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The subjective dimensions of sound quality of standard production electric vehicles ☆

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ABSTRACT

Sound quality for internal combustion engine vehicles is well documented in literature, and the underlying dimensions that govern the sound character have been identified. However, little is known about the dimensions that govern sound quality and character of electric vehicles. Electric vehicle sound signatures are characterized by significant high frequency content caused by the tonal harmonics that are emitted from the electric drive systems. Currently, the quiet sound emissions of electric vehicles at low speeds pose a safety risk to pedestrians and cyclists. Legislation in several countries stipulate that a warning sound should be added to the inherent signature sound of these vehicles to enhance the audio-detectability of these vehicles. Furthermore, consumer perceptions of the interior sound quality point to an unsatisfactory and bland sound character. Could the electric motor sound be modified in such a way that it not only satisfies legislation, but also improves consumer satisfaction? The effects of various sound modifiers are investigated, by means of jury testing, in order to asses the influence on juror satisfaction. The results revealed that enhanced sounds were preferred above standard production electric vehicle sounds. It was concluded that electric vehicle sound quality is complex and the multi-dimensional sound space should be considered as a whole, rather than mere individual subjective semantics.

1. Introduction

The market acceptance of electric vehicles is somewhat determined by the inherent sound quality and the effect of these sound cues on vehicle occupants and the surrounding environment [1]. Literature focusses on three common aspects of electric vehicle (EV) sound. Firstly, electric and hybrid electric vehicles (HEV's) generate minimal sound when driving at low speeds [2]. This leads to very quiet environments in the interior as well as exterior of the vehicle. The low sound emissions are beneficial towards reducing noise pollution levels in cities and creating a quieter city scape. The diminished noise pollution levels are considered to be a great attribute of electric vehicles, especially towards future cities. Secondly, the quiet nature of these vehicles result in some negative aspects with regard to the low noise levels. Literature portrays electric vehicles as being too quiet. Electric vehicles are considered so quiet that they actually pose a safety risk to pedestrians and cyclists [3]. The magnitude for concern is such that legislation and guidelines in US, EU and Japan now suggest that electric vehicles should emit an additional warning sound at low speeds [4–6]. Thirdly, the inherent sound quality of electric vehicles are a subject of interest for consumers. Lennström et al. [7] suggests that electric vehicle sound is bland in character. A study by Cocron et al. [8] investigates the concerns with regard to inadequate acoustic driver feedback experienced whilst driving an electric vehicle. A study by Lennström et al. [9] investigates the high frequency content of electric vehicle sound, and shows that these high frequencies lead to annoyance.

Taking these three aspects into consideration, one is left to ponder about the ways to develop an alternative sound signature or improve current EV sound such that it satisfies safety and consumer requirements. Such a sound would be sufficiently quiet, yet have inherent warning characteristics and be associated with desirable EV sound quality. Could such a sound be created and how would one go about it? A study done by Cocron et al. [8] suggests that a warning sound should signify a change in speed. Thus warning sound concepts should correlate with vehicle speed or motor speed. One possible method could be to use the current

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electric motor noise or develop an artificial sound signature using motor rpm and motor orders. However could these speed dependent sound signatures improve the sound quality? And how would they compare to current production electric vehicle sounds? Do enhanced electric vehicles sounds improve or diminish juror satisfaction? As such it was necessary to investigate the subjective dimensions that govern consumer perceptions of electric vehicle sound satisfaction.

To this end, several commercial EV sound signatures were measured during Wide Open Throttle (WOT) acceleration [10]. The test vehicles of BMW and Renault were selected for the jury evaluation process. One of the vehicle sound signatures was selected as a base stimulus and was adapted in several dimensions to provide enhanced speed related sound concepts. Consumer satisfaction was evaluated through jury testing and the principal components of EV signature sound were determined through statistical analysis.

2. Experimental procedure

The WOT sound signatures of five standard production EV were measured in the motorbay of the vehicle as to obtain the unfiltered electric motor sound. The motorbay refers to the compartment where the electric motor and inverter is situated, either under the hood or in the rear of the vehicle. The Motorbay sound is inherent and authentic to the character of the electric vehicle and its components, which is necessary to avoid a false sound perception [11]. These standard production EV sound signatures were measured and compared in a study by Swart et al. [10] where the full experimental details are provided. A study by Sukowski et al. [12] reported that the highest jury response rate was provoked by acceleration conditions and thus the WOT stimuli were considered. It was found that there was very little variation in the five acoustic stimuli from the respective electric vehicles. As such, only two standard production stimuli, namely the BMW i3 and Renault ZOE, were selected for this study and evaluated against several enhanced sound signatures. The full details of these stimuli are discussed in Section 2.2.

