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Noise Emission of Electric Street Sweepers – Perceptual Evaluation of their Sound

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Summary

In the last few years there has been an increasing market adoption of electric vehicles. Advantages are a reduced environmental impact concerning consumption of nonrenewable energy sources but also concerning CO_2, dust and noise emissions. Reduced noise emissions are especially promising for street cleaning in urban settings where residents or pedestrians are frequently exposed to noise of cleaning vehicles. In the course of the German research program "Schaufenster Elektromobilität" electric street sweepers were analyzed concerning their noise emissions. Conventional diesel-powered and electric street sweepers in different operating modes were recorded in a typical environment. The annoyance of the recorded sounds was evaluated in a listening test. Subsequently the influence of different noise components on the annoyance was analyzed and dominant factors were determined. In these type of vehicles, the contribution of the functional equipment to the overall noise is much higher than the contribution of the drive system. To utilize the advantage of low sound emission of electromobility the noise emissions of the functional equipment should be reduced. Thus city cleaning vehicles wouldn't pollute urban soundscapes.

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1. Introduction

In the last decade an increasing market adoption of electric vehicles could be observed. Advantages are a reduced environmental impact concerning consumption of nonrenewable energy sources but also concerning CO_2, dust and noise emissions. Besides passenger cars, utility vehicles such as street sweepers could also benefit from these advantages.
Street sweepers operate in urban environments where they manage the fast accumulation of debris is common. Pedestrians as well as residents are frequently and involuntarily exposed to the noise emissions of street sweepers. Low noise emissions are promising because the annoyance of pedestrians and residents could be minimized. Electrical street sweepers offer potentially lower overall noise emissions due to the silent power unit. Besides power unit sounds, street sweepers emit functional sounds originating from brooms and fans and other aggregates. Compared to the power unit sounds, these sounds dominate the auditory perceived annoyance because of their signal properties like tonality or sharpness but also loudness. Thus a change to an electrical power unit might not results in a significant improvement of street sweeper sounds. To make full use of the advantage of low sound emission of electro mobility the noise emissions of the functional equipment should be optimized.
The goal of this study was to analyze the auditory perceived annoyance especially concerning the contribution of each functional sound source to the overall annoyance of a compact street sweeper. At first a free interview was conducted in a typical setting. Based on the results of the interview sounds were recorded. In a listening test subjects rated the annoyance of the stimuli. The results help to deduce promising goals for the optimization of the noise emissions of the functional aggregates.

2. Sound Recordings

Before the measurement was executed existing guidelines for street sweepers were examined. The directive 2000/14/EC for noise emission by equipment used outdoors includes a measurement instruction for the power level measurement using the enveloping surface method for street sweepers. However these instructions exclude the emissions

of the brooms since they should not touch the ground during measurement. In order to conduct perceptually representative recordings a reasonable measurement setup had to be devised.
The typical environment for compact sweepers are pedestrian areas, as big sweeping trucks are not maneuverable enough. As observed during the free interview, pedestrians typically avoid proximity to the street sweeper especially the lane in which the sweeper is moving. Thus pedestrians are typically in a lateral position in relation to the street sweeper. The reasonable maximum distance is often limited by the width of the pedestrian area and noise emissions of other sound sources which start to mask the sweeper sounds with increasing distance from the sweeper. Thus a distance of 4m from the moving lane of the sweeper to the recording position was defined for recording which represents the typical position of a pedestrian in relation to the sweeper. The resulting measurement setup is displayed in Figure 2.

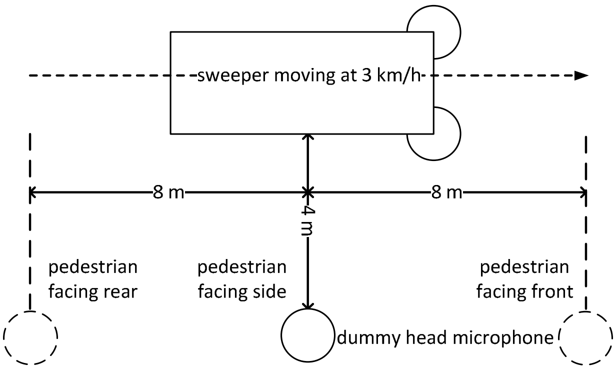

Figure 2. Measurement Setup: 3 different typical pedestrian positions were used for the recordings

