyance and contributes to significant public health problems [39]. In terms of road safety, annoyance and detection should be studied in an integrated way, in order to understand and predict the effects of environmental noise on human behaviour and performance. Furthermore, these variables should be analysed and should be used as evidence when taking decisions in the planning and implementation of road infrastructures or vehicle features. Recent progress in this area has contributed to a reduction in road-traffic noise through the development of more efficient pavements and quieter vehicles, such as hybrid and electric cars. However, traffic noise plays a key role in road safety as it enhances the detection of other road users or vehicles, and consequently provides relevant information for road users and promotes the awareness of hazardous situations.

Previous works have demonstrated that pavement type and vehicle noise significantly affect the levels of environmental noise and associated subjective annoyance measurement [40] and detection levels [41]. Vehicle type affects both detection levels and annoyance ratings with a positive correlation between sound intensity, detection rates and annoyance. Regarding pavement type, detectability and annoyance rating revealed it to be more sensitive to this variable, in particular in lower speed traffic environments, such as those where hazardous situations with vulnerable road users might occur. In this context, a trade-off between detect-

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ability and annoyance levels should be addressed, accounting for the vehicle detection levels and overall traffic annoyance ratings.

As previously described, noise exposure can be described with physical measures that can be defined in different ways and be easily measured. Noise annoyance, in turn, is a subjective parameter considered to reflect the internal exposure to noise by associating the physical stimulus with the sensorial, perceptual and physiological consequences that it produces in the human organism.

From a methodological perspective, noise annoyance may be assessed either in field or in laboratory studies. Field studies are usually related to long-term annoyance and allow the study of factors encountered in real-life situations (e.g. noise sensitivity and noise source characteristics [42]).

Experimental methods in controlled environments allow the systematic manipulation of the traffic noise and related vehicle detection variables as a function of conditions such as pavement, vehicle type, background noise or user characteristics. The main goal of these kinds of methods is to quantify perceptual and/or behavioural performance as a function of the manipulation of physical or psychophysical (in this case, psychoacoustic) variables. Therefore, psychophysics can contribute substantially to the study of noise annoyance because it reduces the subjectivity of comfort or annoyance reports and allows the analysis of the effects of the variables on their own and the interactions between them [43, 44]. Each of the psychoacoustic indicators isolated might be unable to predict the annoyance on their own, but psychoacoustic metrics can correlate with non-sensory parameters and together can result in robust predictors or estimates [45]. Furthermore, simulated environment experiments can increase the ecological significance of the task and allow researchers to simulate real-life situations when studying the influence of acoustical and non-acoustical indicators on annoyance.

Based on the research goals and experimental design, requirements and criteria are defined (stimuli, space and material, procedure) to carry out the psychoacoustic experimental protocol in controlled environments. Prior to the experimental activities with human participants, an ethical approval from the local ethics committee will be required. Researchers should submit the selection criteria of the participants, experimental protocol and data management plan. For inclusion in the sample, participants are required to undergo an audiometric test to confirm that they have normal hearing. A learning phase or a familiarisation with the stimuli might be necessary for specific perceptual and detection tasks. Sometimes, the participant can freely hear the different stimuli and in other situations can, for example, compare each stimulus with the other sounds to set a relative scale.

The annoyance assessment of each participant is performed in a quiet room. Usually, sound stimuli are randomly presented together with channel reversed stimuli to avoid inter-aural biases following the adaptive or the constant stimulus method [46]. Participants are requested to assess the annoyance by responding to a Likert scale, between 5 and 11 points (from 'less annoying' to 'very annoying'). Some specifications and recommendations for this kind of instrument can be consulted in the ISO standard 15666:2003.

4. General outcomes

To support the previously discussed methodology, the main general outcomes of the research, which has already been carried out and of that which is also ongoing in this area, are examined. Two experiments in particular are addressed. One experiment was designed to verify if close proximity tyre/road noise measurements were suitable to rate traffic annoyance and the other one is a full application of the method described, aiming at verifying if virtual sounds generated from close proximity tyre/road noise measurements (virtual stimuli) can be used to rate annoyance correctly.

Some pavement surfaces were common to both studies, such as granite cubes (GC), concrete blocks (CB) and asphalt concrete (AC), and the testing speeds were 30 and 50 km/h. These conditions were used to illustrate hereafter the main results of the studies. Tyre/road noise measurement details can be found in [12] and [14].

The stimuli in both experiments were composed of the combination of pavement surface type with testing speed, and presented to voluntary listeners.

The annoyance assessment procedure of each participant was the same in both experiments. Each participant listened to the experimental noise trials and was requested to assess the annoyance of each noise trial with a 10-graded interval scale from 1 (less annoying) to 10 (very annoying).

The first approach to the problem consisted of checking if CPX annoyance ratings would have a similar trend to the CPB real annoyance ratings and then check if real annoyance ratings would have a similar trend to the virtual annoyance ratings. These trends were confirmed.

The mean annoyance rates, as expected, have the highest levels for the CPX stimulus, as they were recorded at the source, and lower levels for the virtual CPB stimuli, as they are deprived of engine, mechanical and background noises. This is clear for tyre/road noise coming from low noise surfaces. However, real ratings can be predicted by a simple model as a function of virtual stimuli annoyance rates and account for both the effect of speed and the type of pavement. In addition, using this methodology, it was possible to detect significant effects of type of pavement and speed on annoyance rates.

Psychoacoustic metrics can correlate with non-sensory parameters and together they can result in robust predictors or estimates. Good significant correlations of loudness with speed and pavement type have been found in previous studies. The final step to validate the method to assess annoyance using virtual sounds consisted of correlating the psychoacoustic metrics with the annoyance rates, aiming to use them as predictors. For the CPX annoyance prediction, there were no clear advantages for using loudness to predict annoyance. The fit of the annoyance rate against loudness was good for both acoustic and psychoacoustic indicators. However, for CPB annoyance rates, the quality of the prediction greatly improved for virtual stimuli and was better for loudness.

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5. Discussion and conclusion

The methodology developed to assess tyre/road noise has been demonstrated to be efficient and will have a wide impact in the field, mostly in methodological and practical terms.

In general, the methodology significantly simplifies field procedures, allowing a reduction in experimental costs and a better control of variables, and it also brings great benefits with an increase in the accuracy of annoyance ratings.

On the one hand, the method examined allows researchers to fully achieve the objective of strictly assessing tyre/road noise annoyance by ignoring vehicle mechanical noises and generating virtual stimuli with tyre/road noise only. On the other hand, improvements in the simplified sound propagation algorithm can be made, for example, by including effects such as absorption and reflection. In addition, by adding engine noise, from electrical or traditional vehicles, and other noises, the masking effect of traffic annoyance could be better studied and understood.

There are several major advantages of using virtual instead of real stimuli; since besides the better control of experimental factors, there are also improvements in the quality of the recordings, and time consumption and costs are substantially reduced.

The most important practical impact of the method is the possibility to accurately establish requirements to control traffic noise based on indicators that better describe the annoyance triggered by the most significant source, the traffic.

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