Impact of low frequency road traffic noise on indoor environments for different facade structures

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Abstract

Road traffic noise is a major environmental problem in Europe where at least 20 percent of the EU population live in areas where traffic noise levels are harmful to health. Recent changes and regulations in Swedish law enables a higher sound pressure level at facade, making it easier to build closer to roads. Typical noise reduction measures improve sound insulation at mid and high frequencies well, while not being as effective at lower frequencies of 20–200 Hz. As a consequence, more low frequency traffic noise indoors can be expected as we build closer to trafficked streets. This thesis aims to investigate the effect of low frequency traffic noise inside dwellings where (1) a study of traffic modelling and field measurements on a selection of different facade structures is made to determine the indoor low frequency traffic noise and (2) a psychoacoustic study is carried out where the annoyance level from low frequency traffic noise is investigated through listening tests.

The measurements suggest that none of the studied apartments have good insulation for low frequency noise. For all of the studied facades, peak pass by sound levels due to heavy vehicles are above our audible threshold and also at certain frequencies above the recommended Swedish guidelines for indoor low frequency equivalent levels.

The listening test suggests that the largest annoyance for inhabitants inside dwellings comes from heavy vehicles while light vehicles pose no greater annoyance even if the peaks of the low frequency sound levels inside the dwelling are above the equivalent level guideline values. Furthermore, the listening test results suggest that the annoyance that inhabitants experience is not only from low frequency components from vehicles passing by at a constant speed with no significant tonal changes. Instead they suggest that the low frequency components constitute the annoying part when there are clear tonal changes such as in situations with accelerating vehicles.

Keywords: building acoustics, urban acoustics, psychoacoustics, low frequency noise, facade insulation, Nord2000, CNOSSOS

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1 Introduction

1.1 Background

Recent studies shows that environmental noise, in particular road traffic noise, is a major environmental problem in Europe. At least 20 percent of the EU population live in areas where traffic noise levels are harmful to health. Long-term exposure to noise can cause a variety of health effects including annoyance, sleep disturbance, negative effects on the cardiovascular and metabolic system, as well as cognitive impairment in children [1]. New Swedish regulations [2] regarding traffic noise, enables a higher sound pressure level in the proximity of facades when projecting new houses making it possible to build closer to busy streets. Up to a 60 dBA equivalent A-weighted sound pressure level (SPL) can be accepted compared to a previous 55 dBA and the level can even be deemed higher depending on the size of the apartment such as 65 dBA for apartments with a size of 35 m^2 or less. Typical noise reduction measurements such as noise screens, facades and windows improve sound insulation at medium and high frequencies while not being as effective for lower frequencies, therefore a more low frequency character of traffic noise indoors can be expected as we build closer to trafficked streets [3].

In general, low frequency noise (LFN) is more problematic from noise in general and should be treated differently. Because of the long wavelengths of low frequencies, the atmospherics, ground and other natural boundary absorption's are negligible. Even noise barriers and obstacles are often ineffective against low frequencies since the wavelengths easily bends over it (diffraction). Therefore, when noise has travelled a long path, the spectral content is biased towards low frequencies and in facade structures, the sound insulation of facade components are generally lower for low frequencies. To make matters even worse, low frequency sounds that enters the room can resonate in so called room modes, enhancing the sound at certain positions. As a result of this chain, small levels of LFN outside the room may become audible and high inside dwellings [4].

Swedish regulations regarding traffic noise are represented as single value, equivalent and maximum A-weighted levels which do not take the frequency spectrum into account. It has been shown through past studies that A-weighting undervalues the disturbance of low frequency noise and in many cases, an equivalent A-weighted value does not properly represent the entire situation. The commonly used level indicator for traffic noise in Sweden is L_{Aeq24h} which is an equivalent noise level of an average of the energy over 24 hours. When it comes to traffic noise inside dwellings, the equivalent levels do not ”catch” the audibility of a passing car which is described by a peak or maximum level. Therefore even an apartment that is accepted through the applicable regulations, the inhabitants inside the dwelling can still be disturbed since the passing cars, especially heavy vehicles (e.g trucks, busses) are audible and gets more audible in lower frequencies as we build closer to a road. Furthermore, the SPL for low frequency sounds need to be studied in relation to humans ability to perceive the sounds since a higher SPL is required for low frequency sounds to be audible and is often masked out with other background noises [3].

This thesis aims to investigate the effect of low frequency traffic noise indoors and is divided in to two parts: (1) a study of traffic modelling and field measurements on a selection of different facade structures to determine the indoor low frequency traffic noise (2) a psychoacoustic study where the annoyance level from low frequency traffic noise is investigated through listening tests.

1.1.1 Current regulations

According to Boverkets byggregler BBR [5], the most common apartments which are classified as class C have the following indoor regulations and Swedish public health agency (FoHM) [6] have **recommended** guide values for indoor levels low frequency noise (LFN). The outdoor regulations are facilitated by the Swedish Gouverment [2].

	Equivalent SPL from traffic [dBA]	**Maximum SPL night time [dBA]**
In spaces used for sleep, or rest	30	45
On facade	60[1]	

Table 1.1: During night time (22:00-06:00), the peak level can not be exceeded more than 5 times and never more than 10 dB. 1) If the apartments is smaller than $35m^2$ the limit is instead 65 dBA.

Frequency	**31,5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
SPL [dB]	56	49	43	42	40	38	36	34	32

Table 1.2: Recommended equivalent indoor levels which should not be exceeded at low frequencies

The recommended levels from FoHM are represented as equivalent levels, however since there are no information regarding maximum levels for low frequency levels, the recommended equivalent levels are used as a comparison for peak levels.

1.1.2 Purpose

The purpose of this master thesis project is to study low frequency noise from traffic and its effect and compare it to measurable quantities and regulations in Sweden such as FoHMFS.

1.1.3 Limitation

In this study, the low frequency range is defined as 20-200 Hz and the study of vibrations are excluded. In all measured apartments the air terminal device has remained open during facade measurements. Because of issues of finding volunteers to measure apartments, the facade measurements were conducted on only six different apartments and only 4 of them were in the vicinity of a road with higher volumes of traffic.

2
Theory

2.1 Traffic noise models

Traffic noise models are used to predict sound pressure levels from road traffic using mathematical modelling of the propagation of sound, environment and of the noise sources. There are different traffic noise prediction models such as Nord96, Nord2000, CNOSSOS and different countries use different models as a standard. CNOSSOS is an attempt created by the European Union to have a common noise assessment for the member states and is the most recent model which some countries are already starting to adapt as a standard.

The different models are set up in two ways, one source model and one propagation model. The source model is used to calculate the instantaneous sound power level for a single vehicle at a specific point, given the vehicle type (category) and its speed while the propagation model explains the propagation of the source models through different environments.

2.1.1 Source models

In the majority of the models, noise from vehicles are seen as two main noise sources namely rolling and propulsion noise. Rolling noise is due to the tyre/road interaction and dominates at high driving speeds. Propulsion noise is produced by the drive line of the vehicle such as engine and exhaust systems and dominates at low driving speeds. The contribution of each source is dependent on two main parameters, speed and vehicle category. Vehicle categories are generally set up as light (passenger cars) and heavy (trucks, busses etc) but both Nord2000 and CNOSSOS also introduces the category medium which is excluded in this study since the standard in Sweden is to calculate with only light and heavy. A comparison between the source models for Nord96, Nord2000 and CNOSSOS and can be seen in table 2.1 to highlight similarities and differences among the models [7] [8] [9].

	Nord96	Nord2000	CNOSSOS
Bands	n/a	1/3 Octave	Octave
Frequency range [Hz]	n/a	25-10,000	63-8000
Speed range [km/h]	30-100	30-130	20-130
Source height [m]	0.5	0.01, 0.3, 0.75	0.05
$L_{W,r}$ **Rolling noise**	n/a	$\mathrm{A}_r + B_r \log_{10}(v/v_{ref})$	$\mathrm{A}_r + B_r \log_{10}(v/v_{ref})$
$L_{W,p}$ **Propulsion noise**	n/a	$\mathrm{A}_p + B_p \log_{10}(v - v_{ref}/v_{ref})$	$\mathrm{A}_p + B_p \log_{10}(v - v_{ref}/v_{ref})$

Table 2.1: Traffic source model differences

Nord96 which is a standard in Sweden calculates the total A-weighted source strength as a a single number while the rest of the models calculates a source strength that varies with frequency and driving speed. A_r, B_r describes the sound power coefficient for the rolling noise while A_p and B_p describes the sound power coefficient for propulsion noise. These coefficients are given in the models for Nord2000 and CNOSSOS, they are however based upon different noise emissions databases and vary with frequency.

In CNOSSOS, the effect of a road surface on rolling noise for each frequency band i and vehicle category m is added to the total power of the source as following

$$\Delta L_{WR,road,i,m} = \alpha_{i,m} + \beta_m \log_{10}(\frac{v}{v_{ref}}) \tag{2.1}$$

where α_m is a spectral correction in dB at a reference vehicle speed $v_{ref} = 70$km/h and β_m is the speed effect on rolling reduction for each vehicle category [10].
One drawback with both Nord2000 and CNOSSOS is that neither model estimates peak values but only equivalent levels. Nord96 is the only model that calculates peak values, however using a similar method as the Nord96 model, one can estimate the peak levels from Nord2000 and CNOSSOS using the source model.

2.1.1.1 Peak levels

To estimate peak levels of a single vehicle, it is modeled as an omnidirectional source with spherical propagation and constant acoustic power. The instantaneous SPL L_{peak} at a horizontal distance r can be written as

$$L_{peak} = L_w - 10\log_{10}(4\pi r^2) + \triangle L_i \tag{2.2}$$

where L_w is the sound power level of the source, r is the horizontal distance between source and receiver so that $r^2 = L^2 + x^2$ and $\triangle L_i$ is the ground effect. Assuming that the ground is hard and the difference in travelled distance between the direct and reflected wave is small compared to the wave length, $L_i = 6$ dB [11]. This simplification can be made since the peak levels will only be calculated in a range from 25-200 Hz were the wave lengths are considered long. L_w is calculated by using the equations and coefficients for the different models as seen in table 2.1 and adding the sound power levels as following.

$$L_w = 10\log_{10}\left(10^{\frac{L_{W,r}}{10}} + 10^{\frac{L_{W,p}}{10}}\right) \tag{2.3}$$

In the case of CNOSSOS, equation (2.1) is also added to the equation. For a constant driving speed, L_w is constant, then the maximum level of the pass-by situation is given at a point of passage, meaning when $x = 0$ and $r = L$

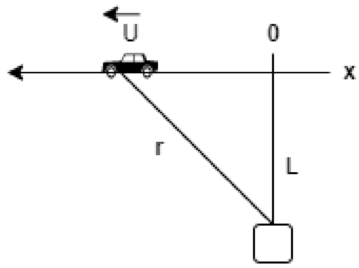

Figure 2.1: Geometry of situation for a pass-by situation, distance to receiver is given as $r = \sqrt{L^2 + x^2}$

In addition, a FAST time weighting is applied to L_{peak} to account for the contribution that a level meter would give as following (25267)

$$L_{peak,T} = L_{peak} + 10\log_{10}\left(\frac{2r}{vT}\arctan\frac{vT}{2r}\right) \tag{2.4}$$

where r is the distance from source to receiver, v the speed of the vehicle and T the time weighting which is 0.25 for FAST [12].

2.1.2 Propagation models

2.1.2.1 Nord2000

Nord2000 propagation model is based upon geometrical ray theory and calculates sound attenuation (the measure of the energy loss of a sound propagating in a medium) along a propagation path with the terrain and ground type in consideration between source and receiver. The SPL is given at the receiver point as following,

$$L_R = L_W + \Delta L_d + \Delta L_a + \Delta L_r + \Delta L_s + \Delta L_t \tag{2.5}$$

where L_W is the sound power level of the vehicle type calculated in the source model, while the propagation effects: L_d of spherical divergence, L_a of air absorption, L_r of obstacle dimension and surface properties, L_s of scattering zones and L_t of the terrain (ground and barrier). The model utilises eight ground types for ground effect corrections ranging from ”very soft” to ”very hard”. Furthermore, weather classes can be chosen which determines the speed of sound as a function of height above ground and is given in a statistical database in the model for the Nordic countries.

