Off-peak low noise heavy-duty vehicles, facade insulation and indoor noise disturbance

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ABSTRACT

Off-peak delivery of goods can result in increased transport efficiency, fuel savings, less pollution and increased traffic safety. However, unless carefully managed it causes increased annoyance and health risks for inhabitants exposed to the transportation noise during hours used for recovery and sleep. The presented work focuses on heavy-duty vehicles with Diesel engines during the “last mile” of the transport corridor through densely populated city centers. The aim is to study preconditions, open questions, and problem areas when nighttime soundscapes are altered by low noise vehicles. By using measured and simulated sounds, different driving conditions and acoustical treatments of vehicles and facade were studied at the facade and indoors in terms of 1/3-octaveband levels and judgments in listening tests. The evaluation shows that low-frequency noise of the vehicles is important indoors, while high-frequency noise is the major contributor outdoors. According to the listening tests the low-frequency noise is coupled to the degree of reported arousal, indicating that reduced low-frequency noise is especially important at nighttime. It was concluded that an acceptable indoor environment was achieved with a modified truck that is driven by a responsible driver, and by using “noise proof” windows with higher sound insulation.

Keywords: low noise vehicles, off-peak delivery, sound insulation, perception

1. INTRODUCTION

This paper treats some aspects of outdoor and indoor sound of heavy-duty trucks. The focus is on the “last mile” of the transport corridor through densely populated city centres, i.e. transport through rather narrow street canyons lined with residential housings. The focus is on the whole chain from specific vehicles to the outdoor and indoor noise and resulting disturbance, and on a methodology for developing noise improved heavy-duty trucks for off-peak delivery. The noise of the loading or unloading of the goods at the destination is beyond the scope of the paper.

Off-peak delivery concepts and implementation have gained increased interest the last decades. The main benefits by avoiding daytime hours with road traffic congestions, cyclists and pedestrians is increased transport efficiency resulting in time savings, fuel savings, and reduced exhaust gas emissions. Drivning during hours with few individuals in the streets results in fewer interactions and increased traffic safety. However, the noise emissions of the vehicles have to be managed since it may cause increased annoyance and health risks for inhabitants exposed during hours generally used for recovery and sleep.

The sounds and noises that surround us are important for our health and general well-being, pleasant sound may increase the well-being whereas environmental noise may decrease it. An important factor contributing to environmental noise is road traffic noise. A continuous exposure to road traffic noise leads...
to a reduced well-being and increased discomfort [1]. Within the EU sleep disturbances and annoyance, mostly related to road traffic noise is considered to be the main issue of environmental noise [2]. In EU more than 30 percent of the citizens are exposed to road traffic noise levels above 55 Ldn dB [3]. WHO calculates that 587,000 years are lost in disability adjusted life years (DALYs) due to annoyance of environmental noise and 903,000 years due to sleep disturbance of environmental noise [2].

Apart from sound pressure level numerous other factors contribute and modulate noise annoyance. Ouis made a main distinction between acoustical factors and nonacoustical factors [1]. Acoustical factors includes apart from sound pressure level, frequency spectrum, duration, and fluctuation. Nonacoustical factors are time of the event, social attitudes and evaluation of the source, cultural background, age, gender, social status, and education level. But also individual moderators such as sensitivity to noise, anxiety about the source, personal evaluation and coping capacity affect the degree of annoyance. The latter are a strong hinder when drawing conclusions on long-term effects of well-being as well as physiological effects.

The quality of sleep is affected at an early stage, the Night Noise Guidelines for Europe conclude that for $L_{\text{night}}$ sleep disturbances of environmental noise commence at 30 dBA where vulnerable groups begin to be affected, body movements, awakenings, self-reported sleep disturbances and arousal is reported to increase [4]. $L_{\text{night}}$ is the outdoor night-time noise indicator in which the A-weighted long-term energy equivalent sound level is determined over all the night periods of a year as defined in ISO 1996-2. The night is eight hours, usually 23.00 – 07.00 local time (22.00 – 06.00 in Sweden). Complaints begin at a threshold of 35 dBA. Between 40 and 55 dBA there is a sharp increase in sleep disturbance for a large part of the population and above 55 dBA adverse health effects occur frequently [4]. There is also evidence of increasing risk of myocardial infarction.

