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Noise Emission of Electric Street Sweepers – Transfer Path Analysis

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Summary
The sound emission of vehicles is mostly discussed regarding user expectations and quality perception. In the context of municipal utility vehicles the aims are different. The noise emission of street sweeper vehicles and other municipal utility vehicles are a constant source of annoyance in public urban areas, both to pedestrians and residents, who are involuntarily exposed to this noise. The increasing adoption of electrically powered vehicles is a chance to reduce these disturbances. Unfortunately, solely replacing the power unit is not sufficient. Measurements and perception experiments within EBALD research project have shown that the noise of functional equipment is an essential factor regarding noise emission. The correlation between the annoyance ratings and the signal components showed that the sweeping unit (suction fan), the suction intake and the circular brooms are the primary sources of annoyance. These sources and their transmission paths have to be modified to reduce the annoyance of the perceived sound to increase the acceptance by both pedestrians and residents.

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1. Introduction

1.1. Background

The sound emission of vehicles is mostly discussed regarding user expectations and quality perception. In the context of municipal utility vehicles the aims are different. The noise emission of municipal utility vehicles like street sweeper vehicles are a constant source of annoyance in public urban areas, both to pedestrians and local residents, who are involuntarily exposed to this noise.

Besides the sustainability objectives – protection of resources and the environment – the increasing adoption of electrically powered vehicles could reduce these noise disturbances. The reduction of noise emissions might also open new fields of application for street sweepers, like night-time sweeping in inner cities or residential areas.

1.2. Electrification

Sweeper machines come in different sizes and performance classes for different fields of application: big *street sweeping trucks* for urban and trunk road cleaning, *compact sweepers* for minor roads and pedestrian areas, and small *floor sweepers* for industrial and indoor cleaning.

For smaller floor cleaning machines electric power units are already common, as they have only low battery requirements due to their low weight and performance. Indoor use demands zero emission and short operating distances make charging easy. Big street sweeping trucks have high weight and high performance functional units. This circumstances lead to high requirements for energy supply and batteries, what makes electrification uneconomic at the current state of technology.

Medium scaled compact sweepers with 0,5 ... 4 m³ hopper volume are widely used for urban sweeping. Their mid-range size and performance parameters make them ideal for electrification and first electrically powered models have been introduced to the market.

Conventional compact sweepers have a diesel-hydraulic system – they are diesel-powered, but use hydraulic drives for the functional equipment. Simple electrification concepts keep the hydraulic system but replace the diesel drive by an electric system, whereas other vehicles use a fully electrified concept. Even though the electrification of some functional components (e.g. linear drives) is technically demanding, full electrification may have additional benefits concerning energy efficiency as further energy conversion steps would be avoided.

In the course of the EBALD research project a *Tennant "Green Machines" 500ze* electric compact sweeper was analyzed and tested both in all-day cleaning service and under controlled repeatable conditions. The 500ze uses an electric power drive and hydraulic functional equipment.

1.3. Noise Characteristics

First field tests with an electrified compact sweeper have shown no effect on the reduction of noise. Unfortunately, replacing the power unit is not sufficient. Measurements and perception experiments in the course of the EBALD research project proved that the noise of functional equipment (brooms, suction fan, etc.) is an essential factor regarding the sweeper's noise emission [1].

2. Main Sound Sources

2.1. Operational Modes

In general, there a two different operational modes for (electrified) compact sweepers, that show dramatically different acoustic behaviour.
In *transit mode* the sweeper drives from the depot to the site of operation or from one site to another. Only the electric power train and necessary auxiliary equipment is working, but no functional equipment is in use. In this situation the sweeper behaves like a normal (slow) electric vehicle. The acoustic impression is inconspicuous, what can even be critical for pedestrian safety.
In *sweeping mode* the compact sweeper drives at walking pace and the functional equipment for cleaning (brooms, suction fan etc.) is in use. Perception experiments [1] have shown that the noise of this functional equipment plays a fundamental role on the overall noise emissions and which is the main reason for the high auditory perceived annoyance.

2.2. Operating Principle of Sweeping Mode

Figure 1 shows the basic construction of the Tennant 500ze electric compact sweeper. Although the arrangement of the components and detailed design may be different, the general structure can be compared to most compact sweepers of other manufacturers.
Compact street sweepers use rotational disc brooms (1) to loose dirt and transport it to the suction mouth (2) below the vehicle in the middle of the lane. Loose dirt can also be bound with water to prevent dust. Debris is transported from the suction mouth into the hopper (4) via the suction tube (3) by a partial vacuum, that is generated by the suction fan (radial ventilator, 6) behind the hopper. Due to the reduction of the flow velocity and mechanical filters (5) inside the hopper, debris and waste is contained and clean process air is blown off.

