Generating consistent exterior vehicle sound from interior sound

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ABSTRACT

While exterior sound of electric cars is regulated by law, interior sound is not. Apparently, there is a wide range for possibilities for interior sound design. However, an inherently consistent overall sound design requires interior and exterior sound to be related. Naturally in cars with internal combustion engines, there is always a consistent relation between interior and exterior sound. This contribution examines a database of interior and exterior sound recordings of cars with combustion engines in different load states. The relation between the sounds is established by spectral estimation of transfer functions and the dependency on the number of cylinders, fuel, load state, as well as at front and back exterior sound is investigated. The transfer functions are finally modeled as time-invariant filters. A listening experiment studies how detailed the modeling should be in order to generate consistent exterior sound from given interior sounds.

Keywords: Sound Design, Active Sound Generation, Interior Vehicle Sound, Exterior Vehicle Sound
I-INCE Classification of Subjects Number(s): 11.6.4, 13.2.1, 52.3, 63.7, 74.8

1. INTRODUCTION

The low exterior sound level of electric vehicles counteracts the increasing noise level in urban spaces, however it yields potential risks for traffic participants, e.g. pedestrians and cyclists, especially at vehicle speeds below 30 km/h. In order to avoid these risks, several legal regulations are on their way specifying e.g. minimum sound power levels (1) or sound characteristics (2). A lot of research started about how the characteristics of such synthetic sounds should be (3, 4, 5).

Although quiet cars are generally preferred by most drivers, it is important that sound provides them an immediate feedback about the driving situation, e.g. load-dependency (6). Other studies describe the interior sound of cars with electric engines as barely sporty (7). Thus, sportiness in electric cars appears to require Active Sound Generation (ASG). The application of familiar characteristics known from combustion engines to design sounds for electric cars is presented in (8). It allows maintaining the tradition of manufacturer-individual and utilization-fitted sounds using gradually abstractions by different synthesis approaches.

However, a consistent vehicle design requires consistency in all modalities, including a consistent relation between interior and exterior sound design. The acoustic consistency can be achieved by a joint design of interior and exterior sound. Inherent joint acoustical design can be found in cars with combustion engines.

Therefore, we exemplarily investigate the relation of interior and exterior sound of cars with combustion engines to estimate and model transfer functions that can generate consistent exterior vehicle sound from interior sound. The presented filter model allows simple interpolation for different load states or engines speeds while keeping the same filter structure for front and back exterior sound.

This paper is arranged as follows: It describes the analysis of the sound recordings and the modeling of filters that generate exterior sound from interior sound. The subsequent sections evaluate the quality of the filtered sounds in listening experiments where participants have to assign the sounds to categories, such as cars, load states, and recording positions. The paper concludes with suggestions that could decrease the confusion of categories by simple modifications.

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2. FILTER DESIGN

2.1 Analysis of Recordings

Our analysis is based on an AVL database of simultaneous microphone recordings carried out at the driver position (interior sound) and in front of and behind the vehicle (exterior sounds). The position of the front microphone was 1 m away from the hood and the back position was placed 0.5 m from the exhaust pipe (45° tilted in order to avoid aeroacoustic interference), cf. Figure 1 (left). In addition to the microphone recordings, the current engine speed (rpm, revolutions per minute) has also been recorded.

All recordings have been adjusted to the same sampling rate of 16 kHz. In order to achieve ecologically valid representatives of the exterior recordings, both of them have been attenuated to simulate the typical pass-by distance of 7.5 m, assuming free field radiation, see Figure 1 (right). This attenuation also results in similar loudness levels for interior and exterior sounds within each data set.

The analysis of the idle state employed the whole recordings (a section of approx. 15 s), whereas each run-up was subdivided into sections (of approx. 15 s) to cover a range of 1000 rpm. Within these sections, power spectral density was estimated by calculating an 8192-point Welch periodogram. Each resulting transfer function was derived by dividing the respective interior from each exterior periodogram (front/back). To simplify the subsequent modeling, these transfer functions were smoothed by a 100-tap moving average filter.

