Dieselness of Car Noises in Different Driving Conditions

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Introduction

Due to the rising demand for high-power engines, although strict emission regulations must be fulfilled, the share of diesel-powered cars is steadily increasing. Since the sound quality of diesel engines has improved over the years, these entered both executive and luxury car segment, where the expectations of sound quality are exceptionally high. The parameters of the engine control unit can significantly influence the engine sound. Doing so, one has to keep in mind that Sound Quality and fuel efficiency are often conflicting objectives.

The typical sound character of diesel engines, the so-called dieselness, has been studied for instance by Bodden et al. (2005), Fastl et al. (2008), Frère et al. (2009) and Patsouras et al. (2002). A dependency of the dieselness on the driving condition of the vehicle is indicated by their results.

In the presented study the dieselness of a car in different driving conditions and with different parameters of the engine control unit is evaluated in psycho-acoustical experiments. In order to analyse the influence of the driving condition on the perceived dieselness, sounds recorded at different engine rotational speeds and engine loads were rated. Among the examined sounds, the driving condition with the most typical diesel engine sound can be determined.

Experiments

Stimuli, Setup and Subjects

Exterior noise measurements of a gasoline-powered vehicle (G) and a diesel-powered vehicle (D) were conducted in a semi-anechoic chamber with an acoustic roller dynamometer. Both vehicles were of the same model and driven by six-cylinder engines differing in the used fuel. For the diesel-powered car, four different parameter sets of the engine control unit were measured. Each vehicle and parameter set was measured in idle condition and with 1500 rpm, 2000 rpm and 3000 rpm engine rotational speed, each with 0 %, 30 % and 50 % engine load. In all figures the engine rotational speeds are identified by symbols, i.e. circles (idle), left-pointing triangles (1500 rpm), diamonds (2000 rpm), right-pointing triangles (3000 rpm) and engine loads are identified by colours, i.e. white (0 %), grey (30 %), black (50 %).

In the experiments 1.5 s of the measurements were played back, with a Gaussian shaping with 50 ms rise and fall time applied to the beginning and end to avoid clicks. The sounds were presented diotically via electrodynamic headphones (Beyerdynamic DT48A), free-field equalized according to Fastl and Zwicker (2007, p. 7) with the original sound pressure level.

All experiments were conducted in a darkened, soundproof booth. The same 15 subjects (3 female, 12 male) with an average age of 25 years in a range from 23 to 28 years participated in all experiments. All subjects had normal hearing and no prior experience in psychoacoustic experiments or the development of engine sounds.

Random Access

Method

Random access, introduced by Fastl (2000), is a method where the subjects have to perform a ranking of the stimuli, in this study, from low to high dieselness. For the ranking procedure a user interface was designed where the subjects have random access to the stimuli i.e. can listen to the sounds in any sequence and as often as they like. The ranking could be changed until the subjects were content. Each subject ranked each sound set three times and, since the subjects had direct access to the sounds, no trial run was necessary. Apart from a general description of the method where the subjects were asked to rank the sounds according to the typical sound of a diesel engine i.e. from low to high dieselness, no further instructions were given.

Results

Three settings of the diesel engine control unit were chosen for the random access experiments and evaluated in separate tests. Ten sounds for one parameter set were ranked, originating from the idle condition and three engine rotational speeds combined with three engine loads. In addition the

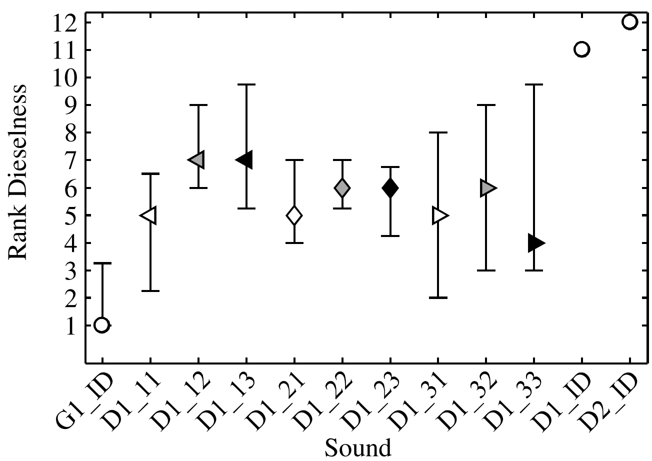

Figure 1: Ranking from low to high dieselness for diesel engine control unit settings 1 (D1) in four driving conditions, idle (circle), 1500 rpm (left-pointing triangle), 2000 rpm (diamond), 3000 rpm (right-pointing triangle) and three different engine loads, 0 % (white), 30 % (grey), 50 % (black). Inter-individual medians and interquartile ranges of the intra-individual medians of the random access ranking.

