TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

DIPLOMARBEIT

# LOW FREQUENCY NOISE LEVEL

# STUDY ASSESSMENT IN VIENNA

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Wien, Oktober 2017

# KURZFASSUNG

Vorliegender Beitrag berichtet über die Ergebnisse von Schallpegelmessungen an einer Reihe von Standorten in der Stadt Wien, Österreich. Primäres Ziel war es herauszufinden, inwieweit die Messergebnisse mit entsprechenden Informationen in der E.N.D. (Environmental Noise Directive 2002/49/EC) Karten übereinstimmen. Darüber hinaus wurde die Beziehung zwischen dem niederfrequenten Segment der akustischen Exposition gegenüber den Breitbanddaten untersucht. Die Ergebnisse deuten auf den Verkehr als Hauptquelle der städtischen Lärmexposition hin. END-Karten bieten die Möglichkeit sich einen aufschlussreichen. Überblick über die städtischen Lärmverhältnisse zu verschaffen. Das Messergebnis einzelner Standorte kann jedoch erheblich von END Daten abweichen. Nummerische Werte des niederfrequenten Schallpegelbereichs wurden im allgemeinen höher als die des breiten Frequenzniveaus eingeschifft. Die Ergebnisse zeigten auch eine starke Korrelation zwischen messbasierten L50 und NR Werten.

# ABSTRACT

This present contribution reports on the results of sound level measurements in a number of locations in the city of Vienna, Austria. Thereby, a primary objective was to determine the degree to which the measurement results agree with corresponding information in the E.N.D. (Environmental Noise Directive 2002/49/EC) maps. Moreover, the relationship between the low-frequency segment of the acoustical exposure to the broad-band data was investigated. The results point to traffic as the main source of urban noise exposure. END maps appear to provide a reasonable general overview of the urban noise circumstances. However, measurement result at individual locations can considerably deviated from END data. Numeric values of low-frequency sound level range were found to be generally higher than those of the broad-frequency levels. The results revealed also a strong correlation between measurement-based L50 and NR values.

Keywords

noise pollution, annoyance, low frequency, Environmental Noise Directive, sound frequency spectrum, equivalent levels, percentile levels, acoustical measurements, noise rating, room criterion, spatial sound distribution, waveform description.

# CONTENTS

# 1 INTRODUCTION

## 1.1 Overview

The industrialization and mobilization of human endeavor have lead to increased noise production across the full range of sound frequencies. This global problem is known as noise pollution.

Acoustical planning, as defined by the Environmental Noise Directive (E.N.D.) of the European Parliament and Council, represents the process of controlling future noise by planned measures. Due to its nature and behavior, noise is a difficult matter to identify and measure let alone to find strategies to attenuate its effects. The physical means by which noise is detected, recorded, measured and diminished have advanced considerably. Despite these advancements, lack of actual proper field measurements may hide the true nature of the problem. Measurements in controlled environments used in concordance with simulations generally refer to a narrow spectrum of frequencies, a largely ideal acoustical environment and a generalized model of the human ear. Many earlier studies may be suspected of failing to control the variety of confounding effects of the data reported.

## 1.2 Motivation

The shear vastness of sources and the complexity of noise propagation in an urban environment require field measurements. As there is a general lack of accurate acoustical field measurements, the following research could help lead to a better evaluation of the daily acoustical environment quality. This may also imply a broader recording frequency spectrum.

The sensitivity of the human body towards sound is not limited to the auditory system. Either physical or psychological, noise outside the human hearing spectrum may have severe effects on people.

Noise below 250Hz is generally considered to constitute low-frequency noise. The legislation tends to ignore sound below 20Hz as it is not considered noise on the grounds that it is inaudible.

Low frequency noise is of a particular importance as it covers a wide range of frequencies and can have numerous and diverse sources (especially in urban environments). Due to the nature of low frequency noise, typical active or passive noise attenuating or insulating solutions have very little to no effect when the sound sources cannot be individually identified.

## 1.3 Goals & Hypothesis

Vienna is a dynamic acoustical environment. Field measurements can reveal noise values with various different sources, patterns and potential effects. The goal of the present study is a better understanding of the true nature of such an acoustical environment and the role that low frequency noise plays in it.

It is assumed that measured noise pressure levels exceed the E.N.D. noise map estimations in the city of Vienna. This difference is considered to be due to low frequency noise previously not included in the assessments.

To investigate if the low intensity noise represents an annoyance factor in the acoustical environment of Vienna, comprehensive measurements of noise in a wider frequency spectrum at key points of the city need to be performed. In interpreting the results, three questions need to be answered:

- How do the measured values relate to the E.N.D. noise map estimations?
- How do the measured values in the low frequency spectrum relate to overall noise equivalent levels?
- How does noise distribution affect the acoustical environment in the chosen locations?

## 1.4 Background

### 1.4.1 Overview

Noise exposure in Vienna, as in other cities, often remains above the target limits. Many measures, some of which were started as early as the mid-1980s, have contributed successfully to reducing noise pollution in the recent years.