The model makes use of Fresnel zones to predict sound propagation over flat terrain with varying ground types, the ground effect is calculated for each type inside the Fresnel zone and given as a weighted average. The resulting levels are given as Leq which is a measure of the constant noise level that would result in the same total sound energy being produced over a time period [8].

2.1.2.2 CNOSSOS

CNOSSOS propagation model is based on standard french noise prediction model NMBP-2008 which uses the principle of ray theory and calculates sound attenuation when its propagating from source to receiver for homogeneous atmospheric conditions and downward-refraction propagation conditions.

The model calculates up to a 2 km maximum path distance from source to receiver and meteorological conditions are taken into account. The noise sources are expressed as point sources and their directional sound power is determined. Thereafter, the probability of favourable conditions for each direction source to receiver is calculated and each propagation path is routed. Furthermore, to simplify the model and calculation time, a ”mean ground plane” is introduced which is estimated between the source and receiver and applied in ground effect attenuation’s. This means that the actual ground in the model is replaced with a imaginary plane which represents the mean profile of the ground. For each propagation path the attenuation in favorable and homogeneous condition, and occurrence of favorable conditions are calculated and lastly the long term sound level for each path is determined.

The long term sound level L_{LT} along a path is determined by summing the sound level in homogeneous conditions L_H and in favorable conditions L_F which are then weighted by a probability p of favorable conditions in the direction of path. The probability p are given as percentages which changes depending on the time span during the day e.g day, evening or night.

$$L_{LT} = 10\log_{10}\left(p \cdot 10^{\frac{L_F}{10}} + (1-p)\cdot 10^{\frac{L_h}{10}}\right) \tag{2.6}$$

The total sound level is then given by summing each long term sound level at receiver point given from each path of the sources, which gives an $L_{Aeq,LT}$ which is given as a A-weighted sound pressure level at a receiver point on a specific time interval LT such as 24 hours [9].

2.2 Building acoustics

2.2.1 Reduction index, level difference

Reduction index R, is a measure to determine the power loss of sound between a receiver and a sender room. It is described by the ratio of transmitted power W_t and the power W_i incident on a surface wall such as a facade. R is the corresponding logarithmic quantity defined as following [13].

$$R = \log_{10}(\frac{W_i}{W_t}) \tag{2.7}$$

Laboratory measurement procedures are made to determine the sound reduction index of a building element by measuring all sound energy transmission from the sending room to the receiver room that takes place by way of the actual element between the rooms. R is given as laboratory ratings for specific materials or constructions however, the actual in-field performance seldom matches theoretical or laboratory ratings for the construction because of flanking paths, poor construction practices etc [14]. Therefore, for field measurements, the reduction index is determined by the standard ISO-16283 [15] where instead the apparent reduction index R' is determined which includes flanking transmission as following

$$R' = L_s - L_r + \log_{10}(\frac{S}{A_s}) \tag{2.8}$$

where L_S is the SPL in the source room, L_R the SPL in the receiver room, S the area of the separating wall between source and receiver and A_s the absorption area in the room. R takes the absorption in the receiver room into account meaning it is frequency dependent. Typically, partitions have reduction index values that increases with increasing frequency and is generally lower at low frequencies.

Another way to specify the sound insulation is by calculating a level difference between the source and reciever room as following

$$D_{nt} = L_s - L_r + \log_{10}(\frac{T}{T_0}) \tag{2.9}$$

where the quantity D_{nt} is denoted as standardized level difference with T_0 being a reference reverberation time set equal to 0.5 seconds for dwellings and T the measured reverberation time in the receiver room. It is argued that this quantity is more in line with the actual sound insulation experienced by the users than the R'-value [13].

2.2.1.1 Weighted reduction index

A single figure descriptor is established to show the normalized, or standardized weighted sound insulation levels. This single figure is calculated in ISO-717-1 [16] and is evaluated by comparing the measured apparent sound reduction index R' and normalized level difference D_{nt} to a reference curve. The reference curve is moved in increments of 1 dB steps towards the measured, R' and D_{nt} respectively, until the sum of unfavourable deviations is as close to 32 dB as possible. The single rating number given in decibel is then the reference curve value at 500 Hz.

To adapt the single value to account for different noise sources, spectrum adaption terms C and C_{tr} are used as described in ISO-717-1. Both describe a single A-weighted value, C is most used for road traffic at high speeds (e.g motor ways) and C_{tr} for street traffic accounting for low frequency noise [16].

2.2.2 Reverberation time

Reverberation occurs when sound waves within a room are repeatedly reflected of surfaces meaning the energy of the sound waves lingers on instead of converting to different types of energy such as heat. Reverberation time T_{60} is defined by the time in seconds that it takes for a sound to reduce in SPL by a factor of 60 dB after it has been silenced. Assuming that the room is diffuse, it can be estimated as

$$T_{60} = \frac{0.161V}{A_s} \tag{2.10}$$

where V is the volume of the room and A_s the absorption area which describes how much sound energy is absorbed and transformed into heat and transmitted through an absorbing body. A_s is defined as

$$A_s = 4mV + \alpha S \tag{2.11}$$

where the term $4mV$ describes the absorption in air and α the absorption coefficient of a specific material and how much of surface area S the material covers. The absorption coefficient of a material is frequency dependent and therefore the reverberation time will not be the same for all frequencies, most of common used materials for example absorb high frequencies better than low frequencies, meaning the energy of low frequency sound waves are often higher in a room and can increase sound levels within a room by up to 15 dBA [14].

2.2.3 Room mode behaviour at low frequencies

At low frequencies, the sound pressure level indoors normally changes substantially depending on the position within a room because of a phenomena called room modes. Sound waves in enclosed spaces such as a room are reflected from boundary surfaces; walls, floor and ceiling creating standing waves. Resulting sound fields around the room are then the combination of the direct sound and the reflected sound and modal resonances are established meaning the pressure will be different at different positions in the room [14]. The simplest form of room modes are single dimensional axial standing waves as shown in figure 2.2

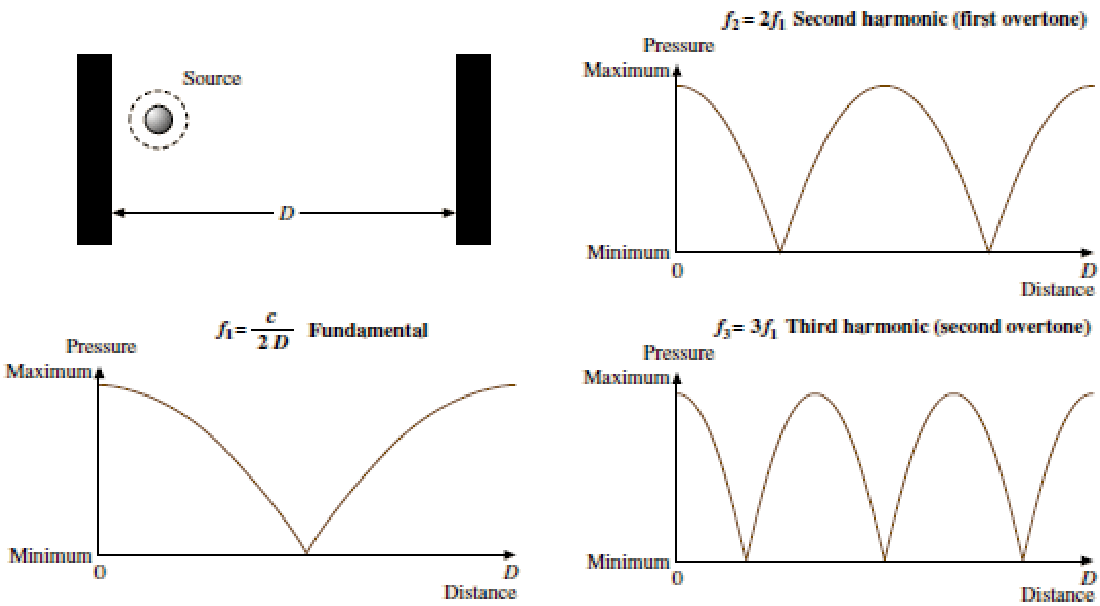

Figure 2.2: The three first axial room modes visualized [14].

Such axial standing waves occur at following frequencies,

$$f = \frac{nc}{2D} \tag{2.12}$$

Where c is the speed of sound in the medium, D the distance between two boundaries and $n = 1, 2, 3...$ Axial standing wave room modes occur at integer multiples of specific 1/2-wavelengths of sound as shown in fig 2.2 which are called harmonics or overtone of the fundamental frequency. Problematic modes occur mostly in lower frequencies since the wavelengths often match a rooms boundary. This becomes even more complex in two and three dimensions where we then also have tangential and oblique modes and the sound field is more unpredictable with uneven sound distribution patterns. This can become a problem during measurements and calculations, since if not handled properly, measurements can yield in errors. Some areas inside the room will have higher levels of sound (since a standing wave is reinforcing the pressure at those locations) and some areas will have lower levels of sound (since the standing wave is canceling much of the pressure at those locations), but only at specific frequencies. Axial modes have the longest paths between reflections, which means that they are the dominating groups of modes in the frequency response as well as in the decaying sound field and therefore the dominating room mode as well [17].

Special care and consideration is required to measure and characterize indoor sound levels and properly describe the sound from the outside to the inside of a building. For example, in small rooms the number of room modes is insufficient at low frequencies with the result that the reverberation time measured in one of the lower bands might be determined by the behaviour of a single mode. The basic notion behind reverberation time measurements is that the room is considered diffuse, therefore it is hard to get accurate reverberation times at low frequencies and therefore also the reduction index. Section (traffic noise modelling) describes a couple of methods that can be used to predict and calculate the SPL in low frequency ranges outdoors near the vicinity of facades. These methods are well documented and have a proven accuracy, however it is still complicated theoretically to calculate and determine the indoor low frequency levels with good accuracy. Small changes in construction and room size will impact room modes and change the SPL indoors, seemingly similar situations might yield in big differences in low frequency ranges. Therefore measurements are to be preferred choice of method to investigate low frequency sounds in dwellings [3].

2.3 Psychoacoustics

Sounds are evaluated and perceived differently from person to person. For example, noise induced annoyance is an individual persons reaction to noise with associated emotions such as dissatisfaction, bother, discomfort and depression [18]. To evaluate sounds and its factors such as annoyance, listening tests can be performed. For laboratory listening test, participants can be exposed to almost exact the same sounds under controlled conditions. Headphones are a preferred tool since they can be equalized and calibrated to a controlled condition that reproduces the sounds without the influence of a different room affecting the perceived sounds if a loud-speaker is used. However parameters such as annoyance develops for months or years in real dwellings, it is therefore difficult to study the scale of annoyance with listening tests but useful for relative comparisons.

2.3.1 Hearing threshold and audibility

The average frequency range of human hearing is ranged from 20 to 20,000 Hz and the upper limit tends to reduce as we age. Loudness is based off of perceived loudness and is related to the amplitude of a sound however there is no simple functional relationship between the two. Loudness is affected by the context and nature of sounds and difficult to measure because it is dependent on the interpretation of a listener. The pressure amplitude does not directly relate to the perceived loudness and it is possible for sound waves with larger pressure to sound quieter than sound waves with lower pressure since the sensitivity of our hearing varies with frequency. Figure 2.3 shows a standardized normal equal-loudness-level contours (ISO 226:2003) which defines our hearing threshold and defines combinations of pure tones in terms of frequency and SPL which are perceived as equally loud. For example, a sound with the level of the hearing threshold at 20 Hz is just audible but it would be perceived as much louder if it was at 4k Hz [19]. The following table shows a general characterization of human reaction to change in signal level, it must be noted that the noticeable change in loudness is dependent on the frequency and the nature of the signal and can vary from case to case.

Change in level [dB]	**Reaction**
1	Noticable
3	Very Noticeable
6	Substanial
10	Doubling (or Halving)

Table 2.2: Human reaction to change in level [20].