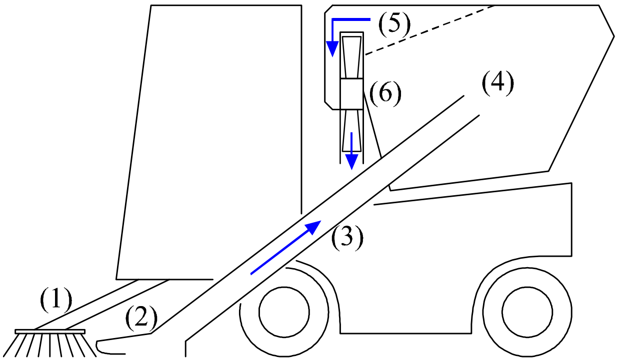

Figure 1. Schematic diagram of the 500ze compact sweeper showing the sweeping equipment.

2.3. Potential Sound Sources

In general the following sound sources can be found at the sweeper, that had to be investigated:

- drive train
- tyre noise
- suction fan
- intake
- sweeping brooms
- debris hopper
- cooler fans
- hydraulics

In transit mode the compact sweeper reaches a maximum speed of 25 km/h. In sweeping mode the sweeper drives at 3...5 km/h. Neither the electric drive train nor the tyre noise play an important role at low speeds. When the functional equipment is in use, they are masked entirely, because of their low sound level.

2.4. Suction Fan

A radial ventilator with scroll housing generates the partial vacuum inside the debris hopper that acts as the power source of the sweeping process. At the Tennant sweeper the exhaust air is directly blown off from the housing without any acoustic damping.
The emitted sound is a broadband noise, dominated by high frequency tonal components. Their frequencies depend on the rotational frequency of the ventilator. For the standard power setting (2400 rpm) the tonal main frequencies are 400 Hz, 800 Hz, 1200 Hz etc. These are the blade pass frequency of the radial ventilator (base frequency) and its multiple harmonics.

The 500ze uses a 10 blade rotor with straight blades. For the standard power level (2400 rpm) this leads to a 400 Hz base frequency; and for the maximum power level (2800 rpm) to 467 Hz.

$$f_0 = n_{\text{blades}} \cdot f_{\text{rot}} \quad (1)$$

The tonal fan sound is caused by the interaction between the fan blades and the housing (especially the fan tongue) [2]. An effective reduction of the fans noise emission requires a redesign of the ventilator rotor and scroll housing, regarding the acoustic and aerodynamic optimization at the operating point. A rotor with backward curved blades and a optimized scroll housing could lead to an improved efficiency and reduced noise [2]. A flow optimization of the whole suction path could reduce pressure loss and raise the efficiency [3].

2.5. Intake

The suction mouth below the vehicle is the intake of the sweeping system. A constant flow with a sufficient velocity lifts and transports the debris to the hopper. It is closed by a blanket at the side and back and has a 40 cm wide mouth to the front. In order to enable larger garbage to pass through, it is covered with a flexible rubber flap, that forms a approximately 1 cm high slit.

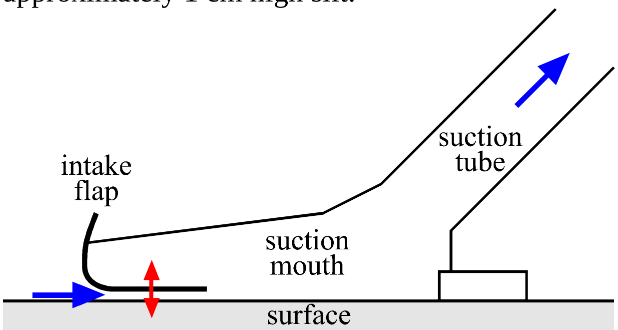

Figure 2. Cross section of the intake

During use this intake flap begins to vibrate at a 20 Hz frequency (see figure 3). The appearance and intensity of the vibration depends on the suction power (rotational frequency of the ventilator), the street surface (flat asphalt or uneven cobblestone) and the intake's geometry (adjustment of the flap, wear of the blanket).
The flap gets into vibration as it is cyclical lifted by the partial vacuum. This vacuum is reduced due to the higher flow and the flap falls down. The impact of the flap generates the transient sound.
The impulsive sound of the intake flap is perceived as very annoying and was often compared with helicopter sounds in interviews [1].
This very noisy vibration of the flap has to be prevented without reducing the sweeping quality.