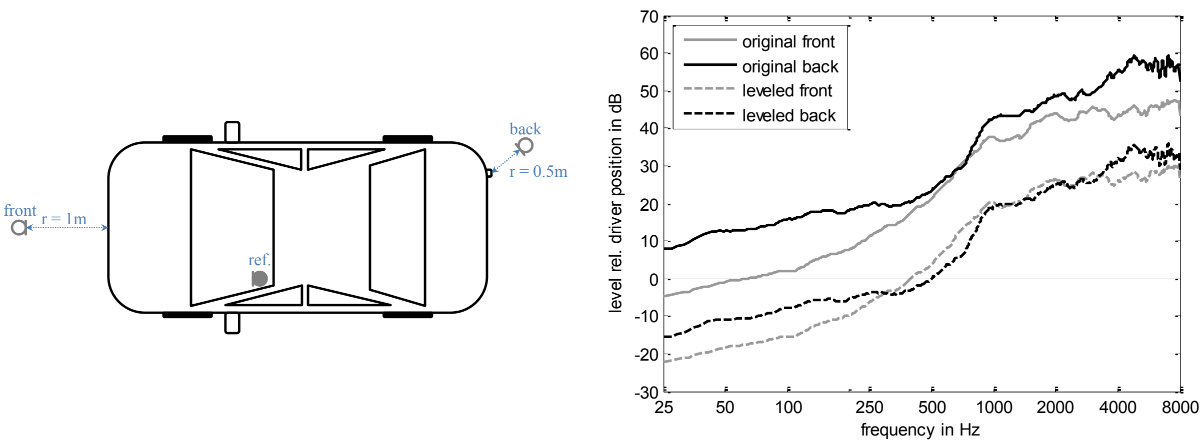

Figure 1 – Simultaneous recording of interior/exterior engine noise; left: recording positions;

right: exemplary original and leveled magnitude spectra of exterior noise relative to driver position.

2.2 Filter Modeling

To provide a suitable modeling of the transfer functions in the final application, a filter design has to meet the following requirements:

- simple parameterization,
- interpolation without artifacts (stable intermediate states),
- efficiency,
- real time capability.

These requirements are fulfilled by Kautz filters (9, 10). The simple structure of second-order sections can be designed to maintain constant poles and keep adjustability while avoiding instable filter states. The design of the second-order sections exhibits a logarithmic placement along the frequency axis.

Figure 2 (left) shows the resulting approximation of modeling an exemplarily target transfer function with different number of Kautz stages. Obviously, 1 or 2 stages are not sufficient to qualitatively match the overall transfer function behavior. However, 4 Kautz stages provide mean modeling errors <1 dB that are sufficiently small to avoid perceivable coloration differences (11), see Figure 2 (right). The maximum error of about 3 dB occurs at low frequencies (below 50 Hz) and is caused by limited coefficient accuracy. This can also be seen in the comparison of the offline Matlab (64 bit) and PD (32 bit) real time implementation. A higher number of Kautz stages cannot solve this numerical issue that is assumed to be perceptually irrelevant in practice.

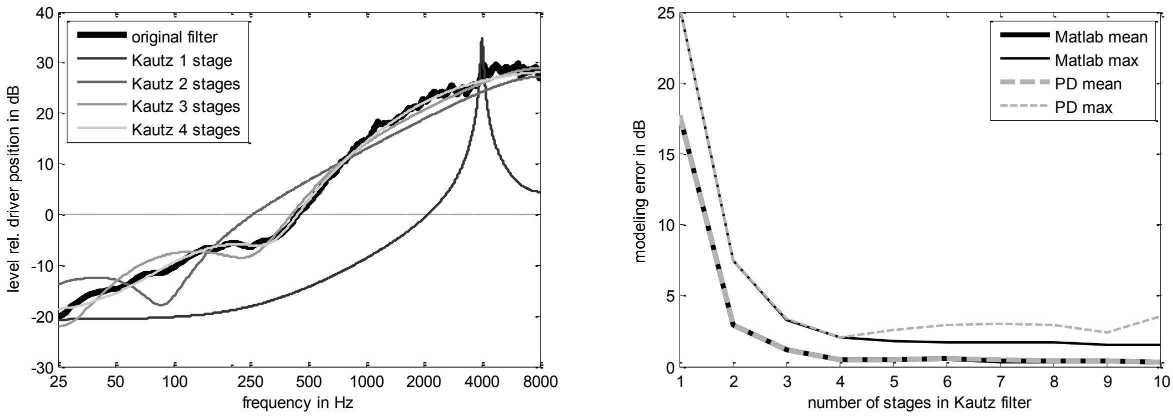

Figure 2 – Modeling of filter using Kautz filters (average 6-cyl. exterior back); left: frequency response of original filter and Kautz filters with different numbers of stages; right: mean/max modeling error for Matlab and PD real time implementation in dependence of number of Kautz stages.