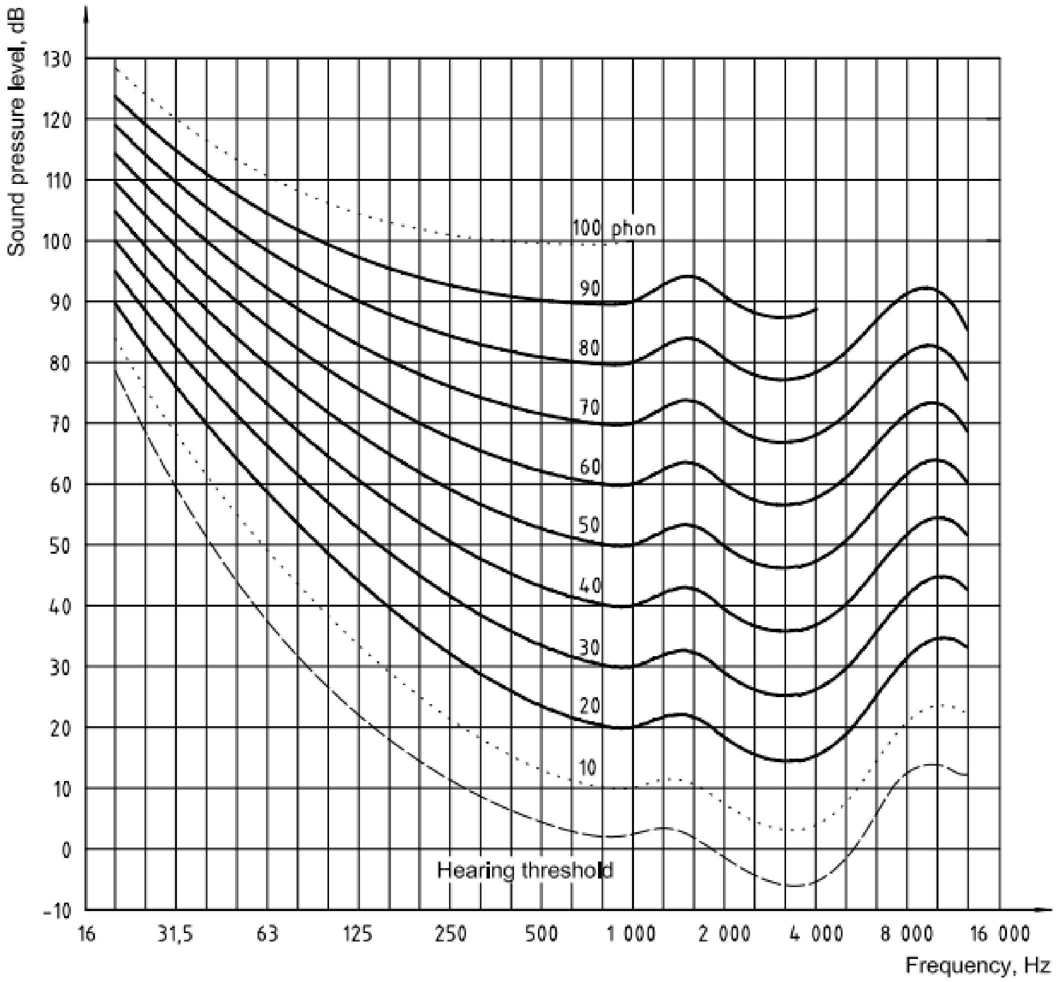

Figure 2.3: Normal equal loudness level contours for pure tones under free field listening conditions. [21]

3
Method

Investigations were done on 6 different facade types ranging from construction years 1938 to 2016. In all apartments, measurements were done in a room that were facing a road. The dimensions of volume of the room, the surface area of the facade wall facing the road and area of windows were all taken. Using ISO 16283-3, facade measurements were done and the reduction index and level differences of the different facades were calculated using ISO 717 and with the result from the traffic models made in Soundplan, the indoor levels were estimated and then compared to Swedish Public Health Agency recommendations (FohM) and the human hearing threshold.

Nord2000 and CNOSSOS were chosen as the traffic noise models since Nord2000 has a frequency range starting from 25 Hz, and CNOSSOS is increasing in relevancy as it is becoming more the norm in EU. Nord2000 and CNOSSOS simulations were only made in Soundplan for the apartments the were in proximity of busy streets with documented traffic flow. Based upon real life data of mean speed and traffic flow taken from Trafikverket [25], the A-weighted equivalent and 24 hour equivalent level at at the facade were calculated. To see how well the facades isolate against pass by noise in low frequencies, the max levels of a single pass by vehicle were calculated by applying the source models to calculate the sound power level of a single light and heavy vehicle respectively and processed described in section 2.1.1.1.

To further evaluate the results, a listening test was conducted to listen to the indoor environments made in one apartment to compare with the measurements results where annoyance and audibility of the low frequency spectrum was assessed.

3.1 Facade measurements

The apparent sound reduction index R'45 and level differences were determined using the industry standard measurement procedures as described in ISO 16283-3 [15]. Two speakers, one sub-woofer, model Presonus Temblor T10 and a Cromo 15+ loudspeaker were stacked and utilized in accordance to the global loudspeaker method by feeding pink noise to the speakers. One Nor140 free field microphone was utilized and the outdoor sound pressure level was measured on 5 positions on the facade and averaged. The microphone was positioned on the facade so that a -6 dB correction could be applied to counteract the reflection from the facade when calculating the level difference as [22];

$$DL = L_1 - L_2 - 6 \tag{3.1}$$

Inside the dwelling, the SPL was measured by utilizing manual scanning with a cylindrical type path by sweeping slowly in the central zone of the room. The sweep was one complete path with a duration of 60 s. The apparent sound reduction index which counts for flanking transmissions was then calculated as following

$$R'_{45} = L_1 - L_2 + 10\log_{10}(\frac{S}{A}) - 1.5 \tag{3.2}$$

where L_1 (dB) is the energy average of outdoor SPL, L_2 (dB) the energy average of the indoor SPL measured in the central zone of the room.

ISO 16283-3 has complementary procedure for low frequency components if the room volume was smaller than 25 m^3 where additional measurements are done in four corner positions. For all apartments, each corner was measured for 30 s even though the volume was greater than 25 m^3 to compare the variation of SPL in lower frequencies. At the end of each measurement, the background noise was assessed in each measurement position to ensure that the signal level in the receiving room was not affected by background noise and at least 6 dB under the measured signal. Results in frequency bands that were under 6 dB were tossed at a later stage of the project. Furthermore, ISO 717-1 [16] was used to calculate the single-number quantities for airborne sound insulation using the result from the measurements as described in section 2.1.1.1.

3.1.0.1 Reverberation time measurement

The equivalent absorption area, A (m^2) is calculated using equation 2.9 therefore the reverberation time in the receiving room was also needed to be measured which was done by using the interrupted noise method as described in ISO 3382-2 [23] with a Nor276 omnidirectional speaker. The speaker was put in a position in the central zone of the room and measurements were carried out in 3 different positions at two different heights. With the high uncertainties of measuring reverberation time under 50 Hz, no reverberation time measurements were done in the frequency range between 20-40 Hz.

3.1.1 Traffic simulations

Industry standard software Soundplan was utilized to calculate the expected levels on the facade. Nord2000 and CNOSSOS have several different vehicle categories, in this study, only category 1 (light, passenger cars) and 3 (heavy, busses/trucks) were used to follow Swedish standard which only uses the two vehicle categories light and heavy. For all simulations, a 90 % light and 10 % heavy vehicle split was used for the hourly traffic flow data. Information of weather conditions were taken from Nord2000 statistic library for Swedish conditions and road surface ABS16 was used. The road ground was considered hard, normal Asphalt and fully reflective.
According to a study made by RISE [24], Nord2000 overestimate levels and suggests to adjust the input data for the rolling and propulsion coefficients to better match

Frequency	Light		Heavy		C
	A_r	B_r	A_r	B_r	
25	69.9	33	76.5	33	0
31	69.9	33	76.5	33	0
40	69.9	33	76.5	33	0
50	74.9	30	78.5	30	0
63	74.9	30	79.5	30	0
80	74.9	30	79.5	30	0
100	79.3	41	82.5	41	0
125	82.5	41.2	84.3	41.2	0
160	81.3	42.3	84.3	42.3	0
200	80.9	41.8	84.3	41.8	0
250	78.9	38.6	87.4	38.6	1
315	78.8	35.5	88.2	35.5	1
400	80.5	31.7	92	31.7	1
500	87	25.9	94.1	25.9	1
630	88.7	26.5	96.5	26.5	1
800	90.8	32.5	96.8	32.5	1
1k	93.3	37.7	95.6	37.7	1
1.25k	92.5	41.4	93	41.4	1
1.6k	92.8	41.6	93.9	41.6	-1
2k	90.4	42.3	91.5	42.3	-2
2.5k	88.4	38.9	88.1	38.9	-3
3.15k	85.6	39.5	86.1	39.5	-4
4k	82.7	39.6	84.2	39.6	-5
5k	79.7	39.8	80.3	39.8	-4
6.3k	75.6	40.2	77.3	40.2	-3
8k	72	40.8	77.3	40.8	-2
10k	67.5	41	77.3	41	1

Table 3.1: The unmodified Nord2000 light and heavy A and B coefficients for rolling tyre noise and the suggested corrections 'C'.

Swedish conditions. In Soundplan, the the corrections in table 3.1 and 3.2 were added and subtracted to each A_p and A_r.

Frequency	Light		Heavy		C
	A_p	B_p	A_p	B_p	
25	89.8	2	97.7	0	-3
31.5	91.6	2	97.3	0	-3
40	91.5	0	98.2	0	-3
50	92.5	0	103.3	0	-3
63	96.6	2	107.9	0	-3
80	94.2	2	105.4	0	-3
100	92	4	101	0	-3
125	87.4	2	101	0	-3
160	86.1	2	101.3	0	-3
200	86.1	6	101.3	0	-3
250	87.2	8.2	102.5	8.5	-3
315	86.5	8.2	103	8.5	-3
400	85.6	8.2	102	8.5	-3
500	80.6	8.2	101.4	8.5	-3
630	80.7	8.2	99.4	8.5	-3
800	78.8	8.2	95.1	8.5	-3
1k	79.3	8.2	95.8	8.5	-3
1.25k	82.4	8.2	95.3	8.5	-3
1.6k	83.7	8.2	92.2	8.5	-3
2k	83.4	9.5	93.2	8.5	-3
2.5k	81.3	9.5	90.7	8.5	-3
3.15k	81.8	9.5	88.8	8.5	-3
4k	79.9	9.5	87.5	8.5	-3
5k	77.9	9.5	85.9	8.5	-3
6.3k	75.1	9.5	86.9	8.5	-3
8k	73.1	9.5	83.8	8.5	-3
10k	69.5	9.5	80.3	8.5	-3

Table 3.2: The unmodified Nord2000 light and heavy A and B coefficients for propulsion noise and the suggested corrections C.

Furthermore, the study shows that CNOSSOS underestimates emission levels for Swedish conditions and suggests to have modified road conditions to better suit Swedish conditions. Therefore the following coefficients are applied to better represent Swedish road conditions as suggested by the study.

Category	α_m**:63**	**125**	**250**	**500**	**1k**	**4k**	**8k**	β_m
1	3.6	3.6	3.6	3.6	3.6	3.6	3.6	4.2
3	4.9	4.9	4.9	4.9	4.9	4.9	4.9	8.1

Table 3.3: Modifications for road condition, CNOSSOS

The source models were modeled in Matlab and the peak pass-by levels were calculated as described in section 2.1.1.1. The described situation is a simplification which only works if the ground is hard and flat, with negligible influence of air attenuation and turbulence. Since only the low-frequency noise is studied for the peak levels and that in every case, the distance of the road is less 100 m the simplifications are valid.

3.2 Listening test

The listening test were taken place in the Living room Lab in the Division of Applied Acoustics at Chalmers University of Technology. The lab is heavily isolated from outside noise and simulates a living room. The test was conducted using stimuli from an audio recording in one of the studied apartments which had the worst indoor environment from traffic noise with a bedroom facing a busy urban road 12 m away. Only stimuli from one of the studied apartments were used since it provides a worst case "scenario" in this study.