The indoor noise is characterised by the maximum A-weighted level per event $L_{\text{Amax}}$ evaluated indoors. The noise results in biological effects with onset of motility at 32 dBA, and both EEG awakening and changes in sleep structure and fragmentation of sleep at 35 dB [4]. The affects on the quality of sleep is reported from 42 dBA caused by waking up during the night or too early in the morning.

WHO guidelines recommend that night noise levels $L_{\text{night}}$ outside do not exceed 40 dB (with 55 dBA as an interim target) and maximum levels $L_{\text{Amax}}$ inside above 45 dBA in the bedroom should be limited as much as possible.

The general type approval procedure$^1$ and limiting values for heavy-duty vehicles is for general purpose vehicles in normal traffic conditions. The Dutch PIEK-standard$^2$ is a step towards low noise transportation. It embraces various driving conditions at low speed and additional requirements on for instance the equipment for the storage, loading and unload of the goods. The procedures for the vehicle measure outdoor noise emissions at the side of the vehicle at a single height.

However, to design low noise heavy-duty vehicles it is of interest to capture the acoustical performance of a specific vehicles in more detail. The outdoor annoyance is of most interest during evenings when the street and balconies directed towards the street are used for recreational activities. The indoor annoyance is primarily of interest during evenings and early mornings when recreation and activities takes place indoors. Sleep disturbance is of most interest during night-time. An optimal design of a low noise vehicle for street canyons has to consider noise emissions in a wide range of directions, the canyon amplification effect, expected performance of facade sound insulation and the resulting indoor noise levels. The present work is a step in this direction.

2. INVESTIGATIONS AND SIMULATIONS

The investigation is based on field measurements, laboratory measurements, simulations and listenings tests. They are briefly explained in the following. Three truck configurations are considered and they may be labelled as

- Std.: Standard heavy-duty truck Volvo FM-499 (13 litre diesel engine, 460 hp, emission class EEV)

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$^1$ UNECE Regulation No. 51 series 3
$^2$ http://www.piek-international.com/english/
- Mod 1.: A similar heavy-duty truck Volvo FM-490 that has been treated with extensive handmade encapsulation of the drive train (e.g. additional shields and absorbers) and an additional laboratory silencer designed to eliminate exhaust orifice low frequency noise (especially the 3rd engine order).

- Mod 2.: The same treated heavy-duty truck as Mod 1. but with modified drive train behaviour.

2.1 Field measurements

Field measurements were conducted at Landsvägsgatan 11, Gothenburg, where heavy-duty vehicles in the street passed by in different driving conditions (Fig. 1). Sound was simultaneously recorded outdoors at the facade and indoors in a room in a flat located at the third floor above the ground floor. The room has dimension 5.16 m × 3.76 m × 2.36 m (L × W × H) and a window and a French balcony towards the street. The window consists of three glasses: One double glassing cassette facing the room and a single glass facing the outside. The double glassing cassette is marked ‘EMMABODA 12, 8402’. The French balcony door has the same glassing cassette. There are no air intakes in the facade.

The sound from the vehicle passing by was recorded using a dummy head (Head Acoustics) and six microphones (Brüel & Kjær Type 4189, 1/2-inch free-field), two outdoors and four indoors in the flat. The Head Acoustics dummy head is placed 1.5 m from the window at 1.2 m height. The four microphones are distributed in the room. There is one microphone at the facade outside the window and one at 2 m distance from the facade/window. The second position is according to the standard for in situ sound insulation measurements of facades.

Figure 1 – The investigated truck Volvo FM-499 at the Landvägsgatan site outside the flat. The flat is the French balcony above the swap body.

2.2 Laboratory measurements

The sound of the standard truck and the two modified versions was recorded in the Truck Noise Chamber (semi-anechoic laboratory) at Volvo Group, Gothenburg (Fig. 2). The laboratory is equipped with a rolling dynamometer for the driving wheels of the truck. It was set to simulate a total vehicle test mass of 20 000 kg and the speed of the truck was manually controlled by a driver and therefore within ±3 km/h, and sometimes varying slightly with time. There is no significant speeds variation during the 4 seconds of recordings used in the sound synthesis described below.