Figure 3 examines the interpolation capabilities between filters for different engine speeds using 4 Kautz stages in the real time application. The left part shows the actual absolute frequency response, whereas the right part exhibits more details by showing relative frequency responses. Along with the original frequency responses for 4 rpm ranges, Figure 3 shows the predictions of the responses for the two middle rpm ranges. These predictions are obtained by interpolating the Kautz coefficients of the filters calculated for the upper and the lower rpm range. The frequency responses of the predicted filters show small deviations from the original responses (< 1 dB) omitting any artifacts, such as severe peaks or notches.

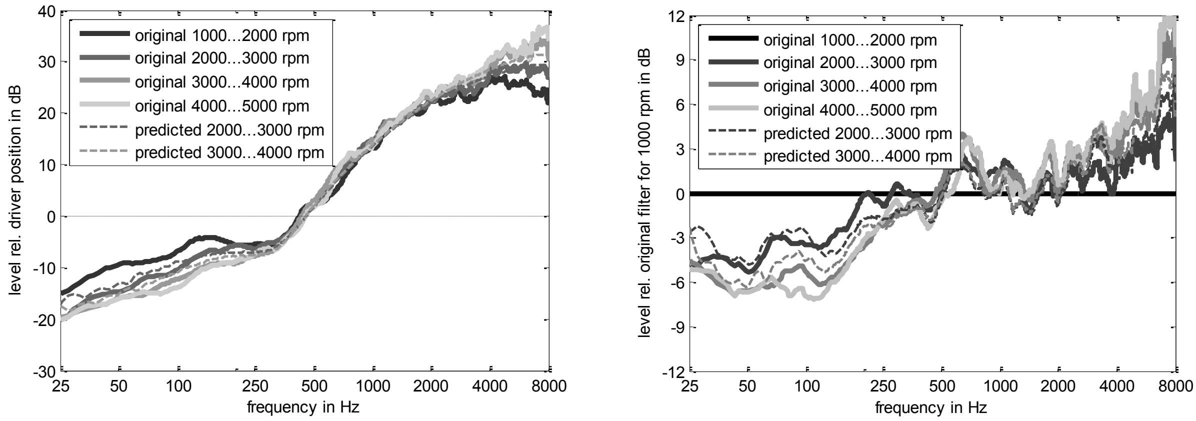

Figure 3 – Prediction of intermediate rpm states; left: filter frequency responses relative to driver position; right: filter frequency responses relative to filter response for 1000…2000 rpm.

3. EXPERIMENTAL EVALUATION

The experimental evaluation compared modeled and original sounds with respect to the hit rate of being assigned to the correct car, position, or load state. The filter models used 4-stage Kautz filters and they were averages for a certain car type, e.g. the 4-cylinder Diesel filter was the average over all 4-cylinder Diesel engines available in the database. All sounds had a duration of 1 s in order to avoid the discrimination of idle and run-up due to pitch changes. For all run-up conditions, the sounds were cut from excerpts where the engines were running at speeds of about 2000 rpm.

3.1 Method and Setup

Each of the two experiments was a two-dimensional assignment/categorization task, e.g. in the first experiment, listeners had to assign each sound to a car (1 out of 3) and its recording position (interior/exterior). Figure 4 presents a screenshot of the employed graphical user interface TCL-LabX (12). Listeners could click on the buttons to play the corresponding sounds and could move the buttons to arrange the sound according to their assignment. The screenshot shows an exemplary assignment of 15 sounds into 3 (cars) x 2 (positions) categories.

