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# A psychoacoustical study of wind buffeting noise

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ABSTRACT

Aerodynamic noise resulting from a vehicle moving through air at high speeds is one of the most important sources of noise perceived by the passengers. It consists of a stationary broadband signal and of modulated and fluctuating components, particularly emphasized by gusts of wind and turbulences generated by the interaction with nearby vehicles. The article reports on a study of the perception of this latter phenomenon, wind buffeting, potentially deleterious to the sound quality of a vehicle. Binaural recordings of nineteen cars were conducted in a wind tunnel with a specific module designed to simulate mild or severe buffeting. Naive and expert participants first rated the unpleasantness of the recordings played at their real levels. There were large differences of loudness between the sounds resulting mostly from the car designs, and loudness was the main factor contributing to the unpleasantness of the sounds. Participants then rated the unpleasantness of the recordings equalized to the same loudness. In that case, unpleasantness was mostly influenced by the buffeting module and related to fluctuation strength, a psychoacoustical descriptor of perceived loudness modulations. We propose an indicator of the unpleasantness of wind buffeting based on fluctuation strength in several frequency bands as well as other descriptors of the spectral balance of the sounds.



## 1. Introduction

A variety of sources contribute to the sounds emitted by a car: engine and exhaust, contact of tires and road, aerodynamic flow as the vehicle moves through air, vibrations of light elements in the cabin (steering wheel, seats, dashboard, etc.), alarms and warning signals emitted inside and outside the vehicle, air conditioning systems, etc. These different sources contribute to different aspects of the overall sound quality of the vehicle, different components of a person's appraisal of the vehicle based on its sounds. Car noises impinge on three categories of persons: the driver and the passengers inside the car, the other road users outside the car, and the neighboring communities. Accordingly, interior and exterior vehicle noises have different effects and functions. On the one hand, exterior vehicle noise is mainly an issue regarding annoyance to the community [1–3], although sounds are also necessary to signal the presence of the vehicle to road users [4–6]. On the other hand, interior sounds contribute to the comfort or discomfort of the driver and the passengers, the appraisal of the character of the car, and is a source of information for the driver. Many aspects of car interior noise have been studied: the booming sound caused by the excitation of the passenger cavity by the engine noise [7], sounds of closing doors [8,9], light switches [10], starter [11], the roughness of the engine noise [12,13] and the identity of a car [14], the influence of the exhaust system on the identity of the car [15], the sound of anti-lock braking systems [15], the influence of direct and indirect fuel injection on diesel engine noise [16], the influence of various events on the appraisal of long sequences [17,18], etc. (see [19] for a review). For instance, Cerrato noted that road-tire and aerodynamic noises contribute to the pleasantness and comfort of the interior noise [19], and Bodden et al. suggested that high-frequency aerodynamic noise may be used to balance aggressive low-frequency engine noise and increase the "elegance" of interior noise [20].

The study focused on this particular source of interior noise: aerodynamic noise caused by the vehicle moving at high speed through air, isolated from other sources of noises in a car. At speeds above 120 kph, aerodynamic noise becomes the most important source of noise in most vehicles. In France, speed limit is 130 kph on highways, and the average measured speed is 117 kph.[1] Drivers are thus often submitted to loud aerodynamic noises and car manufacturers pay a great deal of attention to the design of

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[1] http://www.securite-routiere.gouv.fr/la-securite-routiere/l-observatoire-national-interministeriel-de-la-securite-routiere/comportement-des-usagers/observation-de-la-circulation, last retrieved on Decembre 12, 2014.

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the hood, the position of the pillars, the shape of the windshield and the side view mirrors to tailor the aerodynamic noise experienced by the driver and the passengers. In modern vehicles, aerodynamic noise consists of a quasi-stationary broadband signal, fluctuations caused by aerodynamic turbulences, irregularities of the air flow, cavity resonances, and aspiration leaks, and low-frequency beating noise caused by open windows, sunroofs, and gusts of winds [21,19]. Aerodynamic noise is often experimentally studied by placing a test vehicle in a wind tunnel, which simulates the motion of the vehicle through steady air. But this fails to capture two other phenomena known to be deleterious to the comfort of the driver in real driving situations: gusts of winds and turbulences generated by perturbations of the air flow resulting from the presence of other vehicles. For instance, Peric et al. showed that orienting the vehicle with different yaw angles in a wind tunnel resulted in turbulences that created audible fluctuations of the aerodynamic noise [22]. Such a fluctuating noise is called "wind buffeting". Wind buffeting contributes to the unpleasantness of the interior car sounds [20]. In particular, for sounds with the same loudness, sounds with fluctuations are rated as more unpleasant than sounds without fluctuations [23]. More generally, fluctuations of broadband noises are perceived as unpleasant in a variety of applications. Diesel engines at idle, for instance, make a typical sound whose slow amplitude modulations are perceived as very unpleasant [24–26]. Heat ventilation and air conditioning systems (HVAC) are another example of broadband signals whose slow modulations are perceived as unpleasant [27]. In a different context, the "swishing" (i.e. abrupt and periodic modulations of amplitude) character of wind turbines contribute to their unpleasantness [28].