Two subjective evaluation tests were developed in order to evaluate electric vehicle sound signatures and the manipulation thereof. The evaluations were based on the methodologies recommended by Jennings et al. [13]. The first evaluation used forced choice comparison, whereas the second evaluation made use of bipolar semantic differential scales in order to evaluate the sounds. The evaluations were conducted by means of jury testing in a half anechoic chamber at the Technische Hochschule Ingolstadt, Germany.

2.1. Jury

Jury testing was performed on a group of 32 international students. The jury pool was divided into two groups, Group A consisted of 14 members and Group B of 18 members. Group A had no prior exposure to electric vehicle sound, whereas Group B was exposed to a physical electric vehicle pass-by experience before conducting the subjective evaluation. This was done in order to produce a balanced jury which represents the consumer market that typically consists of members that have prior exposure to EV's and members that don't. Furthermore the influence on the subjective responses due to the pre-test pass-by exposure of an electric vehicles was also investigated. Examination of the completed evaluation revealed one juror member with a slight hearing impairment which lead to his exclusion from the analysis, thus bringing the juror pool down to 31 members. The breakdown of the final jury considered for analysis is provided in Table 1 and shows that the pool was male-dominated and biased towards younger individuals.

Table 1
Jury composition.

Jury Attribute	Group A	Group B	Total
Male	12	14	26
Female	2	3	5
Average Age	22	24	23
Max Age	26	33	33
Min Age	20	20	20

2.2. Test stimuli

The BMW i3 (2014) was chosen as the reference sound upon which sound manipulations were performed. As the BMW i3 is an award winning vehicle and a amongst the leaders in the electric vehicle market, it was selected as the baseline stimulus [14,15]. The Renault ZOE (2013) was also chosen from the study by Swart et al. [10], as it has an alternative exterior warning sound at low speeds [16] and thus provides some variation for the jury evaluations. Manipulation methods such as filters, reverberation and pitch modifiers were used to change the baseline sound. The full set of stimuli is presented in Tables 2 and 3.

2.2.1. Stimuli for forced choice comparison

The purpose of this evaluation was to achieve a ranking of stimuli according to juror preference. One reference stimulus and 8 modified stimuli were evaluated. The BMW i3 Motorbay WOT measurement (Sound A) was chosen as the reference stimulus. The influence of frequency content was investigated by adjusting the high (Sound B), middle (Sound C) and low (Sound D) frequency bands of the reference sound. Low motor orders were added (Sound E) to the existing reference sound in an attempt to improve powerfulness of the sound and reduce sharpness as found by Jennings et al. [13] and Fastl and Zwicker [17] respectively. Harmonies were added in an attempt to improve the musical satisfaction of the sound. A major 7th harmony was chosen such that the main motor order of the BMW i3 forms the 7th in the harmony. Reducing the level of the main motor order, in combination with the added harmonic orders, it is perceived as an overtone rather than the fundamental tone. The Major 7th harmony (Sound F) was added in order to increase pleasantness in the reference sound [18]. The high frequency content of the electric motor sound was reduced by a complete pitch modification of the measured stimulus (Sound G). Side bands (Sound H) were added to mimic effects of amplitude modulation and thereby induce roughness and rumbling sensations into the reference sound. These sensations have been linked with enhancing the sportiness and strength of the sound [13]. Reverberation (Sound I) was added in order to provide a fuller sound character and counteract the dullness [19] of EV sound. The reference sound was altered using Audacity software

Table 2
Evaluation 1 modified sound stimuli.

Label	ID	Description
Sound A	Reference Sound (RS)	BMW i3 motorbay WOT measured sound
Sound B	RS-High-Freq-FX	High frequency band diminished
Sound C	RS-Mid-Freq-FX	Mid frequency band amplified
Sound D	RS-Low-Freq-FX	Low frequency band amplified
Sound E	RS-Low Orders	Low orders added
Sound F	RS-HarmEm7	E major 7th harmony added
Sound G	RS-Pitch-FX	Entire pitch transposed down
Sound H	RS-Side-Bands	Side bands added
Sound I	RS-Reverb	Reverberation added