Microphones (Brüel & Kjær Type 4189, 1/2-inch free-field) were distributed around the truck (fulfilling ISO 3744 for sound power measurements and with additional microphones for detailed investigations). The goal was to have a more extensive characterisation of the total sound emissions rather than the emission in a certain position as in the type approval test. The sound emissions in many directions are important when simulating sound emissions into a street canyon.
2.3 Sound synthesis

For controlled listening test a granular synthesis approach have been used to synthesise the sound emissions of the trucks using the sound recorded in the laboratory. Short time pieces of recorded sounds are stored in a database and later combined to simulate an engine sound for various driving conditions. The approach and its validation have been reported [5, 6].

From the noise source (the vehicle) to the facade the sound is propagating in the street canyon. The canyon affects the sound reaching the facade in two ways. First, due to the multiple reflections on the ground, the canyon walls (facades), the vehicle and other objects in the canyon there are many propagation paths causing constructive and destructive interference. The second effect that also stems from the multiple reflections is that of a reverberation time in the canyon. Steady state sounds become more diffuse compared to the case with only the direct sound and impulse-like sounds gets a reverberating tail. The Landsvägs gatan site had a reverberation time of about 1±0.25 s in the 1/3-octave bands between 63 Hz and 6350 Hz. The amplification effect of the canyon was calculated for the site as function of frequency and source position, using ray-tracing tuned by measured impulse responses at the site, and was included in the model when simulating the noise at the facade.

The indoor sound for different facades were calculated by filtering the noise according to the reduction index of the facade including windows and air intake, and room reverberation was given by convolving with a room impulse response. The reduction index between 20 Hz and 3150 Hz for a number of typical facades, windows and air intakes used in Sweden is listed in [7]. Figure 3 shows the level difference between outdoor and indoor sound for the room in the flat for combinations of walls and windows commonly used in Sweden. Case 1 uses a wooden facade, an untreated window and an ordinary air intake. The other five cases all have a better air intake, which can be shown to give a negligible deterioration compared to having no air intake. Case 2 has an improved window (and the better air intake) and shows a significantly better overall sound insulation except at mid frequencies (around 800 Hz) and toward high frequencies. Cases 3 and 4 use both a new steel frame wall and, respectively, two different new windows. The lightweight wall gives very poor performance at the lowest frequency bands and the choice of window makes a significant difference above 100 Hz. Cases 5 and 6 use both a new concrete wall and, respectively, two different new windows. Using the concrete wall is predicted to give a sound insulation at low frequencies that is better than the one from using the lightweight wall, but comparable to the one from using the wooden wall in case 2. Above 100 Hz, the use of the new noise proof window is predicted to result in a very high noise reduction (Case 4 and 6).

The room properties are considered by measured indoor impulse responses from a source close to the
window to evaluation positions.

2.4 Listening tests

To evaluate what aspects of the heavy-duty vehicles that explain and modulate the perceptual response, a set of listening tests were conducted. The listening tests utilised either the recordings from the field measurements (see 2.1) or synthesised sounds (see 2.3) comparing the six different facades, the modified and the un-modified heavy-duty vehicle, open and closed window, and different speeds (30 and 50 kmph). The participants varied between 13 and 28 participants, mean age varying between 27 and 29 years old, approximately 50 per cent women. All participants reported normal hearing. The participants conducted the experiment in a sound-attenuated room with no visual distractions.

The main aim of the listening test was to discern how well-being was affected by the different vehicles and facades. Using semantic differential the participants rated emotional responses (including valence and arousal; the latter sometimes referred to as activation; see [8–10]) and perceived stress. The participants further rated a set of perceptual measures, including loudness, sharpness, roughness, pitch, valence, arousal, perceived stress and perceived level of “naturalness”.