Since the functional aggregates could be used independently from movement recordings were conducted of the standing and the moving (at 3 km/h) street sweeper. Three different measurement positions in relation to the sweeper were used to account for the directivity of the different functional aggregates. A dummy head microphone was used for the recordings.
Several scenarios were recorded with this measurement setup. One parameter for the recording was the type of the power unit. Recordings of an electrical sweeper (*Tennant 500ze*) and a conventional sweeper (*Bucher CityCat 2020*) were conducted. All functional aggregates were operated in one or multiple typical conditions. In preparation for the annoyance analysis some aggregates were switched off during some recordings. All relevant sound sources of the electrical sweeper which were analyzed in detail are displayed in Figure 1, see [1] for detailed explanation.
The brooms (1) was operated at full speed as during regular operation. The intake flap (2) at the suction mouth was operated in vibrating state as

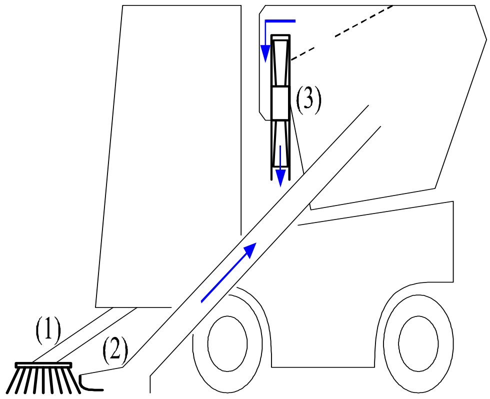

Figure 1. Schematic representation of the street sweeper with all dominant sound sources

suggested by the manufacturer. The suction fan was operated at normal (2400 rpm) and maximum (2800 rpm) speed.
In addition to the street sweeper sounds some passing truck sounds were recorded with a similar setup. These sounds are somewhat similar to the sweeper sounds and are amongst the loudest sounds perceived in urban context. The annoyance ratings for these familiar sounds allowed an easier interpretation of the annoyance ratings of the sweepers.

3. Listening Tests

3.1. Annoyance of electrical sweeper vs. conventional sweeper

3.1.1. Stimuli

In the first step of the annoyance analysis the influence of the power unit was determined. Since the power unit of the electrical street sweeper (*Tennant 500ze*) could not be swapped with a combustion power unit a similar diesel-powered street sweeper (*Bucher CityCat 2020*) was selected. Both sweepers use very similar functional aggregates and are used for the same range of applications. For the easier interpretation of the annoyance ratings a familiar passing truck sound was also selected for the experiment. The sound pressure level of all stimuli was in the Range of 72 dB(A) to 81 dB(A). From each pass-by recording a segment with a duration of 3 s was chosen. Three positions of the sweeper in relation to the recording position were selected, as shown in Figure 2. Two suction fan speeds were selected.