Figure 3.1: The Living room Lab in the Division of Applied Acoustics at Chalmers University where the participants conducted the listening test

3.2.1 Stimuli recording

Two separate microphones were used to capture both the indoor and outdoor noise at the same time. This was done to be able to further verify the level difference and to easier cut the stimuli. Indoors, the microphone was placed in the center of the room at a place of rest. Both microphones were Nor140 and had identical settings with a gain of +30 dB to minimize the noise floor. Before recording, a calibration recording was made with a test tone of 1000 Hz at 120 dB on each microphone to be able to calibrate both WAV-files when processed. A phone was set up to video record each passing by vehicle so that it could be documented. The microphones were recording during evening at 19:00 for 30 minutes and no resident were inside the dwelling during the measurement period. The recording was analyzed, calibrated and cut into stimuli in the software Head Acoustics Artemis Suite. In total, 7 stimuli were created,

- One buss passing by while accelerating
- Two busses passing by
- One motorcycle passing by
- Three passenger cars passing by

3.2.2 Design of listening test

The listening test was designed in Artemis Suite and evaluated using the SQala client. The questions were designed in accordance to ISO 15666 [18] and were rated on a 10 numerical and a verbal scale, formulated as following:

- Imagining you are resting at home, how much does the sound clip you listened to, bother, disturb or annoy you in **general**?
- Imagining you are resting at home, during **night time** (23-07), how much does the sound clip you listened to, bother, disturb or annoy you?
- Imagining you are **working** or **studying** at home, how much does the sound clip you listened to, bother, disturb or annoy you?

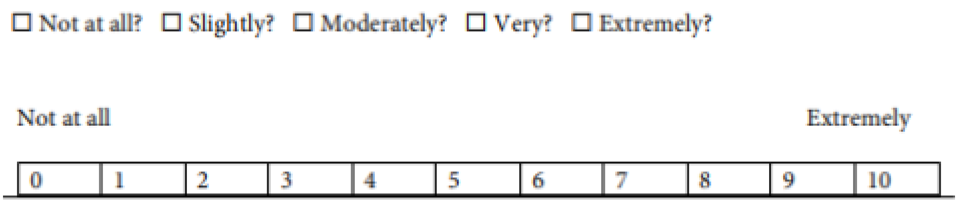

Figure 3.2: The numerical and verbal scale used to evaluate the stimuli

The stimuli were presented in random orders with a category judgment using the scales in figure 3.2 to evaluate the stimuli. Each stimuli was repeated for each question asked but could only be listened to once. Furthermore, a comparison test was set up by having a low pass filter with a cut off frequency of 250 Hz which was applied on all stimuli and compared with the unfiltered original recording of the stimuli to evaluate which recording was the most annoying stimuli. No background noise was added to the stimuli or during the listening test.

A calibrated headphone of model Sennheiser HD650 was used for the listening test to reproduce the listening condition in reality. To calibrate the WAV-file, the calibration audio file was loaded into Artemis and exported to a HDF file which requires to set a peak reference value for the .wav file. At first this was set to a 1 Pa/94 dB. The file was then analyzed to see which unweighted RMS level the calibrated file was shown, since the calibrator was first set to 120 dB, the peak reference value was adjusted until the analyze of the imported file shows the same level as the calibrator produced.

Before start, the participants were asked to fill in a questionnaires which asked if the participants had any hearing disabilities and their general perception of traffic noise both indoors and outdoors. A short introduction was given to the listening test, but background information regarding the project and the thesis was not given until after the listening tests were conducted to not change the perception and evaluation of the sounds for the participants. Overall, each test took around 20 minutes to perform.

3.2.2.1 Result conversion

According to ISO 15666 [18], the result of the questions shall be given as the frequency or cumulative distribution of the individual scores, therefore the result is converted and presented as an amount of people annoyed (%A) and the amount of people highly annoyed (%HA). Highly annoyed refers to the percentage of survey respondents reported to be highly bothered, disturbed or annoyed which is defined as the top 28 % of the scale.

Both the verbal and numerical scales were converted to a 100 scale. The verbal scale was converted as following; “not at all” to 0, “slightly” to 25, “moderately” to 50, “very” to 75 and “extremely” to 100. The numerical scale 0 was converted to 0, 1 to 10 and so on. The cut off for %A was set as 50 and %HA as 72, and averages of verbal and numerical scale results were used for each question in each category to determine the percentage %A and %HA. Since the verbal scale is an ordinal scale, for it to be converted to a numerical scale there needs to be a clear evidence that the step-difference between each category is perceived by the respondent to be equal, therefore both the scales were combined to better visualize this during the listening test.

4

Results

4.1 Facade insulation measurement

The following buildings and facades were studied, the audio recording for the listening test was done in the situation of apartment F.

Fa	**Y**	**Wall construction**	**W**	**P**	**V**	**S**	$\mathbf{f_1}$
		Thickness [mm]	[%]		[m^3]	[m^2]	[Hz]
A	2006	Brick(250), mineral wool(100)	30	2+1	32,8	7,6	42
B	1992	Tree panel + asphalt board, wool(240), gypsum b.	20	3	22,4	6,1	55
C	1948	Brick (240), wood wool(35)	27	2+1	28	7,3	45
D	2016	Brick(250), rock wool(100)	40	2+1	68,3	11,5	34
E	1981	Brick(100), tree panel + m. wool(80), gypsum b.(13)	36	2+1	50	9,3	32
F	1938	Brick(250), wood wool(50)	32	3	48,3	10,75	35

Table 4.1: Fa describes the studied facade/apartment, Y the constructions completion year, W the percentage of window area in the facade, P the number of glass panes, V the volume of the receiving room, S the facade surface area of the receiving room and f_1 the lowest room mode of the receiving room calculated with equation (2.12). Dimensions are missing in construction documents if not stated in table.

Facade B and E are on the lighter side construction wise, while the rest of the apartments are considered heavy constructions. In apartment B, the complementary low frequency procedures as described in ISO 16283-3 were conducted since the volume was smaller than 25 m^3.

The following table describes the single number quantities of ISO 717-1. They were determined as described in section 2.2.1.1 within 50-3150 Hz.

Fa	$\mathbf{R}'_{45,w}$	$\mathbf{R}'_{45,w}+\mathbf{C}_{tr,50-3150}$	$\mathbf{R}'_{45,w}+\mathbf{C}_{50-3150}$	$\mathbf{D}_{ls,nt}$	$\mathbf{D}_{ls,nt}+\mathbf{C}_{tr.50-3150}$	$\mathbf{D}_{ls,nt}+\mathbf{C}_{50-3150}$
	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]
A	49	40	47	46	38	44
B	41	31	38	41	33	39
C	40	35	39	42	36	40
D	40	35	38	40	35	39
E	37	30	35	40	34	38
F	38	31	36	40	34	38

Table 4.2: Single number quantities of facade insulation on the measured apartments with spectrum adaptations, D_{ls} means that the level difference is evaluated using a loudspeaker

Looking at the normalized level difference with traffic noise spectrum adaption $D_{ls}+C_{tr}$, the difference for the heavy facades constructions is up to 4 dB while the difference is up to 9 dB when looking at $R'_{45,w}$+C$_{tr}$. Facade A, C and F have a similar constructions however their $R'_{45,w}$+C$_{tr}$ differ by several dB. The lightest construction 'B' has a higher $R'_{45,w}$ value than the heavier constructions F, C and D, but worse insulation with a C$_{tr}$ adaptation spectrum.

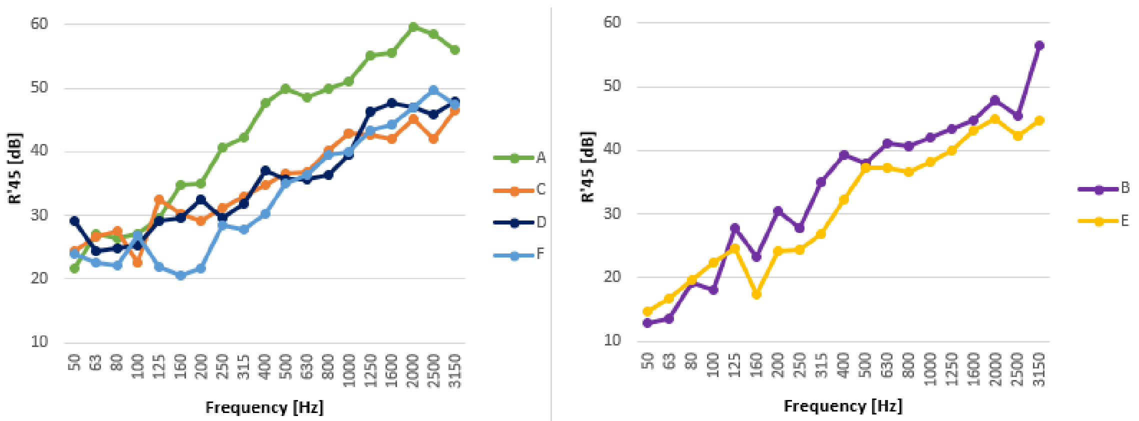

Figure 4.1: The measured reduction R'_{45} for the different facades, grouped in the more heavier constructions to the left and to lighter constructions on the right

Looking at left figure 4.1, the four facades have a similar reduction at lower frequencies but at higher frequencies, the reduction is higher for facade A which explains the high $R'_{45,w}$. The lighter constructions have a lower reduction index overall at lower frequencies but high insulation increasing with frequency.

4.1.1 Level differences

The following figure shows the level difference which is calculated using equation (3.1) for all 6 measured apartments

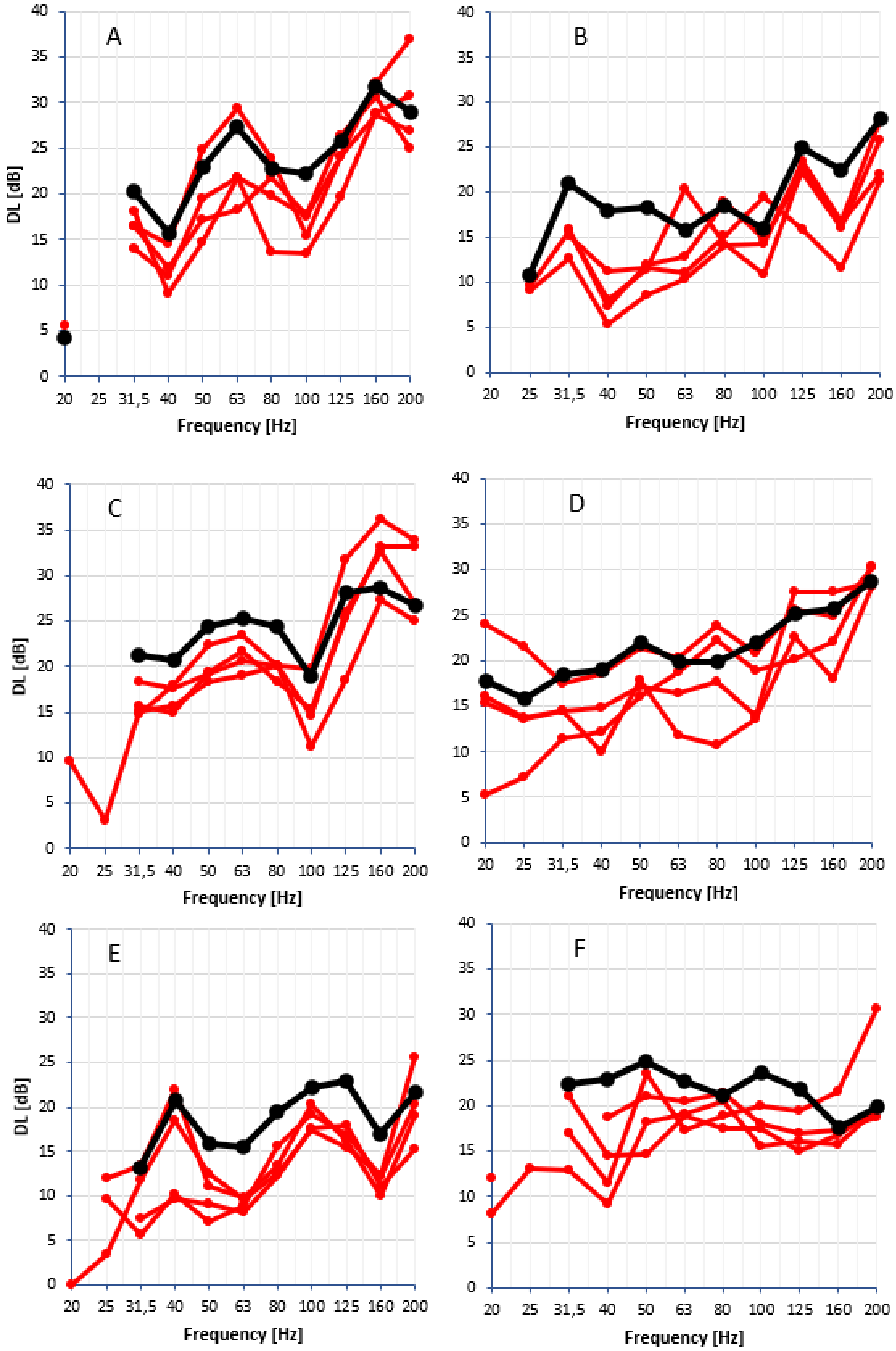

Figure 4.2: The level difference DL in the central zone (black line) and in each corner position (red line) for the 6 measured facade constructions. Data points are missing if the difference of background noise and indoor measurement was smaller than 6 dB.