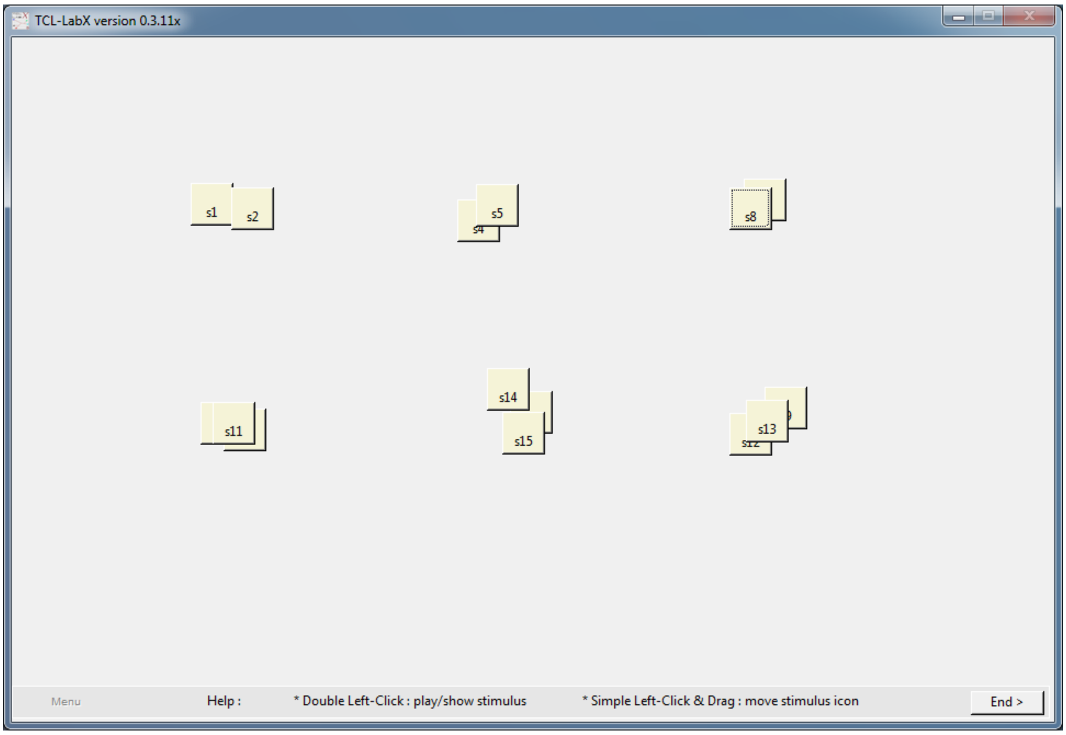

Figure 4 – Graphical user interface used for the listening experiments.

The 17 listeners participated in both listening tests. All of them were part of a trained expert listening panel (13, 14, 15).

3.2 Experiment 1: Different Cars and Interior/Exterior

The first experiment employed 3 (cars) x 2 (positions) = 6 categories. It compared 3 different cars, as well as interior and exterior sounds (back only) of run-ups at full load. The 3 cars were a 4-cylinder Diesel, a 6-cylinder Gasoline, and an 8-cylinder Gasoline engine.

3.2.1 Conditions

In addition to the original sounds and the application of the corresponding filters, i.e. the 4-cylinder filter for the 4-cylinder sound, all other filters had also been included in the experiment, resulting in the 15 sounds. Table 1 itemizes all evaluated sound conditions with respect to the original recording position, the original car, and the applied filter modeled for a certain position and car.

Table 1 – Conditions in Experiment 1

Name	Original position	Original car	Filter for position	Filter for car
4D_interior	interior	4-cyl. Diesel	-	-
4D_back_orig	exterior back	4-cyl. Diesel	-	-
4D_4d_back	interior	4-cyl. Diesel	exterior back	4-cyl. diesel
4D_6g_back	interior	4-cyl. Diesel	exterior back	6-cyl. gasoline
4D_8g_back	interior	4-cyl. Diesel	exterior back	8-cyl. gasoline
6G_interior	interior	6-cyl. Gasoline	-	-
6G_back_orig	exterior back	6-cyl. Gasoline	-	-
6G_4d_back	interior	6-cyl. Gasoline	exterior back	4-cyl. diesel
6G_6g_back	interior	6-cyl. Gasoline	exterior back	6-cyl. gasoline
6G_8g_back	interior	6-cyl. Gasoline	exterior back	8-cyl. gasoline
8G_interior	interior	8-cyl. Gasoline	-	-
8G_back_orig	exterior back	8-cyl. Gasoline	-	-
8G_4d_back	interior	8-cyl. Gasoline	exterior back	4-cyl. diesel
8G_6g_back	interior	8-cyl. Gasoline	exterior back	6-cyl. gasoline
8G_8g_back	interior	8-cyl. Gasoline	exterior back	8-cyl. gasoline

3.2.2 Results

Figure 5 shows the results from the first experiment. The original recordings have been assigned to the correct car with a hit rate of 80%. The modeled versions achieved 82%, whereas the application of the filter models for the other cars slightly reduces the rate to 80%.