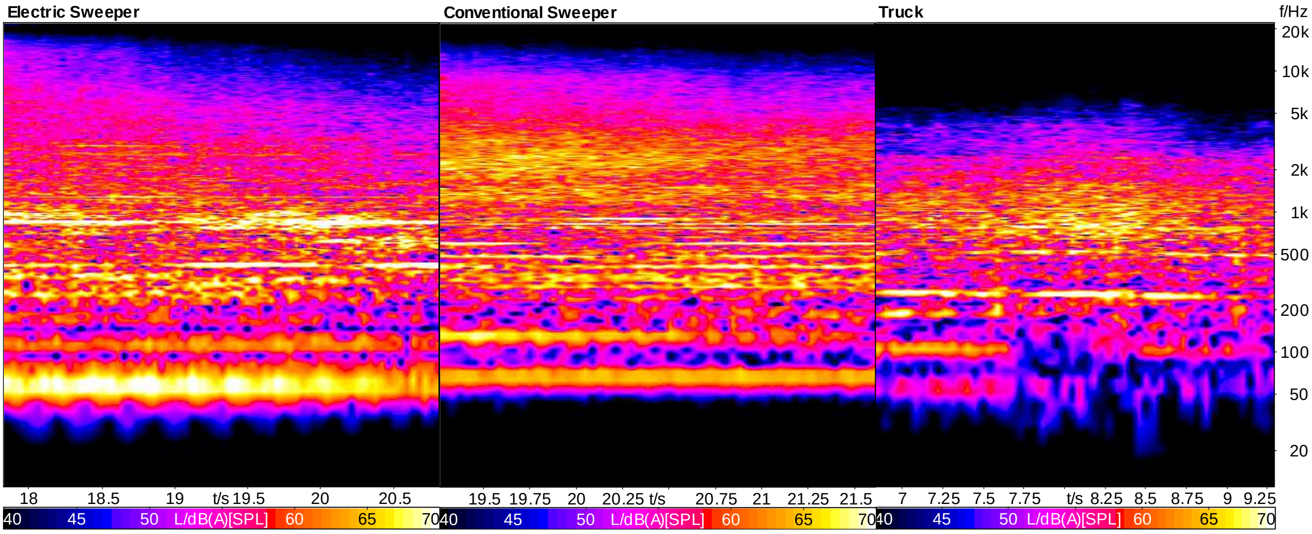

Figure 3. Typical spectra vs. time of each vehicle

3.1.2. Experimental Setup

In the listening test subjects rated the annoyance of each stimulus twice. Stimuli were presented randomly with calibrated headphones. Test subjects rated annoyance on a verbal Rohrman-Scale [2] which was implemented as a slider on a MATLAB graphical user interface, see Figure 5. Before the experiment, the test subjects were given a short introduction for contextuation and were familiarized with the stimuli in a short training. The duration of the experiment for the 32 stimuli was approximately 10 minutes.

3.1.3. Results

All Stimuli were rated by 29 test subjects (18 male, 11 female) with an average age of 32 years. The sweepers were rated as moderately to very annoying whereas the truck stimuli were rated as slightly to moderately annoying. Thus the sweeper noise is more annoying than one of the loudest everyday traffic sounds. The standard deviation was about 16 % of the rating scale. The intraindividual consistence of the rating was on average 10 % of the scale. For each scenario the annoyance ratings of the two types of sweepers were similar. That is why all the annoyance ratings were averaged for each sweeper. The comparison of the sweeper annoyance ratings is displayed in Figure 4.

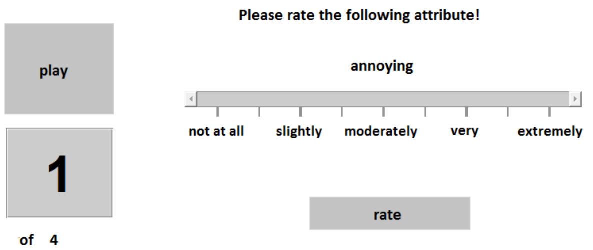

Figure 5. User interface for the experiment

3.2. Contribution of functional aggregates to annoyance

3.2.1. Stimuli

Since the power unit of the sweeper didn't contribute significantly to the annoyance rating, the influence of the sounds emitted by the dominant functional aggregates had to be determined. By modifying the signal part correlating with the sound of the each functional aggregate an optimization of that aggregate can be simulated. In preparation for this experiment additional listening tests were conducted, to rule out the influence of movement of the sweeper and the directivity of the sweeper on the annoyance rating. The movement of the sweeper resulted in transient signals which would have complicated the investigation of the influence of the modification of signal parts on the overall annoyance rating. Since all functional aggregates could be operated in standstill, such recordings were used.