same two idle noises from the gasoline-powered vehicle (G1) and the diesel-powered vehicle with engine control unit settings 2 (D2) were ranked together with the ten sounds of one parameter set. The results of the random access experiments are shown as inter-individual medians and interquartile ranges of the intra-individual medians of the 15 subjects.

Figure 1 illustrates the results of the random access experiment for diesel engine control unit settings 1 (D1. The diesel engine idle noises (circles) showed the most typical sound character of the diesel sounds and D2 was ranked more typical than D1, both points are established by the lack of interquartile ranges i.e. very good accordance of the subjects. In general the idle noise of the gasoline-powered car (G1) was rated with the least typical sound character of a diesel engine, but the upper interquartile indicates that some subjects ranked G1 higher than some of the diesel engine driving conditions with a less typical sound, especially at 3000 rpm. A tendency towards a grouping of the different rotational speeds of 1500 rpm, 2000 rpm and 3000 rpm can be seen with less typical diesel engine sound for high rotational speeds. In those groups the sound character seems to be less typical when the engine load is low, i.e. 0 %, and more typical when the engine load rises, i.e. 30 % and 50 %, especially for lower rotational speeds with a more typical diesel sound.

The results for D2, shown in Figure 2, comply with the already discussed results of D1. Both idle noises are the extreme values, with the lowest rank for the gasoline-powered vehicle and the highest rank for the diesel-powered vehicle. Tendencies for the different driving conditions that already showed in the ranking of D1, are very distinct in the results of the random access experiment of D2. A clear grouping of rankings for the different rotational speeds can be seen with a high overall dieselness for 1500 rpm, low

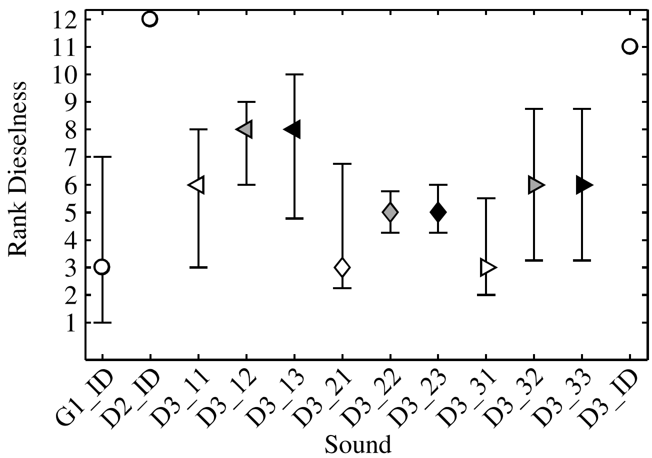

Figure 3: Ranking from low to high dieselness for diesel engine control unit settings 3 (D3) in four driving conditions, idle (circle), 1500 rpm (left-pointing triangle), 2000 rpm (diamond), 3000 rpm (right-pointing triangle) and three different engine loads, 0 % (white), 30 % (grey), 50 % (black). Inter-individual medians and interquartile ranges of the intra-individual medians of the random access ranking.

overall dieselness for 3000 rpm and the 2000 rpm condition in between. For the rotational speeds with a typical diesel sound, the diesel characteristics are more typical with increasing engine load.

Rankings of sounds recorded with engine control unit settings 3 (D3) are shown in Figure 3. The general trends already discussed can be seen, although not as distinct as for D1 and especially D2. A higher rank of G1 and large interquartile ranges clearly indicate that some subjects rated the gasoline-powered vehicle higher than the diesel engine sounds at higher rotational speed with a less typical diesel character.