The implementation of the Environmental Noise Directive (2002/49/EC on the assessment and abatement of environmental noise) is providing data on the noise situation in conurbations caused by road and rail traffic, aircraft and IPPC facilities (industry). E.N.D. recommends the use of computational methods in determining the acoustic indicators. These are necessary for creating a strategic noise map, which in turn is made accessible to the public as a rough assessment of the acoustical environment.

### 1.4.2 Low Frequency

Low frequency sound has features not shared with noises of higher frequency. It crosses great distances with little energy loss and can very efficiently propagate both through solid objects (such as building structure and walls) and open air. As a result, it is also less attenuated by insulating materials.

Low-frequency sound may also produce vibrations and rattles as secondary effects (World Health Organization, Guidelines for Community Noise, 1999). Similarly, it is able to produce resonance in the human body and it causes great subjective reactions. Thus, annoyance ratings grow rapidly towards low frequencies.

### 1.4.3 Objective Attributes

At times when higher frequencies are dampened (i.e. by insulating materials), or during the night (when surrounding noise is reduced), low frequencies will dominate the spectrum of perceived noise (Persson and Bjorkman, 1988).

The following chart depicts the Watanabe and Møller (1990b) of measured human hearing threshold. The values are shown to be very close to the ISO 389-7 (1996) threshold down to 20Hz. Under this frequency, at about 15Hz, a change can be seen in threshold slope.

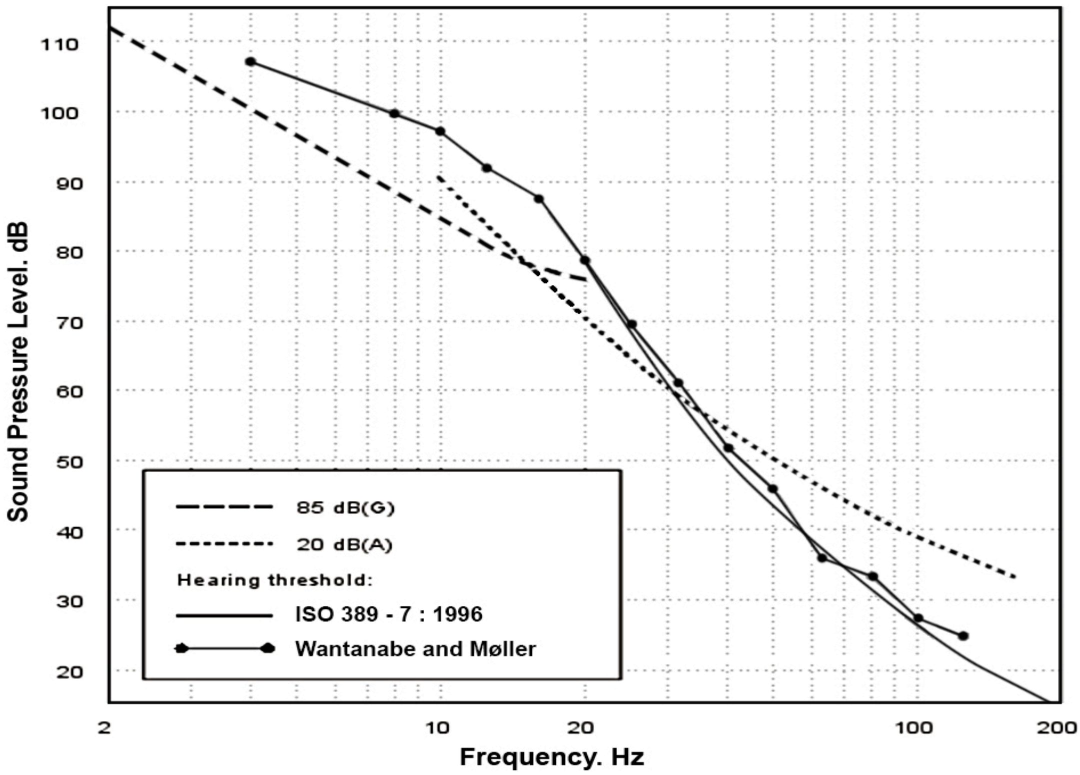



*Fig. 1 Threshold levels - Wantanabe and Møller (1990)*

The chart also depicts the intersection of the 85dB A-weighted and the 20dB G-weighted limit lines. This is considered to be a result of change in the aural detection process and loss of tonality in the auditory sensation. It is though an average value.

Hearing thresholds are in fact individual and may vary based on many criteria. Following experiments (Cohen, 1982; Frost, 1987) and analysis of audiograms of people susceptible to noise (Walford, 1978; Walford, 1983), it can be stated that part of the complainants that spend a great deal of time listening to and for their particular noise may develop in time, enhanced susceptibility to this noise. There is evidence that the brain is able to adapt to stimuli and enhanced susceptibility is a factor in low frequency noise assessment.

Loudness is a measurement that also depends on individual estimation. Loudness is measured against a template tone at 1000Hz. The following chart shows the equal loudness contours above 20Hz. There can be seen a tendency for the lines to come closer together towards low frequencies. If at mid-frequencies a doubling of loudness is expressed by a 10dB increase, at 20Hz the same increase in loudness occurs for a 5dB level change.