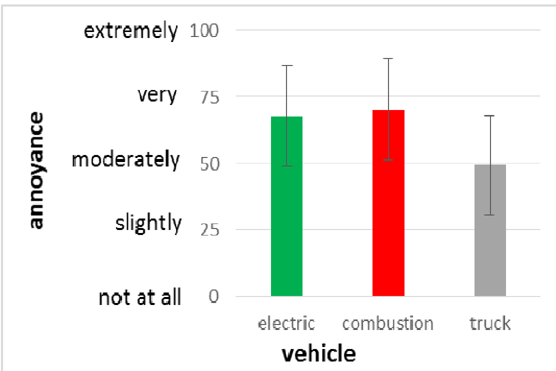

Figure 4. Averaged annoyance ratings over all scenarios for each vehicle

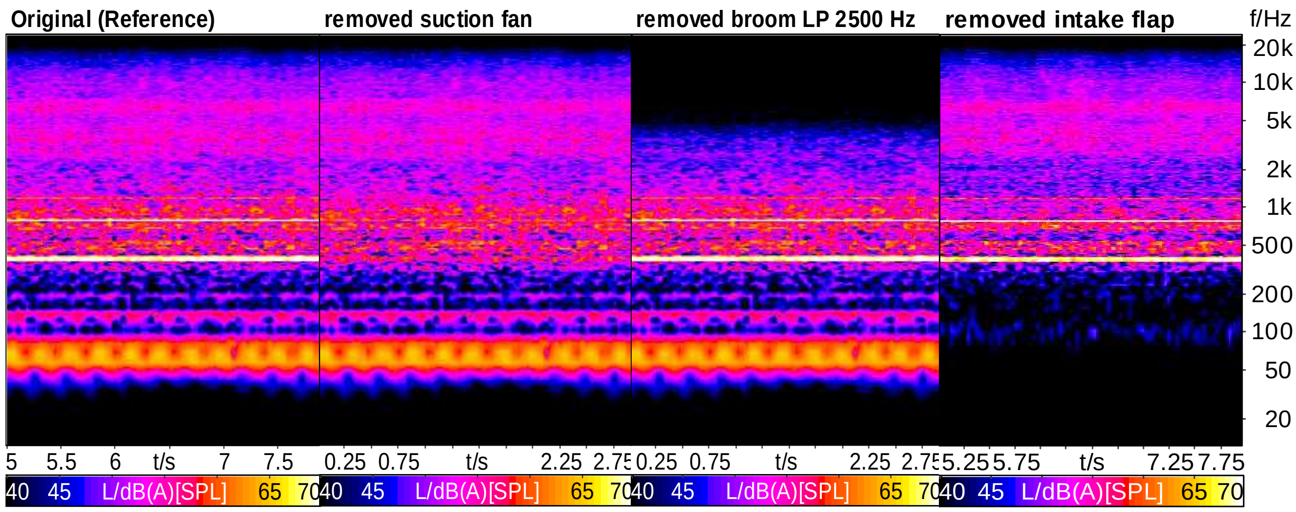

Figure 6. Spectra vs. time of the original and the modified stimuli. For each aggregate the maximum optimization is shown.

The functional aggregates of the sweeper don't have omnidirectional characteristics which might influence the annoyance ratings. However, since the pedestrian position is mostly limited to the lateral position in relation to the sweeper, the directivity only had a minor influence on the annoyance change due the modification of signal parts correlating with each aggregate. One pedestrian position (pedestrian facing front/side, see Figure 2) was chosen as a scenario that represents the average case. The suction fan was operated at two speed levels since both scenarios are typical in everyday use.

For both scenarios signal parts correlating with each dominant functional aggregate (see Figure 1) were modified. The brooms emit a broadband high frequency noise which was filtered with low pass filters with varying cut-off frequency to simulate the noise emissions of different bristle types. An optimization of the intake flap was simulated in two ways. On the one hand the intake flap of the suction mouth was fixed in an open position during recording. On the other hand the dominant low frequent components which are perceived as booming [3] were filtered with a high pass filter with a cut-off frequency of 250 Hz. For the suction fan the base frequency (400 Hz for normal speed and 467 Hz for full speed) and the base frequency as well as the harmonics which are caused by the fan were removed. The resulting stimuli are displayed in Figure 6. In addition to the signal modification for each functional aggregate these modifications were combined to simulate the potential improvement of two at a time or all three modifications.

3.2.2. Experimental Setup

In the listening test subjects rated the annoyance of each stimulus. Stimuli were presented randomly with calibrated headphones. For the rating of the stimuli the individual test method as proposed in [4] was used which allows absolute evaluation even for weak stimuli differences. Test subjects could listen to the sounds as often as needed by clicking on the graphical representation of the stimulus on a MATLAB graphical user interface, see Figure 7. For the rating of the annoyance the test subjects could move these representations along the verbal Rohrman-Scale [2]. Before the start of the experiment test subjects were given a short introduction for contextuation. The experiment's duration for the 32 stimuli was approximately 15 minutes.