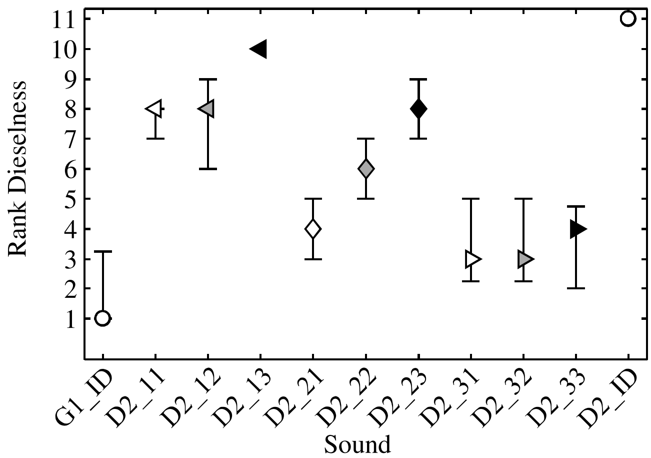

Figure 2: Ranking from low to high dieselness for diesel engine control unit settings 2 (D2) in four driving conditions, idle (circle), 1500 rpm (left-pointing triangle), 2000 rpm (diamond), 3000 rpm (right-pointing triangle) and three different engine loads, 0 % (white), 30 % (grey), 50 % (black). Inter-individual medians and interquartile ranges of the intra-individual medians of the random access ranking.

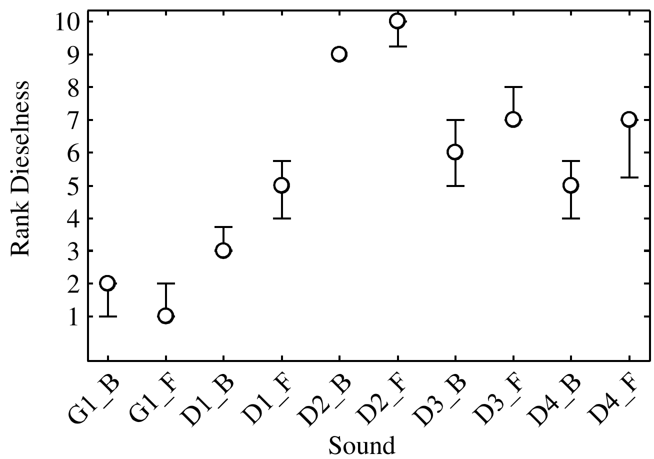

Figure 4: Ranking from low to high dieselness for a gasoline-powered vehicle (G1) and a diesel-powered vehicle with four engine control unit settings (D1-4) in idle (circle) condition at two microphone positions in front (F) of the vehicle and at the B-pillar (B). Inter-individual medians and interquartile ranges of the intra-individual medians of the random access ranking.

In order to investigate the differences between the diesel parameter sets, a random access experiment with noises from the different sets was performed. In addition to the gasoline-powered vehicle G1, the diesel-powered vehicle with different settings D1-3, a fourth engine parameter set D4 was added. All settings were measured at two exterior microphone positions, in front of the car (F) and at the B-pillar (B). The results in Figure 4 show that G1 is always rated least typical for a diesel engine, as expected. D1 is ranked lowest of the diesel vehicle sounds, D2 with the highest ranks, whereas D3 and D4 are ranked in between. The parameter set D2, which had the most distinct influences of the driving condition, also has the most typical diesel engine sound.

Since the ranking results of the random access method do not allow a direct assessment of how much the driving condition influences the diesel engines sound character, a paired comparison test was conducted.

Paired Comparison

Method

In a paired comparison test the subjects listen to a pair of sounds and choose the sound that fits the rated dimension best. If more than two sounds are compared, each sound is compared to each other in a balanced paired comparison test design. Ratios between the rated sounds can be derived by a probabilistic choice model, usually the Bradley-Terry-Luce (BTL) model by Bradley and Terry (1952) and Luce (1959). In this study the implementation of Wickelmaier and Schmid (2004) was used for the statistical analysis. The subjects listened to two vehicle sounds separated by a 200 ms pause and had to choose the sound which had the more typical diesel character. This was done for all sound pairs, each pair could not be repeated by the subject and one of the sounds had to be chosen.

Results

Two of the sound sets from the random access experiment were chosen for the paired comparison experiment, the least typical D1 and the most typical parameter set D2. The results are shown as aggregated choices for all subjects i.e. the number of times a particular sound was selected and as estimates of a BTL model including 95 % confidence intervals.