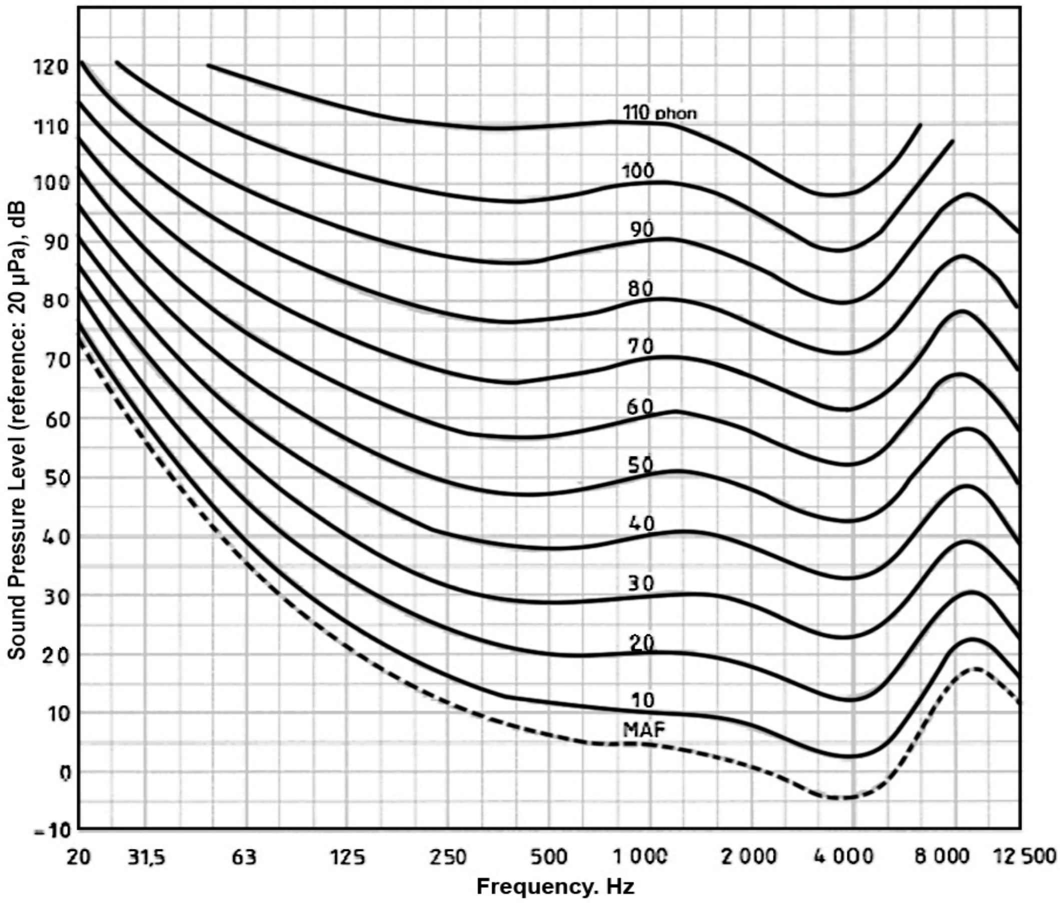



*Fig. 2 Equal loudness contours - ISO 226*

Following the studies of Møller & Andresen (1984) and Whittle et al. (1972) it is generally agreed that at lower frequencies, loudness grows even more rapid at ever-tighter distances between levels. This is an important factor in subjective estimations.

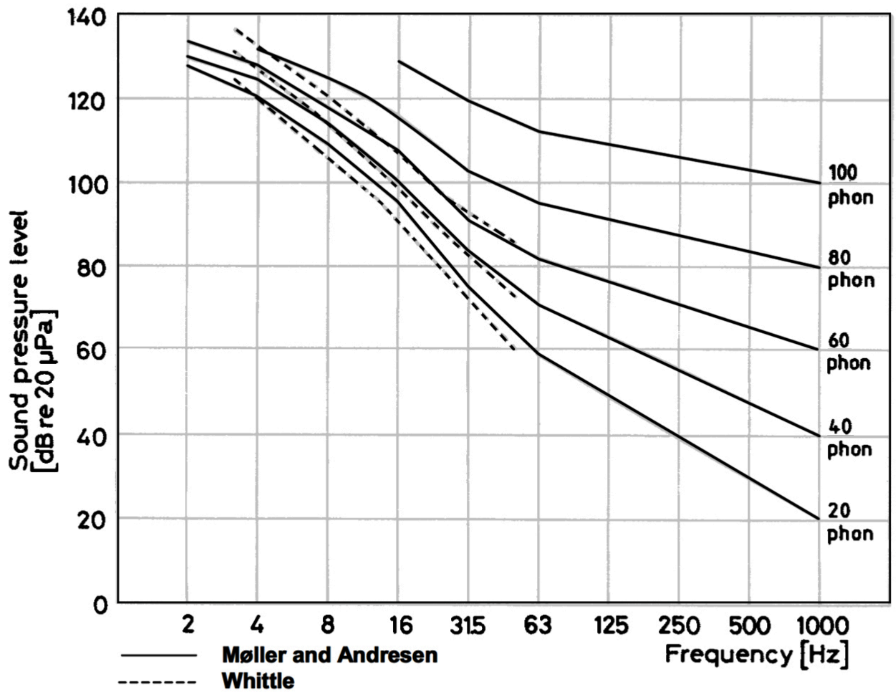



*Fig. 3 Loudness Measurements - Møller and Andresen, 1984*

According to von Gierke and Nixon (1976), low frequency sound is registered by the auditory system through a much more indirect process. The relevant nerves are fired by changes in other biological structures in the ear. These in turn are triggered by nonlinearities of conduction in the middle and inner ear. As a result, harmonic distortions are generated in the higher, more easily audible frequency range.