The (original) interior recordings had been recognized by all listeners, whereas the original exterior recordings achieved a hit rate of 90%. This rate is reduced to 86% for the modeled exterior sounds with the correct filters and 85% when using the other filters.

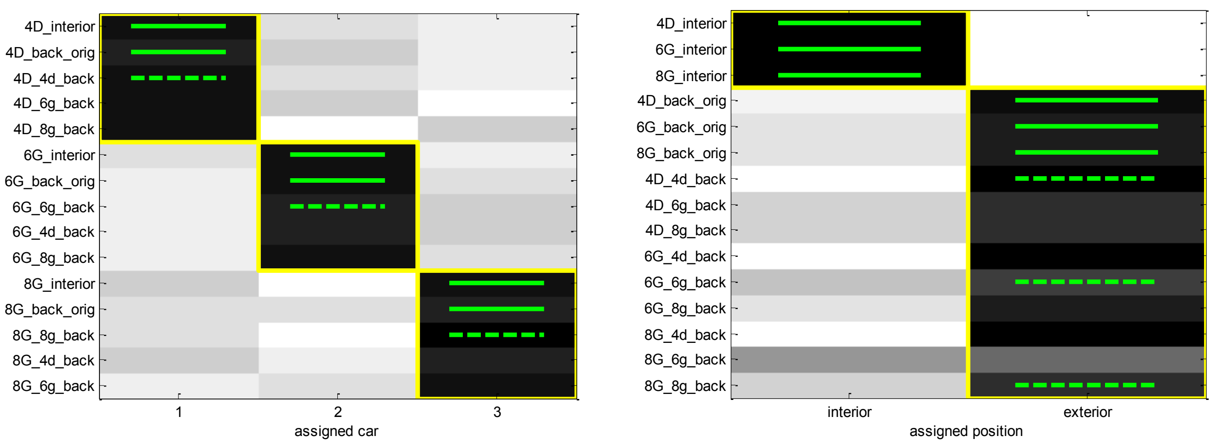

Figure 5 – Assignment to car/position in the first experiment; the darker the elements the more subjects has assigned the sound to this category; solid lines indicate original sounds, dashed lines indicate sounds created by filtering with corresponding filter model; left: assignment of cars; right: assignment of interior/exterior.

3.3 Experiment 2: Different Load States and Interior/Exterior Front/Exterior Back

The second experiment employed 3 (loads) x 3 (positions) = 9 categories. It compared 3 different load states (idle, part load, full load) and interior and exterior sounds. In this experiment, listeners also had to distinguish front and back exterior sounds. The car always was an 8-cylinder Gasoline engine.

3.3.1 Conditions

Again, not only the original recordings and the corresponding filters have been employed but also all other filters, resulting in the 27 sounds shown in Table 2.

Table 2 – Conditions in Experiment 2

Name	Original position	Original load	Filter for position	Filter for load
idle_back_orig	exterior back	idle	-	-
idle_front_orig	exterior front	idle	-	-
idle_int_orig	interior	idle	-	-
idle_idle_back	interior	idle	exterior back	idle
idle_idle_front	interior	idle	exterior front	idle
idle_part_back	interior	idle	exterior back	part
idle_part_front	interior	idle	exterior front	part
idle_full_back	interior	idle	exterior back	full
idle_full_front	interior	idle	exterior front	full
part_back_orig	exterior back	part	-	-
part_front_orig	exterior front	part	-	-
part_int_orig	interior	part	-	-
part_idle_back	interior	part	exterior back	idle
part_idle_front	interior	part	exterior front	idle
part_part_back	interior	part	exterior back	part
part_part_front	interior	part	exterior front	part
part_full_back	interior	part	exterior back	full
part_full_front	interior	part	exterior front	full
full_back_orig	exterior back	full	-	-
full_front_orig	exterior front	full	-	-
full_int_orig	interior	full	-	-
full_idle_back	interior	full	exterior back	idle
full_idle_front	interior	full	exterior front	idle
full_part_back	interior	full	exterior back	part
full_part_front	interior	full	exterior front	part
full_full_back	interior	full	exterior back	full
full_full_front	interior	full	exterior front	full