In Figure 5 the aggregated choices of the paired comparison test for D1 are shown. As already seen in the random access experiment the idle noises mark the extreme values, since G1 was, as expected, rarely chosen and the D1 and D2 idle noises were almost always chosen. The large difference between D1 and D2 becomes also clear, since D2 is always rated to have a more typical diesel sound character.

Finding a Bradley-Terry-Luce model that describes the data can be problematic if some sounds are always chosen over the others. Therefore both diesel idle conditions were excluded from the BTL analysis shown in Figure 6. Also for the least typical diesel engine parameter set D1 a grouping of the three rotational speeds can be seen, with typical diesel sound character for the lower rotational speeds of 1500 rpm and 2000 rpm and less typical diesel sound character at

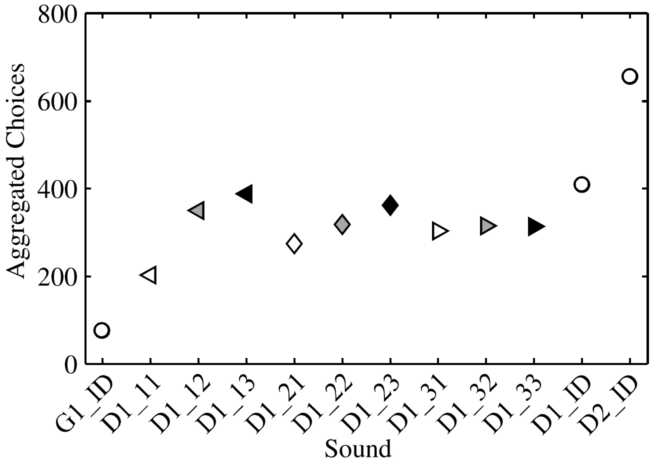

Figure 5: Aggregated choices for all subjects rating the typical diesel sound character in paired comparisons for engine control unit settings 1 (D1) in four driving conditions, idle (circle), 1500 rpm (left-pointing triangle), 2000 rpm (diamond), 3000 rpm (right-pointing triangle) and three different engine loads, 0 % (white), 30 % (grey), 50 % (black).

3000 rpm. For a specific rotational speed the signals sound more like a diesel engine when the engine load is increased, if the sounds at that rotational speed are typical for a diesel engine.

For the second paired comparison experiment the aggregated choices are shown in Figure 7. The previous results are reconfirmed, since the idle condition noises of gasoline- and diesel-powered vehicles are on either end of the scale and the ratings of the different engine rotational speeds and loads follow the already discussed pattern.

In order to calculate a Bradley-Terry-Luce model that fits the data from the second paired comparison experiment, again the diesel idle condition that is always chosen over the sounds has to be left out of the analysis. As expected from

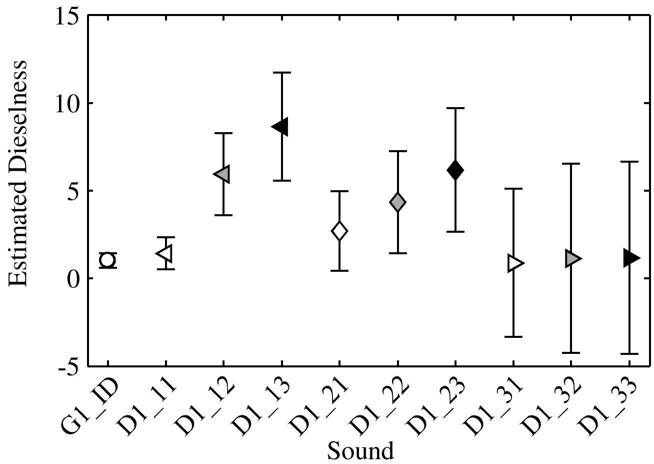

Figure 6: Dieselness estimates by the Bradley-Terry-Luce model with approximate 95 % confidence intervals ($\chi2(35) = 35.17$, $p = 0.634$) for engine control unit settings 1 (D1) in four driving conditions, idle (circle), 1500 rpm (left-pointing triangle), 2000 rpm (diamond), 3000 rpm (right-pointing triangle) and three different engine loads, 0 % (white), 30 % (grey), 50 % (black).