The human body was shown to have sensitivity to vibration from a region below 0.5 Hz to at least 100 kHz and even up to 200 kHz (Rao and Ashley, 1976).

According to Tierney Jr et al. (2003), infrasound perception is not associated to any medical condition. Despite this, infrasound can certainly induce abnormal body resonance. Moreover, it can induce central nervous system and ear symptoms that can lead to stress. This may lead in turn to symptoms of actual medical conditions.

Body organs may resonate with low frequency airborne noise waves. Although, this is to be differentiated from mechanical transmitted vibrations.

Following the works of Brown (1976), Kyriakides (1974) and Leventhall (1977), the most prominent occurrence of body resonance to airborne noise is in the chest area. Despite this, it was not enough to cause significant body vibrations. The body will mask excitations resulting from levels of noise below 70-80dB. This statement was supported also by later studies such as Takahashi et al., (2002) and Takahashi and Maeda (2002).

The same can be said about the direct effects of low frequency noise on the respiratory system (Gierke and Nixon, 1976) and on the vestibular system (Parker, 1976). For lower frequency noise to induce serious effects on the human body, the sound pressure levels required need to be of 140dB and above. Such scenarios are unlikely to be of practical importance except in extreme occupational exposure (such as a rocket launch).

On the other hand, a much more pronounced effect of lower frequency noise on the human body takes place at a more profound level. Acoustical and psychological studies (Kitamura and Yamada, 2002) have shown such noise effects on the limbic system. This part of the brain is responsible for survival and emotional behaviors and thus we have very little control over it. Noise disturbs, and irritates it, thus inducing several symptoms of actual medical conditions such as: sleep disorders, headache, palpitation, vertigo, nystagmus, nausea, mental changes and hallucinations (usually auditory).

Cortisol secretion is used as a stress indicator. The human body is most susceptible to stress factors at night before sleep and about 30 minutes after awakening. Low frequency noise exposure may disturb (Ising and Ising, 2002; Persson-Waye et al., 2002; Persson-Waye et al., 2003), or even induce increased levels of catecholamine and cortisol (Cantrell, 1974; Cavatorta et al., 1987; Welch and Welch, 1970).

Other hormonal changes such as endocrine system are also related to noise. If prolonged they may result gradually in significant health-related effects such as: decreased immunity, increased heart rate and blood pressure, and cardiac arrhythmias (Averill, 1973; Job, 1993; Lundberg and Frankenhaeuser, 1978).

### 1.4.4 Annoyance

Sound waves perform and interact differently, in different scenarios at different frequencies. They are interpreted differently by each receptor according to objective and subjective factors. These factors can be physical or psychological.

The real effect of low frequency noise on the human body lies in the psychological effect as an annoyance factor. Noise annoyance is a state of discomfort associated to acoustical signals, which are not compatible with the activity performed by the listener. This is particularly true when the source cannot be identified. The annoyance factor is always attributed though to specific or complex of origins and is moderated by personal and/or social attributes of the listener.

Some factors contributing to noise annoyance can be monitored and measured. These refer to the nature of the sound, such as: sound pressure level, frequency of the sound wave, duration, repetition and time sequence of the noise. Others relate to the receptors attributes: activity typology, voluntary level of exposure and physical fitness.