As seen in figure 4.2, the difference is highly dependent on the position in the room one is measuring. Corner positions generally yield in lower DL meaning that a higher SPL is measured which is expected. In this study, the central zone is assumed to be the position where the majority of inhabitants is in a position of rest and the following figure shows a comparison of the DL in the lower frequency regions in the central zone

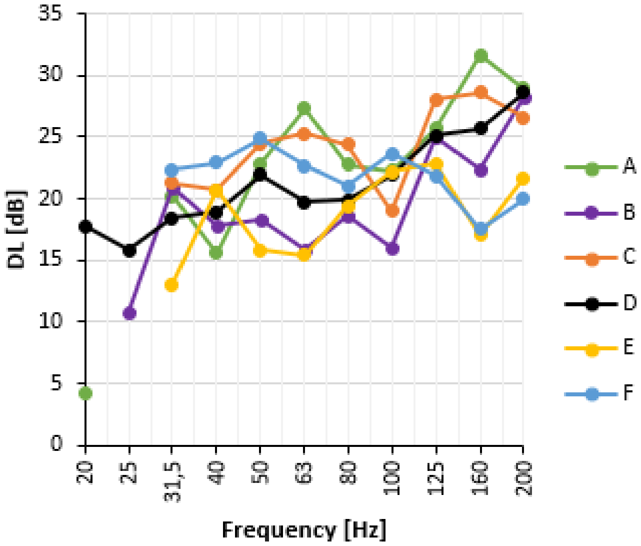

Figure 4.3: The level difference DL in the central zone for the 6 measured facade constructions. Data points are missing if the difference of background noise and indoor measurement was smaller than 6 dB.

The spread in DL is wide for certain frequencies as 40, 63 Hz and 160 Hz with a differences up to 15 dB. At around 40 Hz we have a room mode for facade A as seen in table 4.1 which explains the drop in DL, while the difference at 63 and 160 Hz can be explained because of different window and facade types. Facade A, C and D has identical window constructions with similar DL at frequencies 63 and 160 Hz, the difference can be assumed to be because of the amount of window area on facade. Facade E has also the same window construction however facade with a much lower DL which can be assumed because of lighter facade construction. In general the heavier constructions isolate low frequencies better compared to the two lighter constructions. The following figure presents a mean level difference for the most similar constructions A, C, D and F

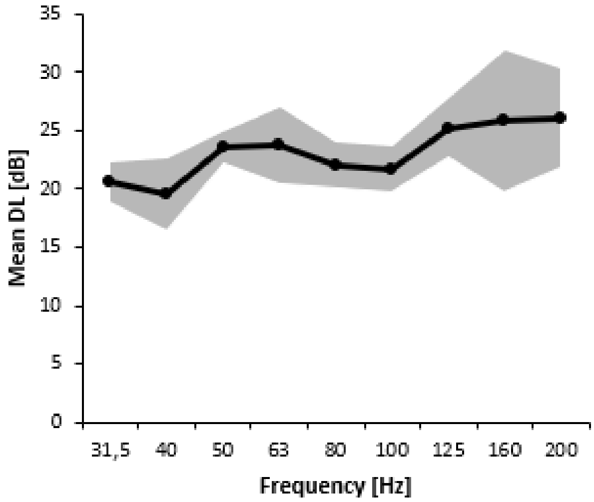

Figure 4.4: The mean level difference measured at the central zone of the room with the standard deviation in the shaded area. Frequencies 20 and 25 were excluded because of insufficient measurements.

The variation is not high except at frequencies above 125 Hz which most likely comes from the low DL value at 160 Hz in the case of facade F which is most likely because of a different window construction compared to the rest of the heavy facades with identical window constructions.

4.2 Traffic simulations

Facade C, D, E, and F were all in the vicinity of a trafficked urban road while facade A and B were facing residential living streets therefore A and B were exempt from traffic simulations in Soundplan. However, for all facades, pass by noise from vehicles could be heard inside the dwelling therefore peak pass by calculations were done for all facades. The following traffic data for the closest road in the vicinity of the apartments were recorded

Fa	Mean traffic flow per day	Mean speed [km/h]	Distance to road [m]
A	N/A	30	20
B	N/A	20	10
C	11985	36	25
D	5562	36	70
E	2980	58	55
F	10276	38	12

Table 4.3: All data were taken from Trafikverket [25] and used as a basis for the traffic simulations. Distance to road was measured from the facade of the room where measurements were conducted to the corner of the road, rounded up.

Through Soundplan, the following L_{Aeq24h} values were calculated, the equivalent indoor SPL was determined in two ways, the first way by subtracting the $D_{ls} + C_{tr}$ values in table 4.2 with the presented L_{Aeq24h} values and the second way by taking the calculated indoor L_{Aeq24h} in 1/3 octave bands subtracted with the measured level difference in each band, and summing all the values to a single value.

Fa	L_{Aeq24h}	$L_{Aeq,nt}*$	L_{Aeq}
	Nord2000 [dBA]	Indoor [dBA]	Indoor [dBA]
C	57	22	23
D	44	9	15
E	52	18	21
F	64	30	34

Table 4.4: Result of equivalent level at facade and indoors from traffic model Nord2000 made in Soundplan for the different apartments, $L_{Aeq,nt}*$ has been calculated using single value $D_{ls} + C_{tr}$ presented in table 4.2

Fa	L_{Aeq24h}	L_{Aeq}
	CNOSSOS-EU [dBA]	Indoor [dBA]
C	56	20
D	42	9
E	49	21
F	62	35

Table 4.5: Result of equivalent level at facade and indoors from traffic model CNOSSOS-EU made in Soundplan for the different apartments, $L_{Aeq,nt}*$ was not calculated for CNOSSOS-EU values since $D_{ls} + C_{tr}$ was estimated using 1/3 octave bands calculations.

There is a difference between 2 to 3 dB between Nord2000 and CNOSSOS model even though the adaptations in the model has been made as described in section 3.1.1. All four apartments, have acceptable equivalent indoor environments according to Swedish regulation for an apartment of class C where the limit is 30 dBA if using a single value as, however the difference is large from 1-6 dB depending on if one is using a normalized DL value with a C_{tr} correction compared to using the level difference of the full spectrum.

4.2.0.1 Peak levels

The following peak levels were estimated using Nord2000 source model in Matlab as described in section 2.1.1.1. The values shown are indoor peak values at a central zone of the room using the level difference measured from figure 4.2

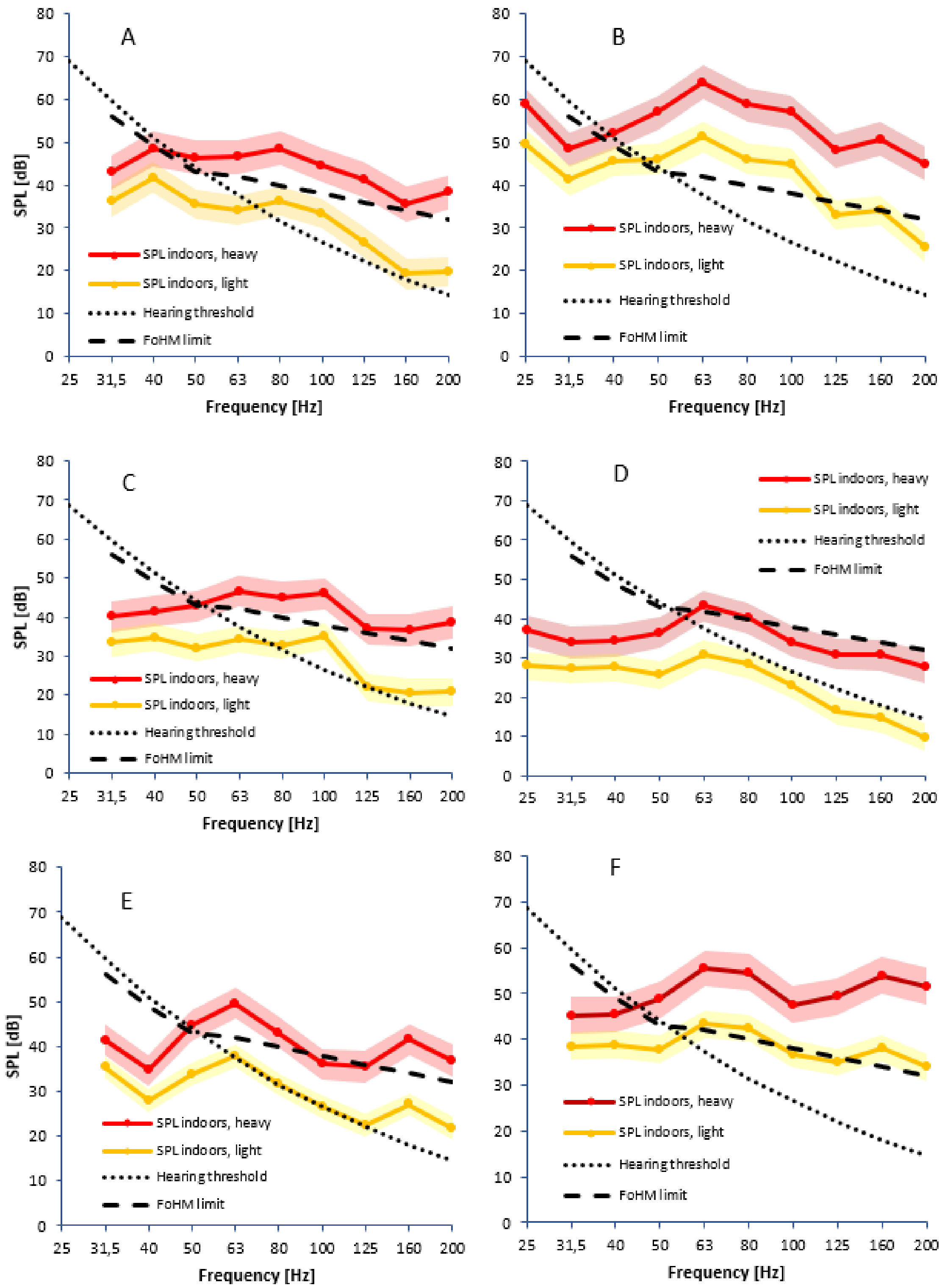

Figure 4.5: The unweighted peak sound pressure levels for heavy and light vehicles passing by at a distance and speed as described in table 4.3 compared to the hearing threshold according to ISO 226 and the Swedish Public Health Agency(FoHM) limit values for low frequency indoor noise. A statistical variation of the SPL of different driving speed ± standard deviation have been taken from Nord96 and applied as seen in the shaded areas.

In almost all of the cases, the audible sounds from pass by heavy vehicles starts at either 40 or 50 Hz. For all facades, audible LF components can be heard from passing by light and heavy vehicles except in the case of facade 'D'. Furthermore, all facades have LF components which is above the recommended FoHM equivalent levels in the case for a passing heavy vehicle.