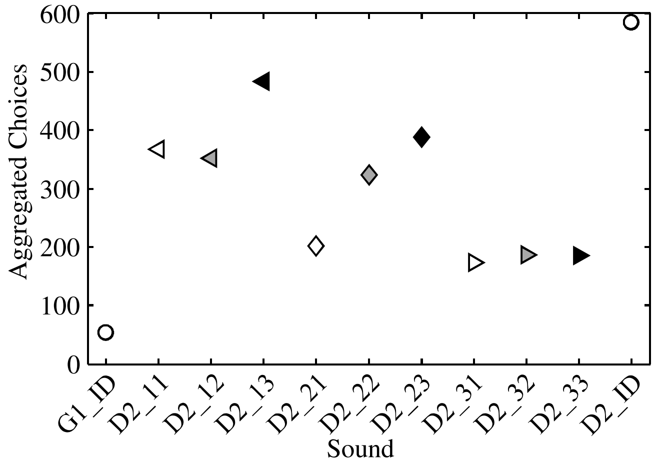

Figure 7: Aggregated choices for all subjects rating the typical diesel sound character in paired comparisons for engine control unit settings 2 (D2) in four driving conditions, idle (circle), 1500 rpm (left-pointing triangle), 2000 rpm (diamond), 3000 rpm (right-pointing triangle) and three different engine loads, 0 % (white), 30 % (grey), 50 % (black).

the random access experiment, in which the different diesel parameter sets were compared, the estimated dieselness values for D2, shown in Figure 8, are in general higher than the values for D1. Of the three different rotational speeds 1500 rpm has the most typical sound character for a diesel engine followed by 2000 rpm and with 3000 rpm engine rotational speed the sound is less typical for a diesel engine. If the sounds at a certain rotational speed have the typical characteristics of a diesel engine, an increase in the engine load leads to an increase in the dieselness. With an engine rotational speed of 1500 rpm and an engine load of 50 % the sound is very typical for a diesel engine, indicating a special speed and load condition which can lead to a very characteristic diesel sound.

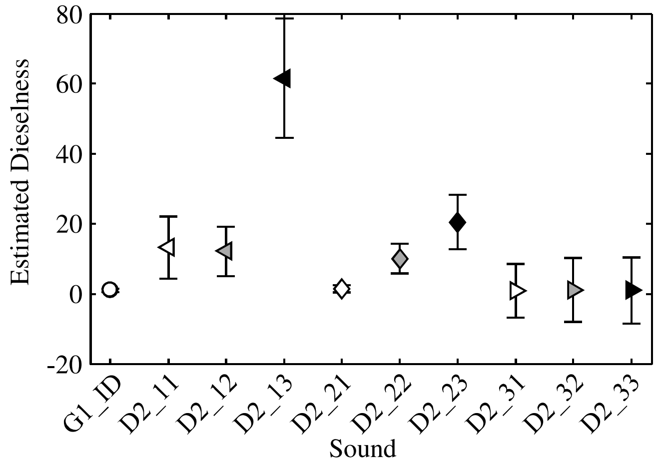

Figure 8: Dieselness estimates by the Bradley-Terry-Luce model with approximate 95 % confidence intervals ($\chi2(33) = 36.87$, $p = 0.706$) for engine control unit settings 2 (D2) in four driving conditions, idle (circle), 1500 rpm (left-pointing triangle), 2000 rpm (diamond), 3000 rpm (right-pointing triangle) and three different engine loads, 0 % (white), 30 % (grey), 50 % (black).

Conclusion

The experiments with the random access method and the paired comparison method showed large influences of the driving condition on the typical sound character of a diesel-powered vehicle.

In all experiments with different diesel parameter sets the most typical sound of the diesel-powered vehicle was recorded when the vehicle was in idle condition.

From the three different engine rotational speeds that were investigated, 1500 rpm was rated very typical for a diesel engine, 2000 rpm slightly less typical and 3000 rpm not very typical for a diesel engine. This leads to the conclusion that with an increase in engine rotational speed the engine sounds less like a diesel engine.

In case vehicle sounds had the typical characteristics of a diesel engine, these increased if the engine load was varied from 0 % to 30 % and 50 %. Specific combinations of engine rotational speed and engine load can lead to a highly characteristic diesel engine sound for the current engine. Still, an increase in engine load tends to result in an increase in dieselness.

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