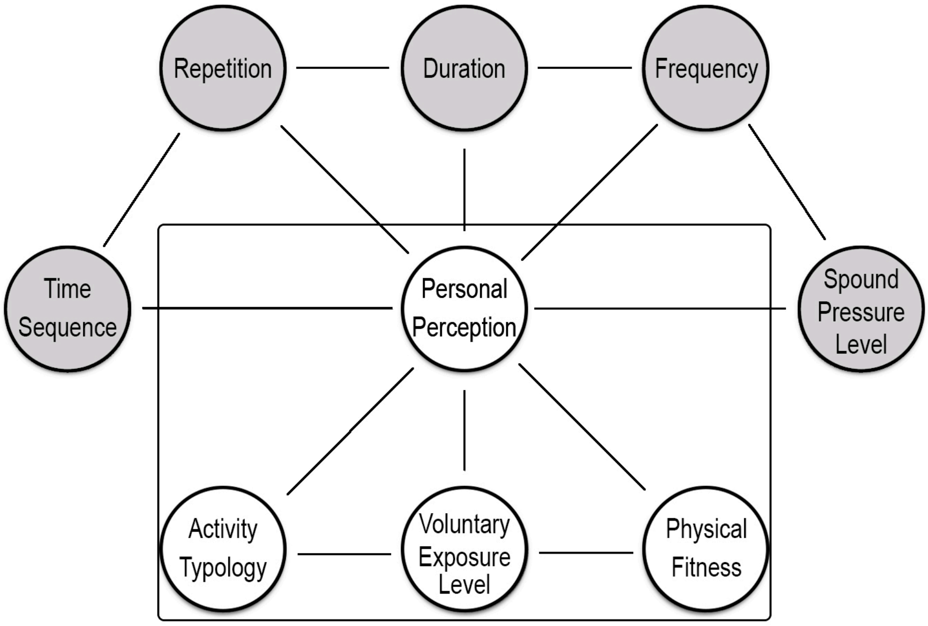



*Fig. 4 Factors contributing to Noise Annoyance - Guski, 1999*

Personal reception is defined by subjective interpretation. According to the paper “Personal and social variables as co-determinants of noise annoyance” (Guski, 1999) subjective interpretations can depend on both personal and social moderators. Personal moderators can be: sensitivity to noise, anxiety about the source, personal evaluation of the source and capacity to cope with respect to noise. At the same time, social moderators can be: evaluation of the source, suspicion of source controllers, history of noise exposure and expectations.

These factors are subject to a complex psychological analysis and may vary based on the subjective interpretation of the receptor. For these factors we will rely on previous studies.

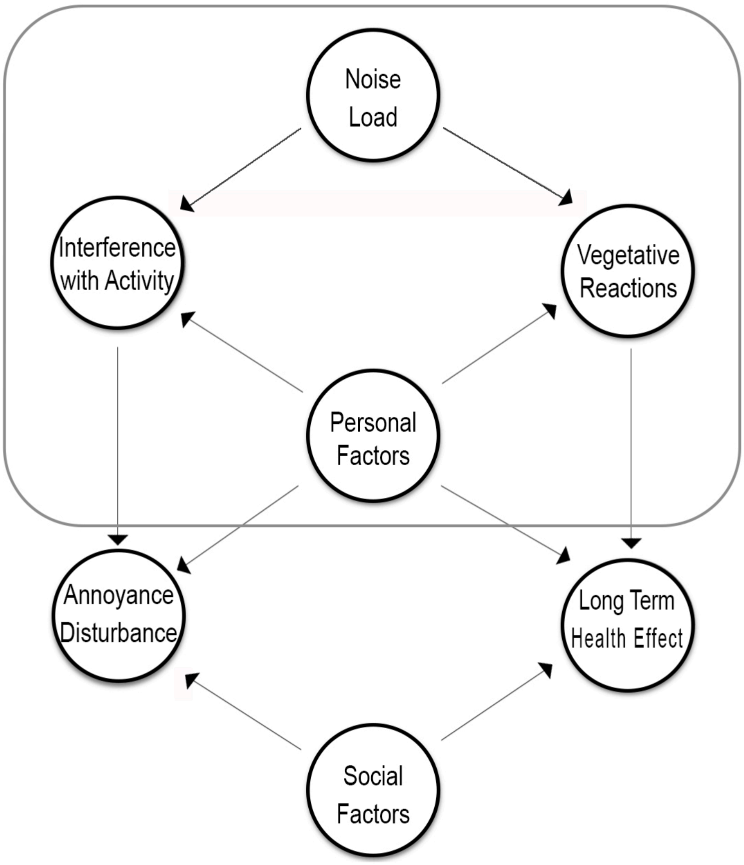



*Fig. 5 Factors moderating noise annoyance - Guski, 1999*

As seen below in the following chart (Møller, 1987), low frequencies have to be at a higher level to be heard but once audible, the annoyance factor increases rapidly. This is important as it shows that loudness contours are reflected in annoyance perception.

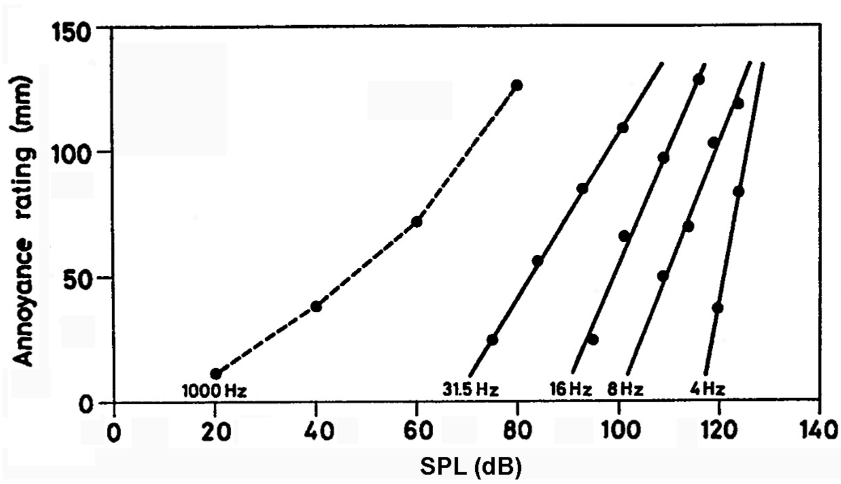



*Fig. 6 Annoyance rating, showing rapid growth at low frequencies - Møller, 1987*

There are though, according to other studies (Persson et al., 1985, Persson and Bjorkman, 1988; Persson et al., 1990), clear differences in the perceptions of tones and bands of noise. Moreover, according to the chart below (Inukai et al, 2000), sound that is audible is not necessarily unacceptable. Unpleasantness contours are in close relation to the perception and activity performed by the subject.

