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Scaling model for a speed-dependent vehicle noise spectrum

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HIGHLIGHTS

- Cluster analysis of vehicle noise spectra.
- Derivation of speed-dependent analytical functions fitting the average spectrum profiles.
- Prediction of vehicle speed based on noise spectrum patterns.

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ABSTRACT

Considering the well-known features of the noise emitted by moving sources, a number of vehicle characteristics such as speed, unladen mass, engine size, year of registration, power and fuel were recorded in a dedicated monitoring campaign performed in three different places, each characterized by different number of lanes and the presence of nearby reflective surfaces. A full database of 144 vehicles (cars) was used to identify statistically relevant features. In order to compare the vehicle transit noise in different environmental condition, all 1/3-octave band spectra were normalized and analysed. Unsupervised clustering algorithms were employed to group together spectrum levels with similar profiles. Our results corroborate the well-known fact that speed is the most relevant characteristic to discriminate between different vehicle noise spectrum. In keeping with this fact, we present a new approach to predict analytically noise spectra for a given vehicle speed. A set of speed-dependent analytical functions are suggested in order to fit the normalized average spectrum profile at different speeds. This approach can be useful for predicting vehicle speed based purely on its noise spectrum pattern. The present work is complementary to the accurate analysis of noise sources based on the beamforming technique.

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1. Introduction

A sound generating device is generally identified according to its acoustic features which are referred to as acoustic signatures and are usually employed to discriminate among vehicles. Such signatures in case of moving sources are mostly linked to the engine vibrations and tire-road friction (Sandberg and Ejsmont, 2002). Among the techniques used to extract features in time-frequency domain there are Short Time Fourier Transform and Wavelet Transform (Munich, 2004; Sun and Qi, 2008). A signal processing time-domain technique used in sensor arrays for directional signal transmission or reception (Van Veen and Buckley, 1988), denoted as Beamforming, has been recently employed in car by-pass noise identification (Ballesteros et al., 2015). This technique allows one not only to locate the main noise sources during the pass-by of a vehicle, but also their characterization in terms of source strength.

Pattern recognition has been the subject of many studies which included techniques of compressed sensing (Candes et al., 2006; Donoho, 2006; Donoho et al., 2006) to disclose important acoustic features of an unknown signal and principal component analysis to dimensionally reduce such features employed to describe the difference between signals (Averbuch et al., 2012; Wang and Qi, 2002; Wu et al., 1999). For a review of such techniques we refer to Kakar and Kandpal (2013). Other advanced methods are based on laser Doppler vibrometry (Ometron, 2013), source height measurement (Glegg and Yoon, 1990), sound intensity (GMNA, 2005), nearfield acoustic holography (Ruhala, 1999) and spatial transformation of sound fields (Hald, 1995).

Different projects have been developed to determine common noise assessment methods for road, railway, aircraft and industrial noise in order to improve the reliability and the comparability of results across the EU Member States (CNOSSOS-EU (Kephalopoulos et al., 2012)). Further projects include prediction algorithms in order to forecast noise from specific sources such as road, rail traffic, aircraft and industrial sites (HARMONOISE (Bullen, 2012; Salomons et al., 2011), IMAGINE project (CORDIS, 2012)), providing a procedure to be adopted for strategic mapping as defined by the environmental noise directive. As for traffic noise, in the Harmonoise/Imagine model, particular attention has been paid to rolling noise, split into the vehicle and track contribution as well as wheel-surface interaction. The algorithms also include noise transport due to the combined effects of air absorption, the ground effect, shielding by topography (including barriers or buildings), atmospheric refraction, and atmospheric scattering. It is known that in the case of traffic noise, the events associated with each single vehicle transit are mainly random and characterized by fast or occasional sequences according to high or low vehicle flow rates. Monitoring traffic noise in a mid-long period (days or weeks) is usually carried out with 1 s temporal resolution recording both the spectrum at 1/3-octave band and the equivalent A-weighted level. In addition, traffic noise usually displays high variability in the noise spectra. For this reason, in this paper we address the question of the measured spectra variability and perform a detailed analysis by considering their average behavior. From these considerations, we developed a completely "blind" approach based upon the building up of statistically relevant classes characterized by "similar" spectrum profiles. The content of each group was then cross-checked against all the available vehicle characteristics. It is found that speed alone is sufficient to discriminate between different clusters, and, correspondingly an analytical model is presented. The model should be useful as a predictive instrument in a number of environmental applications. A similar approach has been applied to recorded hourly noise level profiles in the Dynamap-Life project (Zambon et al., 2014, 2015, 2016a,b).

The paper is organized as follows: In Section 2 we discuss the statistical analysis of the noise spectra produced by 144 vehicles pass-by, regarding their clustering and composition. In Section 3, we present an analytical model which fits the mean noise spectra very well, allowing us to make predictions for different car speeds. Finally, in Section 4 we present the conclusions.

2. Statistical analysis of noise spectra

2.1. *Database description*

Considering the well-known features of the noise emitted by moving vehicles, a monitoring campaign was planned in order to obtain detailed information on the moving sources. The monitoring has been performed in three different places, each characterized by different numbers of lanes and the presence of nearby reflective surfaces. The experimental measurements are part of a project (Zambon and Radaelli, 2012) aimed at providing a control system for real time field monitoring of single vehicle emission. The recorded data have been obtained using a 1/3-octave band spectrum, and further analyzed (Peeters and Blokland, 2007), in order to make it in accordance with the accepted standards ISO 362-1 (International Organization for Standardization, 2007) and Regulation No. 51 (GRB Expert Group, 2007). As equipment, a sound level meter providing the acquisition of A-weighted equivalent level, $L_{\text{Aeq,100ms}}$, (for 1/3-octave band analysis in the frequency range 25 Hz to 10 kHz), a speed detector (radar) and a camera were employed. The camera was used for the identification of regular transits in double lane roads which might be influenced by overtaking and to read the vehicle plate number. The latter was used to obtain information on the year of registration, unladen mass, engine size, power and fuel. In all measuring sites the microphone was positioned 5.5 m from the axes of the road and 1.2 m above the road surface. All the measurements were synchronized by means of a photocell. More details on the experimental setup and procedure are given in Zambon and Radaelli (2012). In this work, we consider the original 1/3-octave band spectra recorded during the vehicle pass-by, which contain the whole vehicle information such as speed, fuel, age, etc.

2.2. *Clustering of vehicle spectra*

The database made of 144 vehicles (cars) was used to identify statistically relevant features. Because of the non-homogeneity of the equivalent level (A-weighted) dataset, L_{Aeq}, due to