3. RESULTS

Figure 4 shows typical outdoor and indoor 1/3-octave band sound pressure levels measured at the Landsvägsatan site for a standard truck accelerating in the street. The outdoor noise is highest in the range 500 – 3000 Hz and stems from the high-frequency and broad banded “knocking” sound of a Diesel engine. The “booming” noise of the low-frequency engine order at 63 Hz (3rd order) and 125 Hz (6th order) are almost 15 dB below. However, the low-frequency orders, especially the 3rd order, results in the highest levels indoors. The exhaust pipe termination is the main source at this order for the studied vehicle. The frequency dependent sound reduction through the facade results in a coupling between changes in the total outdoor and indoor noise levels that is far from one-to-one. Treating the high-frequency engine noise with for instance improved encapsulation of the engine may give a reduction of the total outdoor noise level without a corresponding reduction of the total noise level indoors. In the same manner, treating the exhaust termination noise with silencers reduces the total indoor noise levels without a significant affect on the total outdoor noise levels.

Sound pressure in the street, at the facade and in a room of a flat as trucks pass by was measured at Landsvägsatan in Göteborg. Table 1 list the driving cases considered. Figures 5 shows the maximum sound pressure level for time-weighting Fast $L_{AmaxF}$ of measurements for the three truck configurations when the window and balcony doors are closed. The outdoor levels are measured at the facade and are
Figure 4 – A-weighted 1/3-octave band spectra at maximum sound pressure level at facade (blue) and in room (red) measured in situ at Landsvägsградen 11. The outdoor level is affected by the street canyon and is 6 dB higher than the corresponding free field value due to the facade reflection. The dashed gray lines show the corresponding typical background levels.

Table 1 – Driving cases considered in the measurements at Landsvägsgraden.

<table>
<thead>
<tr>
<th>Label</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idling</td>
<td>Standing still outside the apartment with the engine idling.</td>
</tr>
<tr>
<td>Idling + Compr.</td>
<td>Idling with the air compressor active.</td>
</tr>
<tr>
<td>PTO</td>
<td>Standing still outside the apartment with the engine in power take-off mode.</td>
</tr>
<tr>
<td>Acc.</td>
<td>Driving with full acceleration past the apartment.</td>
</tr>
<tr>
<td>Fixed gear</td>
<td>Driving with full throttle on a fixed gear past the apartment.</td>
</tr>
<tr>
<td>Fixed gear + Compr.</td>
<td>Fixed gear with the air compressor active.</td>
</tr>
<tr>
<td>Fixed gear + Fan</td>
<td>Fixed gear with the engine cooling fan active.</td>
</tr>
<tr>
<td>20</td>
<td>Driving 20 km/h past the apartment.</td>
</tr>
<tr>
<td>30</td>
<td>Driving 30 km/h past the apartment.</td>
</tr>
<tr>
<td>40</td>
<td>Driving 40 km/h past the apartment.</td>
</tr>
<tr>
<td>Background</td>
<td>Typical background noise levels when no vehicles are passing by in the closest street.</td>
</tr>
</tbody>
</table>

For all driving cases the first modification of the truck (Mod. 1) results in lower outdoor levels than the standard truck (Std.) and the second modification (Mod. 2) gives even lower levels. However, the same observations do not hold indoors. Consider for instance the acceleration cases 5 and 6 where the first modification results in no significant reduction indoors between the standard configuration and the first modification. The reason is not only due to the difference in spectral contents between outdoor and indoor noise but also since a room resonance is excited. The level without the contribution of the room resonance is indicated with an additional horizontal line in the blue bar. For the fixed gear case there is
Figure 5 – Maximum in A-weighted sound pressure level in situ at Landsvägsgatan using time-weighting “Fast” for the case with closed window, at the facade (red) and indoors (blue) for the standard truck FM-499 (dark), the modified FM-490 with nominal drive train behaviour (lighter), and the modified M-490 with modified drive train behaviour (lightest).

an outdoor noise reduction between modification 1 and 2, but not indoors. Here the reason is only due to the different spectral contents. Notice that the second modification (Mod. 2) always results in lower indoor levels than the standard configuration (Std.).