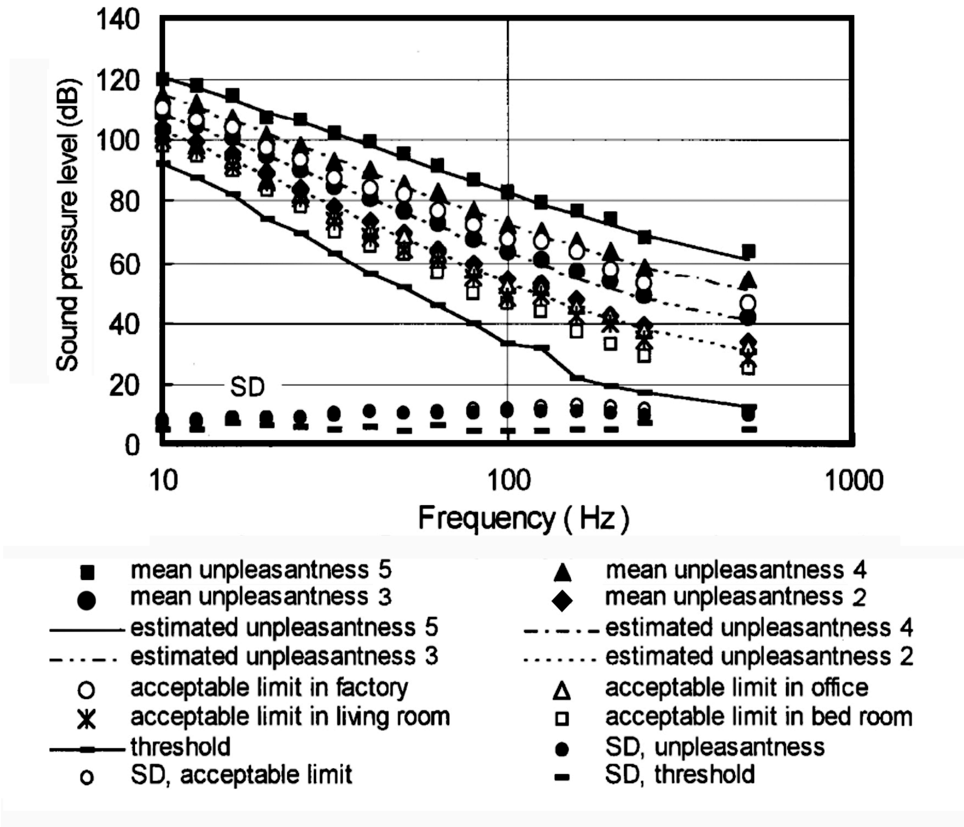



*Fig. 7 Single tone unpleasantness contours - Inukai et al, 2000*

The work of Inukai et al (2000) applies though only to single tones. For wideband noises such as found in real scenarios, spectrum balance needs to be also taken in consideration. The following chart (Bryan, 1976) gives a rough indicator for noise spectrum balance acceptability parameters. Subsequently, other studies have given different (of which some contradicting) results. On the other hand, the work of Bryan (1976) exhibits subjects that have been exposed to real settings and that is why it is found to be more appropriate for the present study.

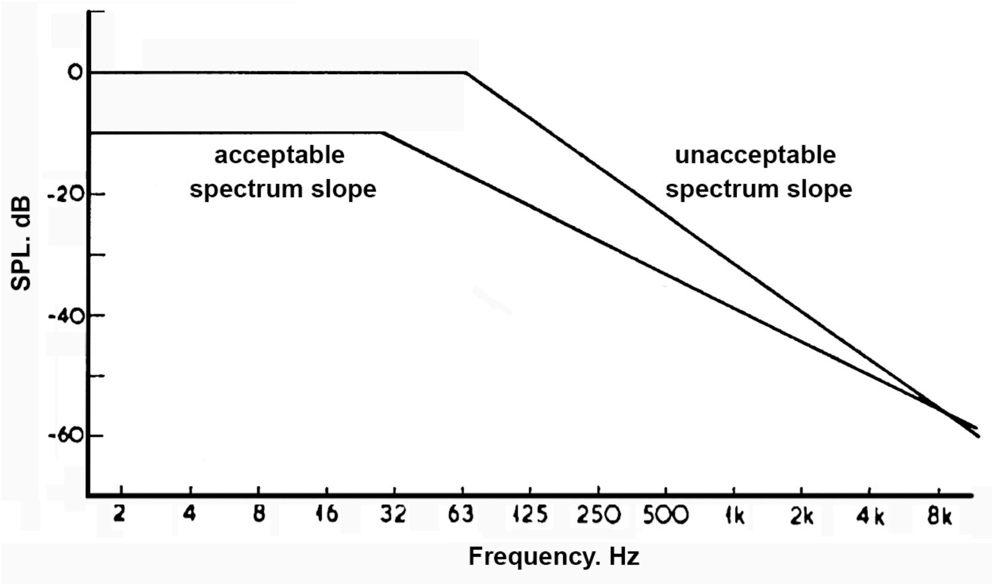



*Fig. 8 Spectrum balance acceptability parameters contours - Bryan, 1976*

Another factor of annoyance is represented by noise level oscillations. In the work of Holmberg et al (1997), significant correlation was found between noise level variation and annoyance. This is generally described as throbbing or of a pulsing nature. Following another study (Bradley, 1994), for the same effect to be noticed, greater fluctuation levels of the low frequencies are implied.