Most product sound quality studies use a psychoacoustical framework: quality, preference, or unpleasantness are measured using various methods (questionnaires, magnitude estimations scales, semantic differentials, pair comparisons, multidimensional scalings, etc. see [29] for a review). These judgements are then correlated with psychoacoustic descriptors (or indicators) using linear or multilinear correlations (see [30] for a review). Most of these studies use the psychoacoustical descriptors developed by Zwicker and Fastl [31,32], or develop their own metric. Almost all of these studies find that loudness correlates best with sound quality judgements (listeners prefer quieter sounds). Another common result is that quality judgements are negatively correlated with roughness (rough sounds are generally evaluated as unpleasant, see for instance [13,33]), sharpness or spectral gravity center[2] (listeners tend to find sharp sounds unpleasant e.g. [34]), tone-to-noise ratio and related metrics (prominence ratio, etc.; sounds with prominent tonal components tend to be judged as unpleasant, although some listeners prefer tonal sounds over noisy sounds, and some other listeners prefer the opposite [35]), and fluctuation strength ([24,33,36,27] see below for a discussion).

Regarding wind buffeting, car manufacturers generally evaluate aerodynamic noise with intensity or loudness based indicators (A-weighted sound pressure level, ISO 532B model of loudness [31], etc.). For instance, Otto and Feng showed that annoyance caused by steady aerodynamic noise was very well correlated with the loudness of the sounds [37]. By definition, such indicators are related to stationary features of the sounds, and cannot capture the potential influence of fluctuations. Blommer et al. have developed an indicator for measuring the influence of buffeting and gusting noises based on the loudness of detected impulses in the noise [21]. Such an indicator has two drawbacks: Detecting impulsive events in noise is far from trivial, and the standard loudness model (ISO 532B) is not relevant for short impulsive sounds [31]. Hoshino and Kato used a different strategy: They developed an indicator based on the loudness of the part of the sound coming from the direction of the driver window [38]. They found this indicator well correlated with judgments of the "loudness of the wind noise", but it is uncertain whether this actually captures the influence the fluctuations.

In fact, the perception of modulated tones and broadband noises has been experimentally investigated in psychoacoustical studies (see [39–41] for experimental studies published in English and [42] for a summary). Rapid modulations (greater than 20 Hz) result in sounds perceived as *rough* [43–45]. For slower modulations, listeners perceive fluctuations of loudness. The sensation of fluctuating loudness is called *fluctuation strength*. Fluctuation strength is maximal for modulation frequencies of about 4 Hz, and increases with loudness and modulation depth. Zwicker and Fastl have proposed a unit for fluctuation strength: the vacil [42]. A 1000 Hz tone 100% modulated in amplitude by a 4 Hz sine wave has a fluctuation strength of one vacil. Zwicker and Fastl have also proposed a model to predict fluctuation strength from a signal's properties. It is based on the modulation index of the envelope of the signal, taking into account masking phenomena, and bandpass filtered around 4 Hz. Such a model successfully predicts the perceived fluctuation strength of modulated tones, but is ineffective for broadband noises. By definition, random noises have random fluctuations that Zwicker and Fastl's model inappropriately considers as contributing to the fluctuation strength, whereas these sounds are in fact perceived as stationary. A more complex model was devised by Sontacchi [46], which is in fact a transposition of a similar model developed for the roughness of broadband signals by Aures and Daniel and Weber [44,47–49]. In this model the input signal is first filtered to account for the effect of the middle ear and passed through a set of band-pass filters modeling auditory filtering occurring in the cochlea. A modulation index is computed from the envelope at the output of each auditory channel. The contribution of the modulation indices in each auditory channels are weighted by a coefficient taking into account the correlations between adjacent bands and finally integrated into a single number for each time frame. This latter step is crucial: In a random noise, the envelopes in each auditory channel are uncorrelated and do not contribute to the global fluctuation strength. For a broadband signal modulated in amplitude, each auditory channel is similarly modulated and contributes maximally to the global perception of fluctuation.

The goal of the study was to investigate the perception of wind buffeting noise and design an indicator of the unpleasantness of these sounds. The overarching principle of the study was to have subjects rate the unpleasantness of the aerodynamic noises of different cars recorded in different buffeting conditions, and to relate acoustic features to the unpleasantness judgements using multilinear regressions and bootstrap. We analyzed the aerodynamic sounds by computing a large set of acoustic features, including the features found in studies of product sound quality (loudness, sharpness, roughness, tone-to-noise ratio, etc.). In particular, we included the fluctuation strength calculated according to the method described in the previous paragraph. Multilinear regression and bootstrap then revealed which features contributed significantly to the unpleasantness jugements.

The study used a set of different cars recorded in a wind tunnel, under three conditions: in a steady flow of air, and with a "buffeting" module placed at two positions. The module was designed to simulate buffeting generated by another vehicle running in front of the test vehicle. We conducted an experiment in which participants rated the unpleasantness of a set of sounds. "Pleasantness" describes the hedonic value of auditory sensations and is therefore directly related the sound's properties (on the contrary, for instance, "annoyance" is a broader concept that also

[2] Sharpness describes the sensation associated with spectral balance; Sharp sounds have much energy in high frequency.