3.3.2 Results

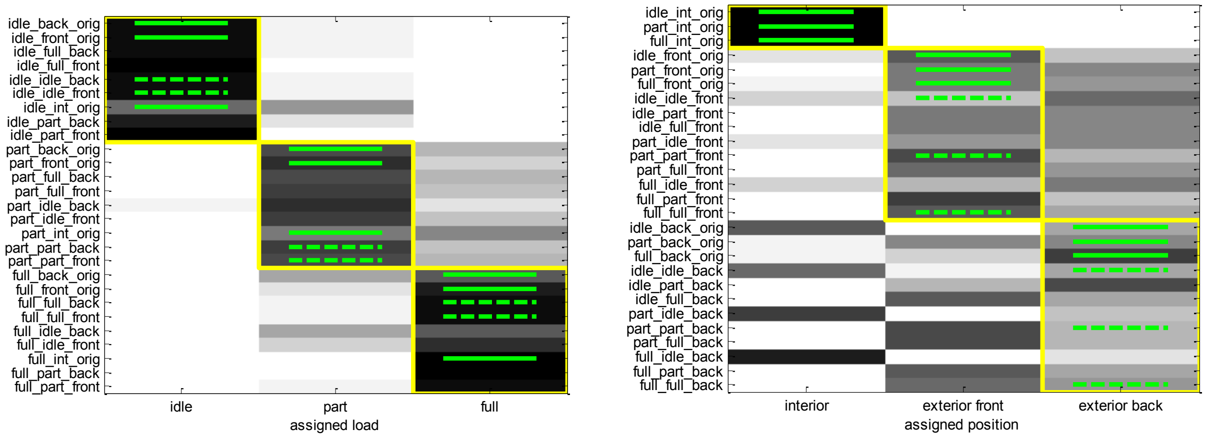

Figure 6 – Assignment to load/position in the second experiment; the darker the elements the more subjects has assigned the sound to this category; solid lines indicate original sounds, dashed lines indicate sounds created by filtering with corresponding filter model; left: assignment of loads; right: assignment of position.

Figure 6 shows the results from the second experiment. The identification of the load state was worst for the original recordings (idle: 82%, part load: 65%, full load: 84%), whereas it was best for the correct models (idle: 94%, part load: 75%, full load: 94%). Application of other models did not change much (idle: 94%, part load 74%, full load: 85%). Interestingly, the original internal idle and part load sounds were wrongly assigned by about half of the listeners.

As in the first experiment, the (original) interior recordings had been recognized by all listeners. The differentiation between front and back exterior sounds was worse. Within these sounds, the assignment of the original sounds worked best (front: 56%, back: 53%), followed by the correct models (front: 53%, back: 35%), and the other models (front: 52%, back: 34%). Summarizing both front and back exterior leads to similar hit rates for the assignment of interior and exterior sounds as in the first experiment (original: 84%, cor. models: 86%, other models: 88%).

3.4 Discussion

The identification of different cars works well for both original and modeled sounds. The hit rate for correct assignment does not decrease much, if the filter models for other cars are applied. Thus, the filter model needs not necessarily be car-specific. Similarly, the differentiation between interior and exterior sounds is possible with a good hit rate for original and modeled sounds. In particular, the interior sounds have been correctly assigned by all listeners in both experiments. However, the identification of front exterior and back exterior sounds, i.e. the discrimination within the group of exterior sounds, is difficult, even for the original recordings. For the modeled sounds, one explanation can be the lack of low-frequency resonances due to smoothing and averaging of the filter responses. The identification of different load states is possible in most cases, while the modeled sounds performed slightly better than the original sounds. For both original and modeled sounds, the assignment of part load conditions shows the highest confusion rate.

Using ASG, the load identification of interior sound could be improved by enhancing high-frequency components. The front/back-confusion of exterior sounds could be reduced by additional low-frequency resonances that simulate typical behavior of exhaust pipes.

4. CONCLUSION

This contribution examined a database of sound recordings of cars with combustion engines to find a plausible filter model that is able to create consistent exterior sound from interior sound. 4-stage Kautz filters provided a well-enough model for averaged filter characteristics and allowed for an artifact-free interpolation, if a time-variant model is desired, e.g. including rpm-dependency. In listening experiments with 17 trained listeners, the modeled sounds have been assigned car, load, and position with a similar hit rate as the corresponding original sound recordings. We finally proposed additional modifications of the filter characteristics that can improve the identification of different load states and confusion of front/back exterior sound, when the filter model is applied to artificial sound for electric vehicles.

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