Unidentified persistent low frequency noise is generally termed as "hum". The descriptions may vary. The higher frequency equivalent may be described as a hiss. Regardless, the characteristics and effects occur all over the world with close similarity. The effects of the "hum" tend to affect more the middle aged and elderly people, especially women.

### 1.4.5 Noise Control

The primary source of interior noise is the use and occupancy of the building. Exterior disturbances act in this case as background noise. Outdoor noise specifically in the presently studied urban environment consists primarily of rail, road and air traffic.

Noise control is applied in three stages: at the source, along the path and at the receiver. The most effective control takes place at the source. This is particularly true in the case of the pervasive nature of low frequency noise. It is achieved during the design and manufacturing phases of the product. It is only when further noise reduction at the source is not practical that the control must take place along the path and/or at the receiver.

# 2 METHOD

## 2.1 Selected Locations in the city of Vienna

For the purpose of this study, certain interest areas were selected as representative scenarios. The selection was done in respect to the E.N.D. estimated map and attempting an even distribution of recordings in the city of Vienna. Each of these locations was chosen to be in the proximity of at least one major low frequency noise source. In the absence of a representative noise producing large industry example, the paper will focus on transportation mediums.

In reaching it's goal, the research intends to determine the way noise performs in each of the scenarios. To this end, several representative recording points were established for each interest area.


*Fig. 9 Map showing the recording points within the city of Vienna*

| Location | Scenario | Time of day |
|---|---|---|
| **Karlsplatz** | Inside/Closed Windows **TUWien/Boecklsall** | Morning<br>Noon<br>Evening |
| | Inside/Open Windows **TUWien/Boecklsall** | Morning<br>Noon<br>Evening |
| | Inside/Basement | Morning<br>Noon<br>Evening |
| | Outside/Park **Resselpark** | Noon<br>Evening |
| | Outside/U-bahn prox. **Otto Wagner Pavillion** | Morning<br>Noon<br>Evening |
| **Alserstrasse Station** | Inside/Closed Windows **Leo-Slezak-Gasse 6 / 3rd floor** | Morning<br>Noon<br>Evening |
| | Inside/Basement **Leo-Slezak-Gasse 6** | Morning<br>Noon<br>Evening |
| | Outside/Block prox. **Leo-Slezak-Gasse 6** | Morning<br>Noon<br>Evening |
| | Outside/U-bahn prox. **Währinger Gürtel 11** | Morning<br>Noon<br>Evening |
| **Stadt Mitte** | Inside/Closed Windows **Marxergasse 13 / Loft-Roof** | Noon<br>Evening |
| | Inside/Open Windows **Marxergasse 13 / Loft-Roof** | Morning<br>Noon<br>Evening |
| | Outside/Block prox. **Marxergasse 13** | Morning<br>Noon<br>Evening |
| | Outside/U&S-bahn prox. **Stadt Mitte** | Morning<br>Noon<br>Evening |
| **Mariahilfestrasse Inner Ring** | Inside/Closed Windows **Gerngross Center** | Morning<br>Evening |
| | Inside/OpenWindows **Gerngross Center** | Morning<br>Evening |
| | Outside/Block prox. **Gerngross Center** | Morning |
| **Schwechat** | Outside/**Airport prox.** | Morning<br>Noon<br>Evening |
| | Outside/Railway, Highway knot **Mannswörther Straße 188** | Morning<br>Noon<br>Evening |

| Location | Scenario | Time of day |
|---|---|---|
| **Mariahilferstrasse Outer Ring** | Inside/Closed Windows **Arnsteingasse 25 / 2nd floor** | Morning<br>Noon<br>Evening |
| | Inside/Open Windows **Arnsteingasse 25 / 2nd floor** | Morning<br>Noon<br>Evening |
| | Outside/Park **Henriettenplatz** | Morning<br>Noon<br>Evening |
| | Outside/Bulevard **Mariahilfer Strasse 172** | Morning<br>Noon<br>Evening |
| | Outside/Railway prox. **Schmelzbrückenrampe 2** | Morning<br>Noon<br>Evening |
| **Meidling** | Inside/Closed Windows **Reismannhof 13 / 2nd floor** | Morning<br>Noon<br>Evening |
| | Outside/block **Längenfeldgasse 31** | Morning<br>Evening |
| | Outside/Under train bridges **Längenfeldgasse** | Morning<br>Noon<br>Evening |
| **Tangente Highway/ Bridge** | Inside/Closed Windows **Baumgasse 79** | Morning<br>Noon |
| | Outside/Block prox. **Baumgasse 79** | Morning<br>Noon<br>Evening |
| | Outside/Highway prox. **Baumgasse 89** | Morning<br>Noon<br>Evening |
| **Tangente Highway/ Tunnel exit** | Inside/Closed Windows **Katherinnengasse 9** | Morning<br>Noon<br>Evening |
| | Outside/Highway prox. **Katherinnengasse 9** | Morning<br>Noon<br>Evening |
| **DonauCity** | Outside/Over tunnel **Donau-City-Straße 11-13** | Morning<br>Noon<br>Evening |
| | Outside **Kaisermühlentunnel Exit** | Morning<br>Noon<br>Evening |

*Fig. 10 Table indicating the location of each recording*

## 2.2 Noise rating methods

There is no universal optimum method to evaluate any acoustical environment. What some gain in precision, others gain in practicality. Moreover, there is always the issue of individual sensitivity and subjective interpretation of the receiver.