The following peak levels were estimated using CNOSSOS source model in Matlab as described in section 2.1.1.1 and converted to 1/3 octave band, compared to the levels given in figure 4.5. The values shown are a indoor peak levels at a central zone of the room using the level difference measured from figure 4.2

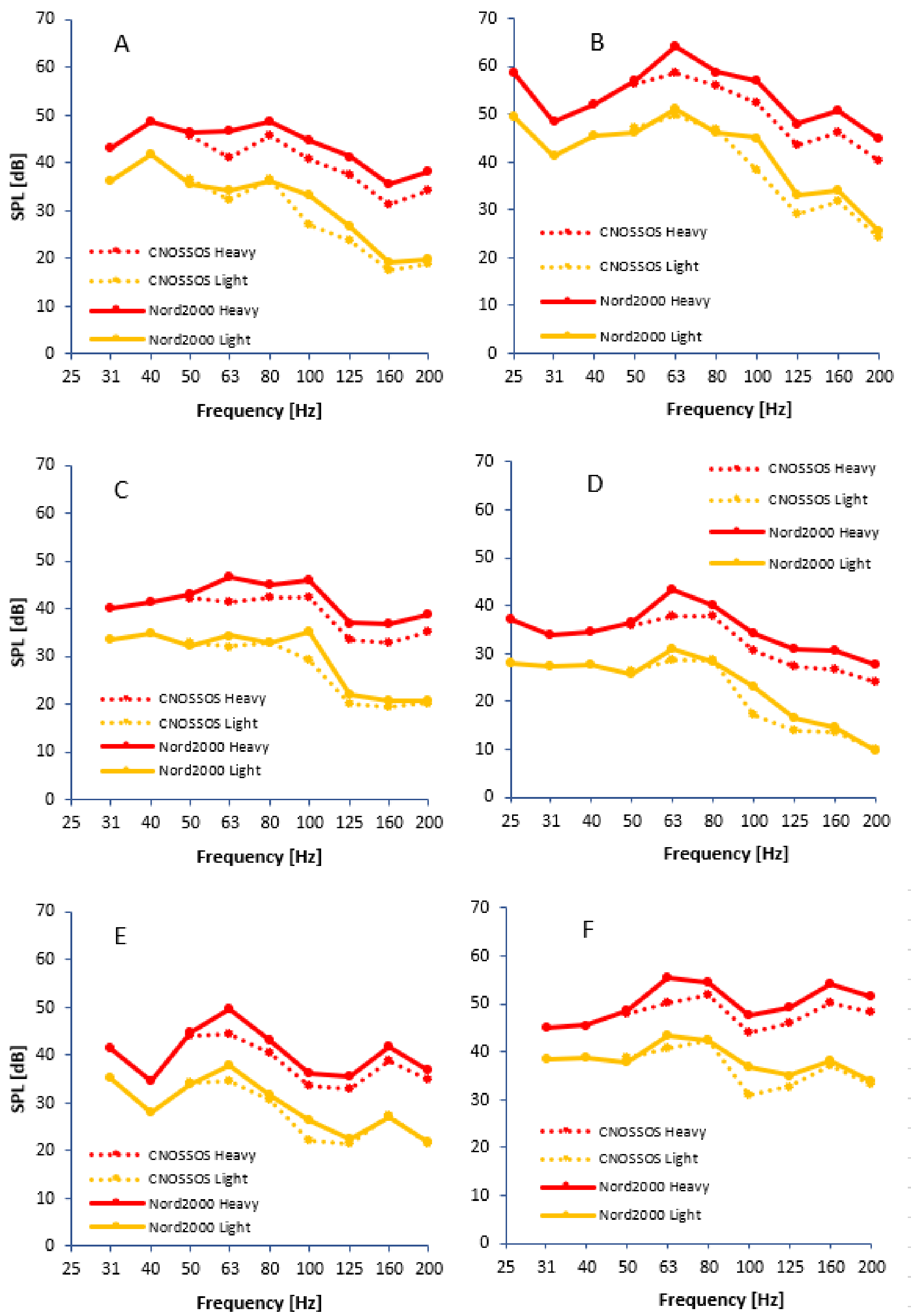

Figure 4.6: The unweighted peak sound pressure levels evaluated with CNOSSOS compared with Nord2000 peak values for heavy and light vehicles passing by at a distance and speed as described in table 4.3.

The peak levels for CNOSSOS shows similar levels as Nord2000 in the case of light vehicles except at 100 Hz. The largest level difference are between the heavy vehicles at 63 Hz where generally Nord2000 estimate's a higher peak level compared to CNOSSOS.

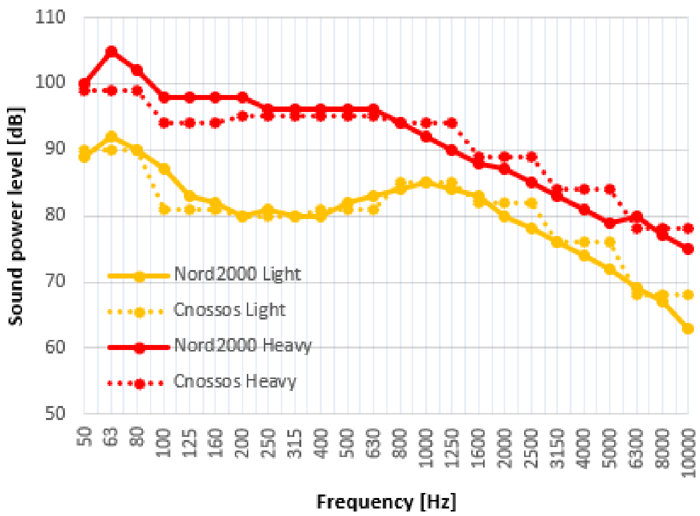

Figure 4.7: The sound power level calculated using CNOSSOS-Eu and Nord2000 source model for both vehicle categories at a vehicle speed of 40 km/h

There is a difference of up to 5 dB between the two source models mainly at 100 Hz for light vehicles and at the lower frequencies between 63 to 200 Hz for heavy vehicles.

4.2.0.2 Unweighted equivalent levels

The following unweighted equivalent levels at a time period of 24h were estimated using Nord2000 and CNOSSOS traffic noise models in Soundplan. The CNOSSOS result were converted into 1/3 octave bands. The following figure shows the indoor equivalent levels at a central zone in the room using the measured values in figure 4.3

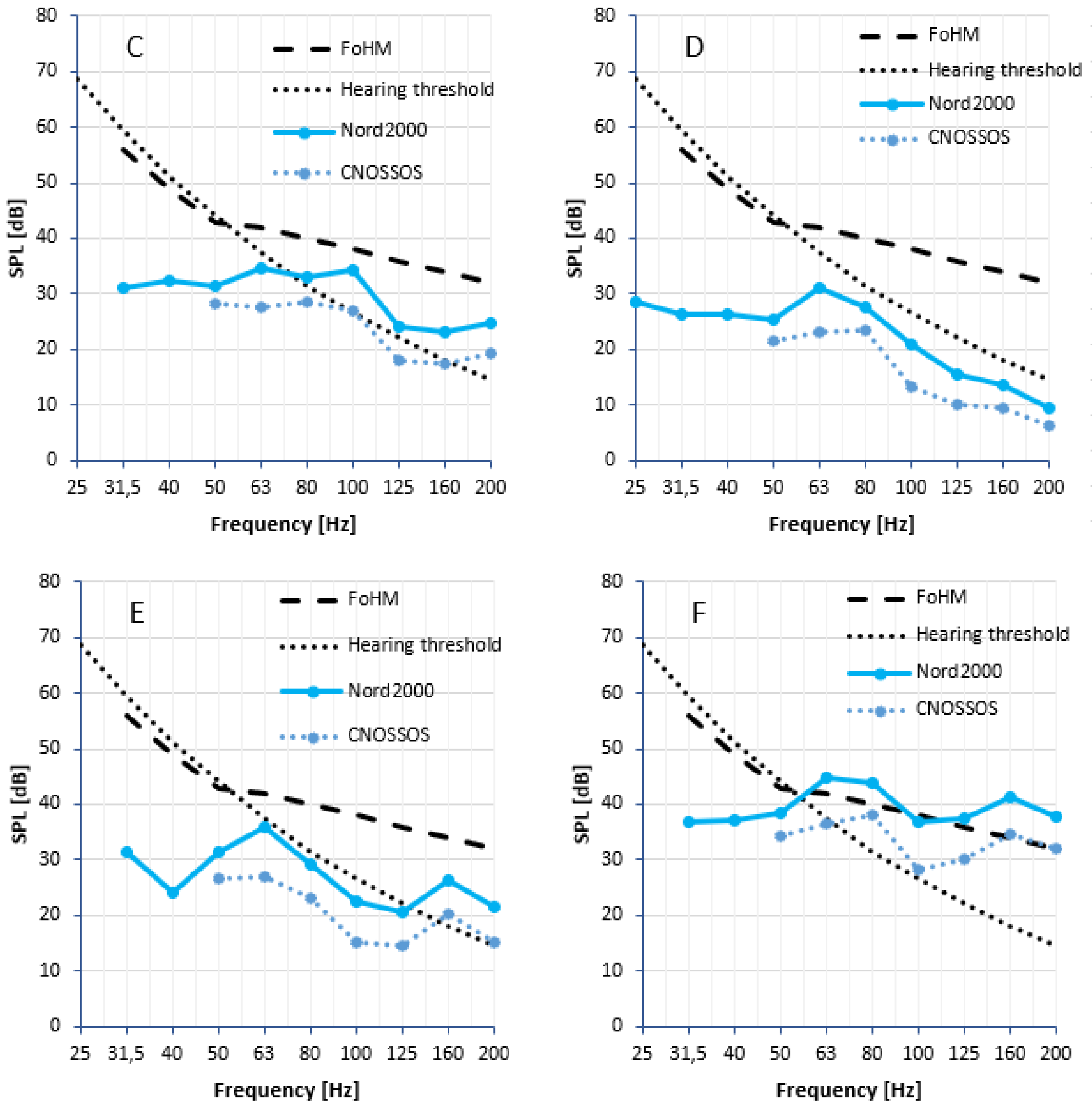

Figure 4.8: The unweighted equivalent sound pressure levels for 24h calculated according to the Nord2000 and CNOSSOS model in Soundplan compared to the hearing threshold and Swedish public health agency limit values for low frequency indoor noise.

In all four apartments, the equivalent level indoor are acceptable compared to FoHM values if using CNOSSOS model or right on the limit on the case of facade F if using Nord2000 model. The largest difference occurs at 63 Hz and is up to maximum of around 6 dB in level difference between the two models. Facade C and F have a similar sound insulation and traffic flow but the equivalent levels differ because of the distance from the facade wall to the road. The equivalent levels should only be compared to the FoHM limit since the hearing threshold is linked to passages, but the hearing threshold is included since it gives a perspective of the audibility of the equivalent levels.
The following figure shows the full spectrum of the equivalent level outdoors on a