It can be concluded that the modifications in general generate the expected results and reduces the outdoor and indoor noise. However, the indoor noise levels are sometimes not reduced since room resonances are excited by the 6th engine order. Using the second modification step gives an 7.5–8.5 dB reduction indoors and a noise levels below 40 dBA for the acceleration case. The same figures for the single gear driving is 5.0–6.5 dB reduction and maximum levels below 43 dBA. This could be compared to the WHO’s guideline limit for $L_{A_{max}}$ of 45 dBA, which also is the maximum allowed indoor level by the Swedish regulation for new flats, or that the onset of motility during sleep starts at 32 dBA. The former is thus fulfilled for the studied case, the latter is only fulfilled for the idling cases. For the open window case all levels, except for idling of the treated truck, is above 45 dBA. More than 10 dB additional reduction is needed to fulfill the recommendation.

The listening test focused on the determinants for the emotional responses to heavy-duty vehicles measured by valence and arousal. The results of the listening tests suggest that valence is associated with how the sounds were experienced in terms of being natural/realistic, whereas the arousal measure covaried with changes in experienced loudness, sharpness, and roughness. The two emotional responses were also determined to change differently in relation to changes of the spectrum. Valence (level of pleasantness) changes with spectral changes at higher frequencies, where less high frequency content increases the level of pleasantness. Arousal (stress levels) instead are more affected by the lower frequencies where stronger low frequency sounds are associated with higher levels of arousal.

However, for newer facades and use of closed noise-proof windows either vehicle has a very low impact on both valence and arousal, which suggests that this is mainly of interest for open windows situations and potential effects during sleep (which was not covered in this project).

In Fig. 6 the measured spectrum indoors is recalculated into spectra assuming model facades 1–6.
that are briefly described in above and in detail in [7], for the fixed gear driving condition with the modified truck (Mod. 2). This is the case that gives the highest indoor levels for the modified truck at the Landsvägs gatan site. The reduction index of the measured facade, $R_{\text{Ref}}$, is exchanged for the reduction index of model cases 1-6, $R_i$, $i = 1...6$, i.e. a correction $10 \log \left( \frac{R_{\text{Ref}}}{R_i} \right)$ as function of frequency. It should be noted that low signal-to-noise ratio indoors affects the results at the higher frequencies, above ca 8 kHz.

Since the results plotted here are for a flat at 3rd floor, the levels are expected to increase closer to ground floor. Based on measurement results and assuming a small spectral change, the ground floor levels are 5–6 dB higher. Thus, for the case 6 facade with concrete wall and a “noise proof” window the levels do not exceed 30 dB at the ground floor. The sound is below the threshold of any reported disturbance in [4]. For all facade cases except the original and case 1 the noise level is below the 45 dB guideline limit also at the ground level.

Figure 6 – Indoor noise levels calculated for model facade cases 1-6 with the measured facade as reference.
4. CONCLUSIONS

It is concluded for the studied trucks that the low frequency noise is important indoors, while high frequency noise is the major contributor outdoors. Thus, recording the A-weighted levels in outdoor positions do not correctly cover the indoors conditions, when the windows are closed.

Every apartment has one or more low frequency resonances related to the geometry of the room and the structure of the walls and windows, which have to be considered when defining basic sound criteria of the source and the building.

The listening test revealed that the low frequency noise is strongly coupled to the degree of arousal (stress) and that lower low frequency noise is therefore important at nighttime.

A characterisation that meets the requirement of $L_{A_{\text{max}}}$ 45 dBA for an acceptable indoor environment for a case with closed windows was achieved with a modified truck that is driven by a responsible driver, and by using "noise proof" windows with higher sound insulation. The levels $L_{A_{\text{max}}}$ do not exceed 30 dB at the ground floor for the facade case 6 with concrete wall and a “noise proof” window, i.e. the level is below the threshold of any reported disturbance in the WHO Night Noise Guidelines for Europe [4].

A specification for a case with slightly open window would require a further reduction of 10–15 dB of the noise emissions of the treated truck. It is not within an easy reach today without change of technology, and it can be argued that it would be realistic to include the open window case in a low noise specification.

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References