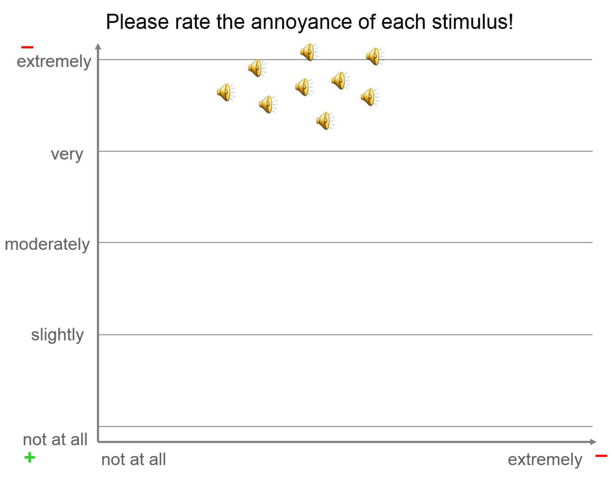

Figure 7 : User interface for the experiment

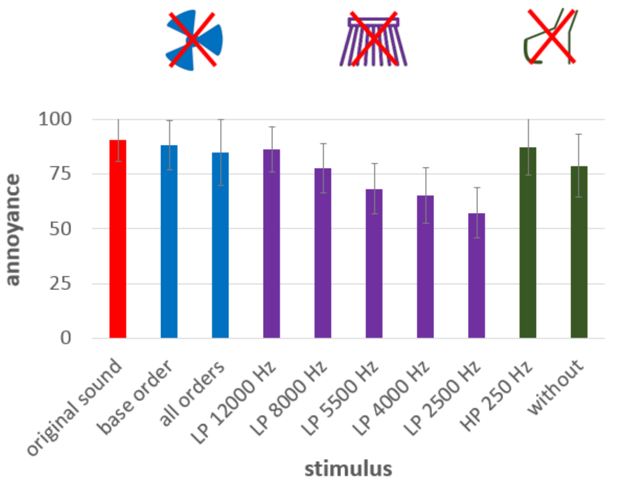

Figure 8: Influence of one modification of the signal parts correlating with one functional aggregate on the pereceived annoyance of the sweeper sound

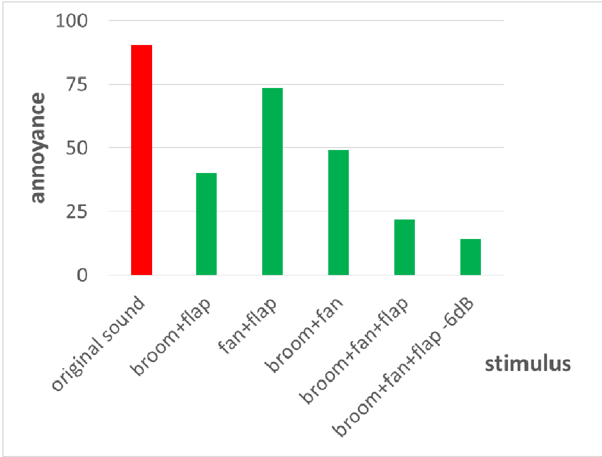

Figure 9: Influence of the combination of multiple modifications on the perceived annoyance of the sweeper sound

4. Results

All stimuli were rated by 20 test subjects (11 male, 9 female) with an average age of 28 years. In Figure 8 the results for each single aggregate modification are presented.

The removal of the signal parts emitted by the brooms has the biggest influence on the auditory perceived annoyance. Test subjects rated the optimized sound about 25 % lower on the annoyance scale. The reason for this can be seen in dominant contribution to the sharpness of the sweeper sound. The removal of the signal parts emitted by the intake suction flap resulted in smaller reduction of the annoyance. A large contributing factor are the booming signal parts, which are known to be annoying sounds [3]. The removal of the tonal components of the suction fan surprisingly resulted in no significant reduction of annoyance, although tonality can be a contributing factor to annoyance.

The results for the combination of two or more sound modifications is displayed in Figure 9. For each aggregate the modification which resulted in the biggest reduction of the annoyance was chosen. The annoyance reduction of the combination of two modifications can be predicted by the addition of the annoyance reductions of these two single modifications. However, if the brooms and the flap have been optimized, the additional optimization of the suction fan would result in an additional annoyance reduction of 25 % on the rating scale. Thus, only if the dominant sources of annoyance have been optimized a modification of other sources as the suction fan will likely have a significant effect.

5. Conclusions

It has been demonstrated that the electrification of the power unit does not significantly reduce the perceived auditory annoyance of a compact street sweeper. The dominant factors are the functional aggregates broom, intake flap and the suction fan. By optimizing these aggregates the auditory perceived annoyance could be reduced greatly. The reduction of noise emission would help to gain acceptance for electro mobility amongst pedestrians and residents and has the potential to open up new application scenarios, e.g. night time sweeping.

Acknowledgement

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