point on the facade where the measurements were conducted

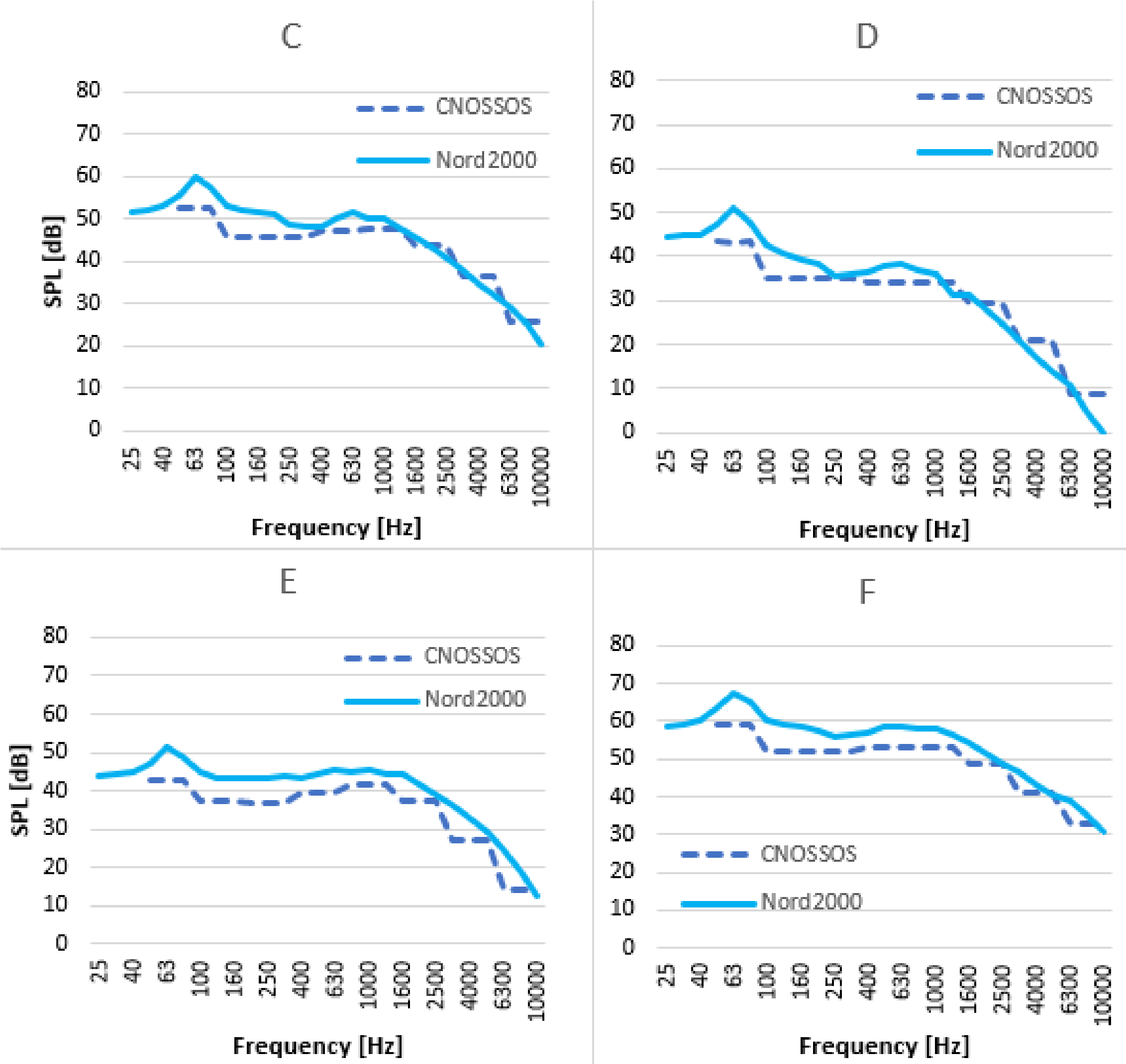

Figure 4.9: The full spectrum of the unweighted 24h equivalent level between the two models calculated in Soundplan.

Comparing the full spectrum, both models follow the same curvature, however CNOSSOS have a lower equivalent level as expected from the result in table 4.4. Furthermore, the peak at 63 Hz for both models shows that the highest equivalent levels are in fact in the low frequency region at 63 Hz.

4.3 Listening test

The listening test had in total of 23 participants ranging age wise from 23-54. None of the participants reported any hearing issues while 6 reported that their current living situation was affected from traffic noise.

4.3.1 Stimuli spectrum

The following figures shows the unweighted spectrum of each stimuli used in the listening test and presented for each participant

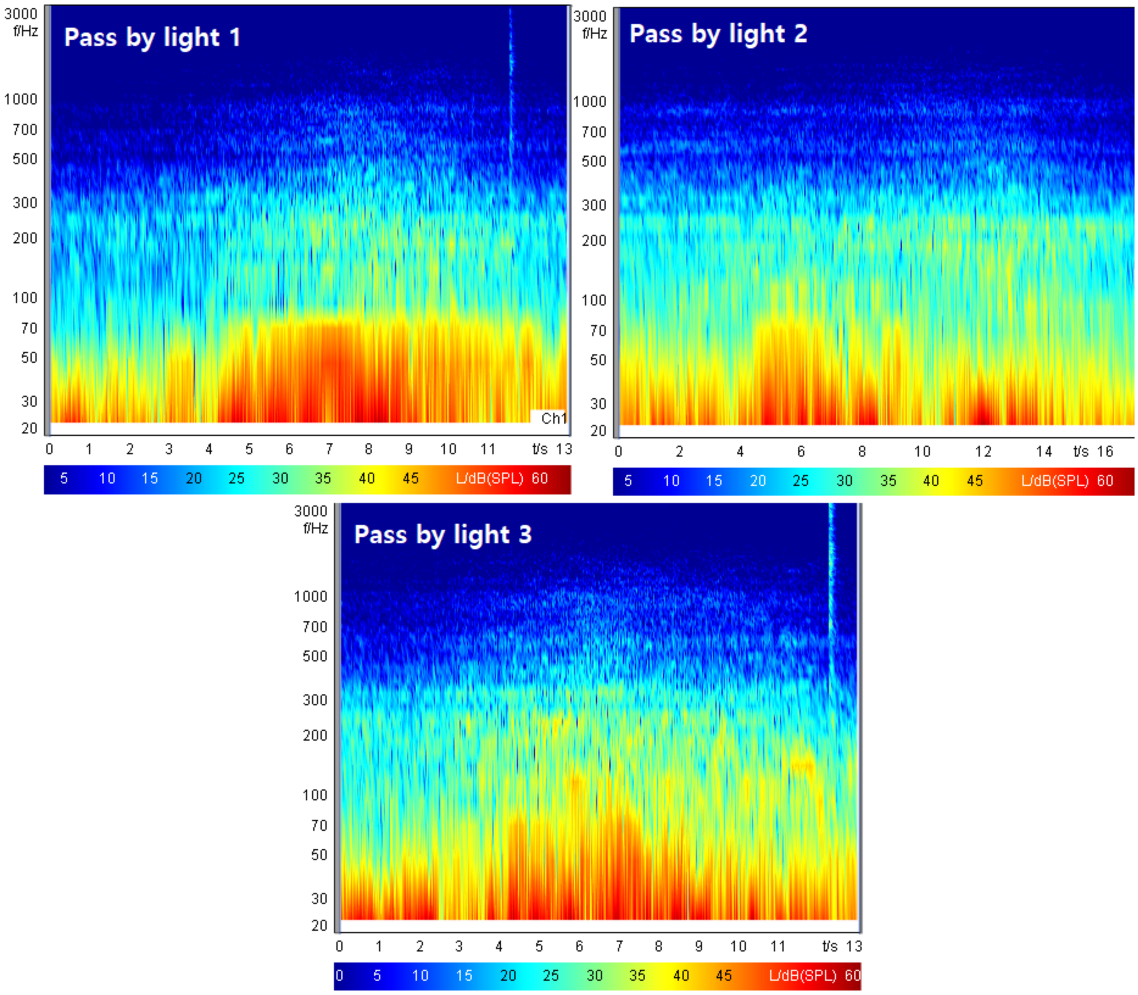

Figure 4.10: Stimuli of three passing by light vehicles measured indoors at the central zone in the case of facade F

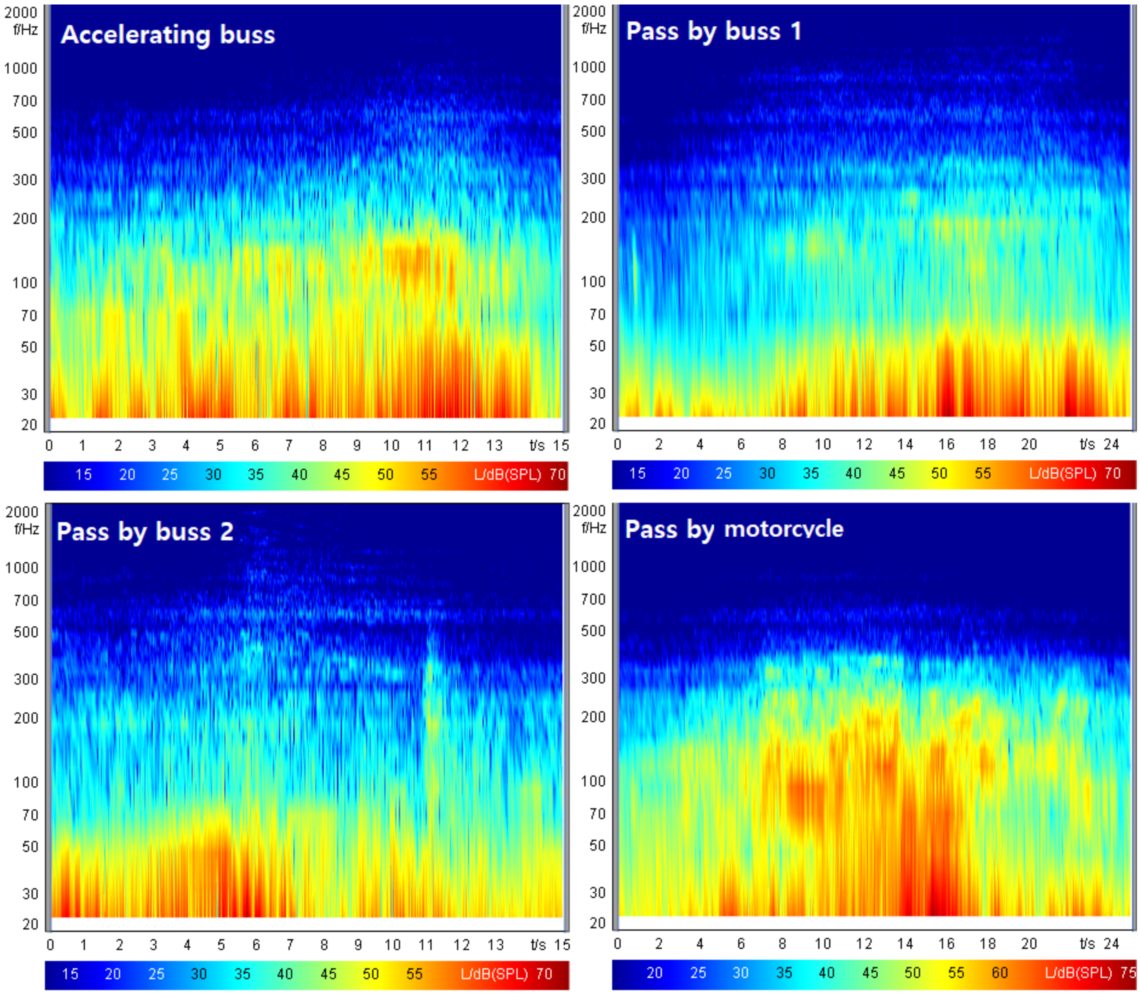

Figure 4.11: Stimuli of four different passing by heavy vehicles measured indoors at the central zone in the case of facade F

It can be seen that the heavy vehicles have a higher SPL for frequencies ranging from 20 to 150 Hz. In the case of an accelerating buss and a pass by motorcycle, the LF energy levels are higher compared to passing by busses and light vehicles with a constant speed. A motorcycle is not counted as a heavy vehicle but is presented as in the same category in this study because of the high sound levels in lower frequencies.

4.3.2 Listening test results

The following table presents a mean to all the answers for questions regarding light and heavy vehicle stimuli. The correlation between the verbal and numerical scale for both stimuli categories are matching.

	Light		Heavy	
	Numerical scale	**Verbal scale**	**Numerical scale**	**Verbal scale**
General	3	Slightly	4.7	Moderatley
Night	3.5	Slightly	5.8	Moderatley
Working	3	Slightly	5	Moderatley

Table 4.6: The mean answer for each question category from 23 participants during the listening test

The following figure shows the annoyance level estimated as described in section 3.2.2.1.

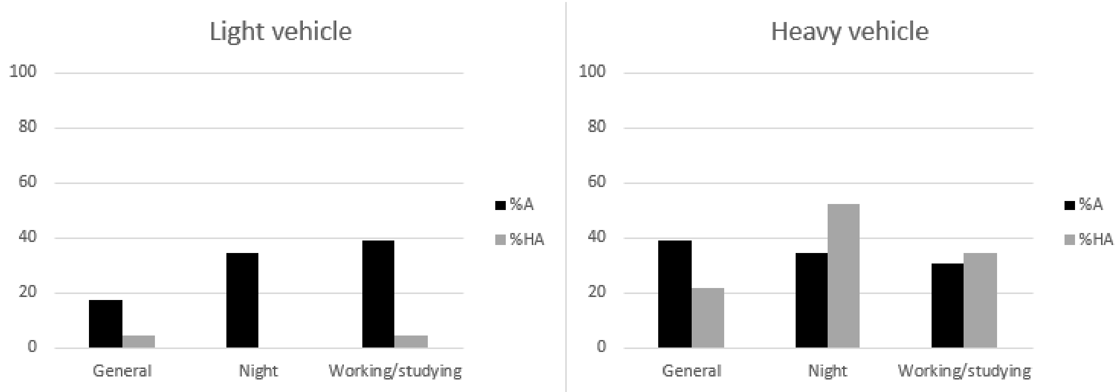

Figure 4.12: The amount of percentage of 'Annoyed %A' and 'Highly annoyed %HA' during the listening test for each question and vehicle category.