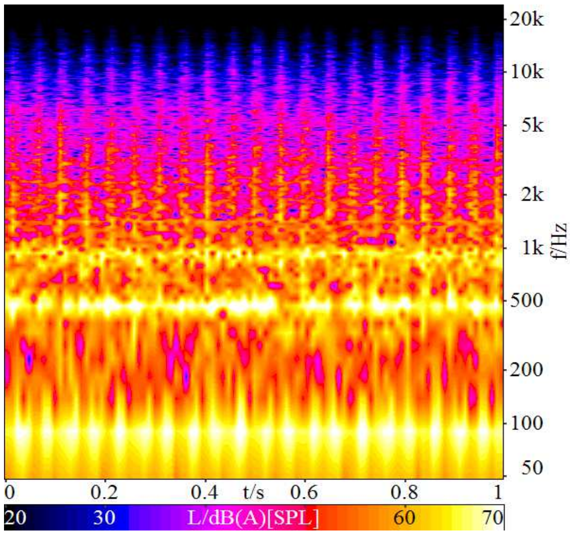

Figure 3. Spectrogram of the intake noise

2.6. Brooms

The disc brooms produce high frequency noise resulting from the fast movement of the bristles over the rough road surface. The sound is dominated by the broom noise in the kHz range. Although this component has only low influence on the total level, the high frequencies noise is perceived as very annoying and therefore proved as the major sound source.
Many different types of brooms are offered for different fields of application. Their construction and materials have a high influence on the produced noise but also on the abrasion. Thus quiet brooms that showed a very high abrasion could be unattractive for practical commercial use, due to higher wear costs.
The noise is radiated directly from the bristles as airborne sound. Casing the brushes seems difficult as these necessarily have to be open to loosen and transport debris and garbage. But beside the modification of broom material, a partial casing could reduce noise of the major sound source.

Figure 4. Left disc broom in working position

2.7. Hopper

The hopper is not an active sound source itself, but can act as a radiating surface for sound emissions. Measurements have shown that the main tonal components of the fan are present on the hoppers surface. These ones can be transmitted from the suction fan either as airborne sound from the fan housing to the inside of the hopper or as structure-borne sound via the mounting of the fan. In fact the directly emitted airborne sound of the fan exceeds the noise emitted from the hopper.
Furthermore the hopper could emit impact sound of larger debris like gritting material. Due to a inner coating, the test showed no perceivable impact sound to be emitted from the hopper, whereas the suction tube in front of the hopper acts as source for such noise.

2.8. Auxiliary Equipment

Beside the main parts of the sweeping unit, auxiliary equipment also plays an important role for the sweepers noise. Two prominent sound sources are the hydraulic system and the cooler fans for the power electronics. Both of them are placed underneath the sweeper.
On standby the hydraulics system emits a very annoying tonal sound. It has a 254 Hz base frequency with a large number of harmonics up to the high kHz range and is emitted by the hydraulic pump, the hydraulic pipes and the connected structural elements. The cooler fans create a broadband flow noise and a typical ventilator tone (550 Hz base frequency plus harmonics).
Both of these sound sources are perceived as very annoying due to their tonal and high frequency characteristics. However, in sweeping mode, when the suction fan is working, their noise spectrum is exceeded by more than ca. 20 dB (see figure 5) and they are totally masked by the other functional equipment's noise.

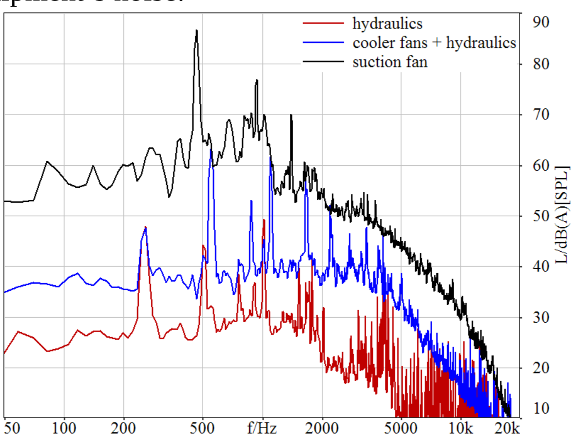

Figure 5. Sound spectrum of hydraulics, cooler fans, and suction fan recorded behind the sweeper

3. Conclusions

Electrified compact sweepers show an acoustic behaviour similar to conventionally powered sweepers. Replacing the drive and power unit shows only a small effect on noise reduction, as the functional equipment's noise is dominating. Measurements on a Tennant 500ze electric sweeper revealed three major noise sources with very different time and frequency characteristics: the rotational disc brooms (high frequency noise), the suction fan (tonal sound) and the suction intake (impulsive vibration).
After the identification of these main sources, their distinct airborne and structure-borne excitation signals and transfer paths must be quantified. So the contribution of these major sources can be reduced to decrease the annoyance of the perceived sweeper sound and thus to increase the acceptance by both pedestrians and residents.

Acknowledgement

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