A higher amount of participants found the heavy vehicles annoying and are more heavily annoyed especially during night times and in working/studying environments and almost all of the participants found the heavy vehicles annoying during night time. For general annoyance, participants evaluated heavy vehicles generally as annoying as if they would be listening to light vehicles in a working or studying environment.

The following results shows the amount of people finding the unfiltered sounds vs stimuli with a low pass filter with a cut off frequency of 250 Hz most annoying.

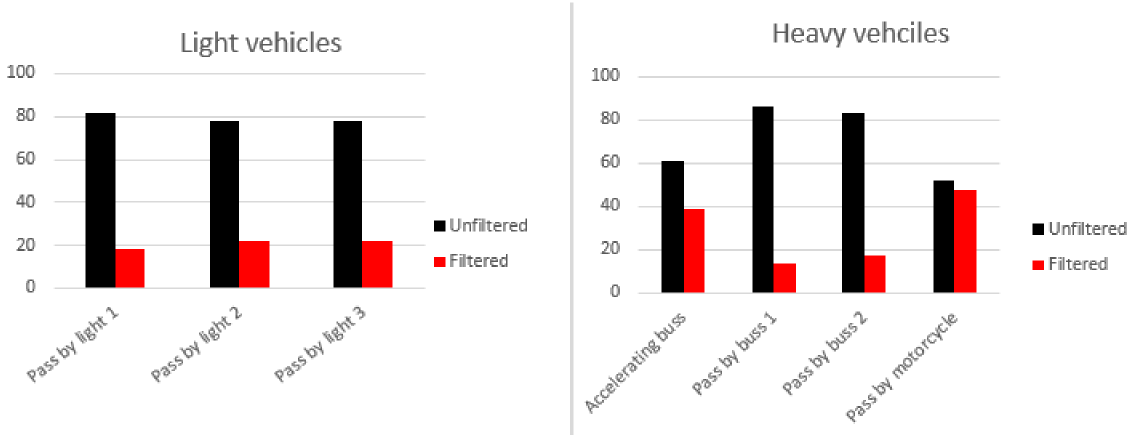

Figure 4.13: The amount of percentage of participants finding the unfiltered or filtered sound most annoying during the listening test

For light vehicles, about 80 % of the participants found the unfiltered stimuli as the most annoying. Again, for heavy vehicles, around 80 % of the participants found the unfiltered sounds in a pass by situation the most annoying.
In a situation of an accelerating heavy vehicle and pass by of a motorcycle, around 40–50 % found the filtered stimuli more annoying. Looking at the spectrum in figure 4.11, the low frequency contents are also higher and more prominent in the two stimuli.

5
Discussion

When projecting new apartments in Sweden, a detailed analysis of the facade insulation for low frequency noise (LFN) is not made since it is already accounted for in the single number quantities shown in table 4.2. The question that arises then is how well do the single values actually represent the insulation from traffic noise at low frequencies? The C_{tr} value adapts the spectrum to take LFN into account and looking at table 4.2, facade A has the highest $R'_{45,w}$ and $D_{ls,nt}$ but at the same time a low C_{tr} correction because of the worse insulation at lower frequencies compared to the mid and high frequencies as seen in figure 4.1. This could be interpreted as that the facade has a bad insulation from LFN, however the value of C_{tr} is highly impacted by the insulation at mid and high frequencies and in reality facade A has the best insulation at low frequencies compared to the rest of the studied facades. Furthermore, two facades with equal single values as in the cases E and F result in the same values of $D_{ls,nt}$ and C_{tr}, but the insulation at low frequencies varies as seen in figure 4.3. It is therefore not ideal to only use a single value with C_{tr} correction when studying insulation from traffic noise as the LF insulation highly varies even though the constructions are similar because of factors such as window- construction and sizes.

For all the studied facades we clearly have audible passages as seen in figure 4.5. In reality audible passages are not always a problem and need to be studied relatively to the situation. For example facade B has a distance of around 10 m to a residential road where the calculated indoor peak level is the highest for all the measured facades. This is however not a problem since there is nearly no traffic in the area and therefore we look at equivalent levels.
But comparing figure 4.4 and figure 4.8 the equivalent indoor levels do not give the full picture of the sound environment inside a dwelling as we have audible peak levels from passages in every apartment at low frequencies. In the case of apartment F, even though the indoor equivalent level are on the limit of what is acceptable according to FoHM regulations, the indoor environment would still not be ideal as seen in the result from the listening test where more than 30 % of the participants found passages of heavy vehicles annoying during night or studying time. As exemplified in figure 4.5 in the case of facade F and looking at the spectrum in figure 4.11 we have tonal components reaching 60 dB inside a dwelling for passing heavy vehicles which could be compared to speech conversational levels.
As we build closer to trafficked roads, single rated values such as $D_{ls,nt}$+C_{tr} becomes obsolete and should not be the only studied value since there is a risk that it undermines the low frequency noise protection inside a dwelling. The peak lev-

els calculated in 1/3 octave bands might be used as an improvement to assess the acoustic quality of indoor environment granted that it is related to the traffic flow, especially at more fragile hours such as night time or work hours which proved to be the most annoying hours as exemplified in the listening test.

Comparing the traffic noise models CNOSSOS-EU and Nord2000; CNOSSOS-EU generally estimates a lower SPL in the source model at low frequencies compared to Nord2000 as seen in figure 4.6 and 4.7. Since CNOSSOS is calculated using octave bands, the coefficient for propulsion and rolling noise for each octave bands could underestimate the noise levels which yields in a smaller levels when converted to 1/3 octave bands. Looking at the equivalent levels in figure 4.8 and 4.9, CNOSSOS-EU has lower equivalent levels compared to Nord2000 which most likely is because of the difference in the source models. Both source model could provide valuable information about pass-by levels in low frequency regions and both CNOSSOS-EU and Nord2000 can be used as complementary data when estimating peak levels at lower frequencies, however there is no clear indication which of the models yields the most accurate levels, therefore it is suggested to look at more recent research regarding CNOSSOS-EU adaptation terms for Swedish road conditions and see how the adaptation in source models compares to the one suggested by RISE [24].

Furthermore, Looking at table 4.4, there is a difference between 1-6 dB between using a single normalized level difference value compared to using the full spectrum when calculating the total A-weighted SPL. The difference could be because of the additional sound pressure levels which are added in the lower bands between 25-40 Hz which is not accounted for in the normalized level difference. However, looking at figure 4.5, frequencies from 25 to 40 Hz deems not to be a problem when looking at audible components since they are below our audible threshold (they should however not be excluded since at such frequencies vibrations can occur which is an aspect that has not been studied in this thesis). For the frequencies that are audible the listening test suggests that audibility is not always annoying for the user and is highly dependent on the type of vehicle and the strong 1/3 octave band components. For example, the majority of participants did not find the sounds as annoying if its peak spectrum was close to FoHM values as shown with the light vehicles in figure 4.12. This suggests that the recommended FoHM equivalent levels could be used as a guideline for peak levels to approximately estimate the quality of the indoor sound environment.
Furthermore, more participants found that the cases with an accelerating buss or motorcycle passing by more annoying when only listening to the filtered sound as seen in figure 4.12. Looking at the spectrum for both sounds in figure 4.11 the low frequency sound levels are high and not as constant, especially in the situation of a motorcycle which has more variation in the strength at the low frequency tones. The result suggests that in a case where a light or heavy vehicle is passing by with a constant speed (meaning that there are no significant variations in strength of the sound), it is not the LF contents that are the most annoying. The reason for this could be masking, looking at the spectra in figure 4.10 and 4.11, the mid frequencies are not higher in SPL than the low frequencies, but they could be perceived as louder

since the low frequency content is closer to our hearing threshold level meaning that the mid frequencies potentially mask out the lower frequency sounds.
It must be noted that for a listening test where the participants are exposed to the sound only once, it is more different than actually living in such an environment and experience disturbance from traffic noise on a daily basis. Furthermore there were only 23 participants in the study and participants with a high or low threshold to annoyance from noise could heavily impact the results. For example, six people stated that they were living in situations affected by traffic noise and their results showed generally a higher annoyance level compared to the rest of the participants.

How reliable are the results in this study? The measurement of low frequency noise can be varying from apartment to apartment with modes heavily impacting the measurements. In this study a large question has concerned, which positions are reasonable to measure in to evaluate the low frequency characteristics of a room? Using a mean value of different positions in the room such as the sweep and four corner positions might not be a valid choice since the mean is highly affected by the corner positions. At the same time, corner positions can not be counted out since inhabitants inside dwellings often place their beds or desktops at corner positions. One suggestion is to use the most likely position of rest inside the room to estimate the quality of the sound environment. In this study, only the central zone has been studied thoroughly since a slow sweep captures the mean of a large portion inside the room and the central zone is most likely a position of stay in a dwelling. An observation is that the standard deviation for DL in the central zone of the facades with similar construction are not that high at certain frequencies as seen in figure 4.4. In the future, one could make a statistical measurement study where the level difference is measured on a wide selection of apartments and calculate a mean DL for lower frequencies. One could us it as a foundation for future traffic noise assessments to approximate for example how many inhabitants would be disturbed if roads are rerouted or new roads are built in the vicinity of existing dwellings.

Looking at this study, it can be concluded that none of the facades has good insulation for low frequency noise. One could even reason that apartment A, C and D which have similar insulation in the low frequencies would get similar results for the listening test as for apartment F if the apartments were closer to a road and had 65 dBA equivalent noise level at facade, which in current regulations would acceptable for smaller apartments. This can potentially put different groups in the society at greater risk for noise exposure such as students with the consequence of future health issues. The question that arises is what is an acoustic engineers responsibility in this? The methods by using estimating peak levels, comparing it to our hearing threshold and the listening tests used to evaluate LFN can not be used as legal documents to prevent apartments from being built since the current laws and regulations does simply not support the framework. However, the following result could perhaps bring light to the issue and be used to exemplify the need of having certain special building remedies and solutions for apartments that are built in areas where the risk of LFN is high.

6 Conclusion

Single values for facade insulation with spectrum adaptation terms does not provide enough information about how well the sound reduction is in lower frequencies. As a consequence, the Swedish regulations in place will most likely not protect inhabitants inside dwellings from low frequency noise as we allow higher sound pressure levels at facade.

The result shows that the studied heavier constructions has a similar insulation in low frequencies between 20-200 Hz with deviations in certain frequencies mainly because of room modes, window construction and size. A proposal for the future is to investigate the possibilities to measure a large amount of facades with similar constructions in Sweden and calculate a statistical curve of the sound level difference in low frequencies to use in future traffic noise evaluations.

In the future, both CNOSSOS-EU and Nord2000 source models can be used to estimate peak levels of cars passing by however there is a difference in sound pressure levels between the two source models and there is no clear indication which of the models is the most accurate. It is suggested in the future to look at more recent research regarding adaptation of CNOSSOS-EU to swedish road conditions. Furthermore, the result shows that none of the studied facades isolate well against passages of cars in low frequencies and more audible tones can be expected as we build the closer to roads. The frequencies 25, 31.5 and 40 Hz could be disregarded in future assessments (vibration excluded) since the result shows that the peak levels from passages fall below our our hearing threshold in all the studied facades.

The listening test for one of the studied facades shows that more than 30 % of the participants find heavy vehicles passing by at night and studying/working time as annoying and that in situations where we have traffic with a constant speed, the low frequencies components are not the most disruptive. Instead, the low frequencies are more annoying when we have clear and strong change in sound pressure level at low frequencies in passages such as in an accelerating situation Furthermore, the results suggests that the FoHM equivalent levels limit could possibly be used as a guideline for peak level assessments in situations where we have no strong change in sound pressure level of the noise during the pass by situation.

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