As a result, several methods of evaluation are required to better describe and quantify the acoustical environment of the city of Vienna. These are to be used in correlation to each other as to produce a more comprehensive picture of the subject assessed.

### 2.2.1 Environmental Noise Directive (END)

Directive 2002/49/EC regarding the assessment and management of environmental noise is the main EU instrument to identify noise pollution levels and to trigger the necessary action both in member states and EU level. The Directive requires Member States to prepare and publish, every 5 years, noise maps and noise management action plans with the consult of the concerned public.

Noise levels generally vary with time, so noise measurement data is reported as time-averaged values to express overall noise levels. Noise equivalent level (Leq) can be used to express an average sound pressure level (SPL) over any period of interest, such as an eight-hour workday. Leq is a logarithmic average rather than arithmetic average, so loud events prevail in the overall result.

### 2.2.2 Day-Evening-Night Equivalent Level ($L_{den}$)

The European Noise Directive introduces a new time related noise metric expression Lden. In this case, each value is described as an equivalent noise average over the day-evening-night (Lden) period. This accounts for the fact that people are more sensitive to noise during the night, so a 10-dBA penalty is added to SPL values that are measured between 22:00 and 6:00. A similar surcharge of 5 dB is also added to the evening period as of 19:00 to 22:00.

These are probably not the best indicators with respect to audibility/detectability due to the large diversity of sources and the intricate propagation of noise in real environments. However, these indicators have the advantages of simplicity and conformity. As the member countries start producing noise maps and making action plans, these indicators will be readily available for communities all over Europe.

The noise maps of Vienna serve the public information as well as strategic acoustical planning and thus form the basis for the environmental noise action planning. However, they are not intended for describing individual noise exposure.

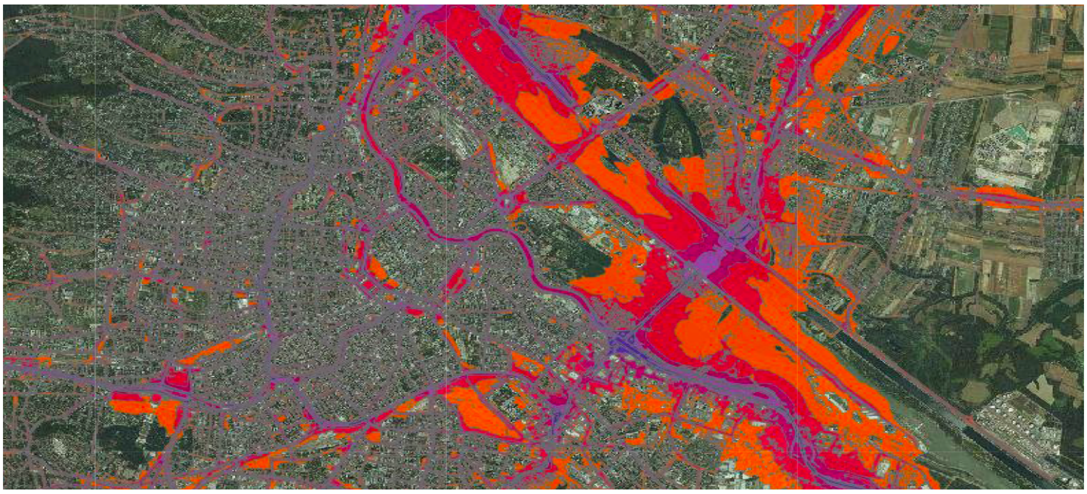


*Fig. 11 Noise Map of Vienna, Austrian Misnistry of the Environment 2015*

Results from road traffic noise measurements along the city streets have traditionally been presented as facade levels. This implies that the reflection from the house facade has been included. Similar results without the facade reflection, so called free field conditions, would be 3 dB lower. Lden values are per definition always referred to as free field conditions. It is therefore important to verify the measuring conditions when comparing results from different studies.

The values in the noise strategic map are expressed as 5dB intervals ranging from 55 to 70dB. They also represent the noise pollution at a height of 4m above the ground, thus distancing them from an accurate estimation at the street level.

Controlled environment measurements are used as reference samples of specific noise sources throughout the city. The noise emissions for road and rail traffic are mainly determined from traffic volume, speed for both personal and cargo vehicles. With the help of simulation programs, values are determined from calculated extrapolations of control environment measurements and applied to real urban scenarios. The calculation procedures in Austria are defined in standards and guidelines as follows:

- Traffic Noise: RVS 04:02:11 (1 March 2006)
- Railway Noise: ONRegel 305011 (1 September 2004)
- Aircraft noise: ÖAL Directive 24-1 (January 2004)
- Commercial or industrial systems:
  ISO 9613-2 (December 15, 1996) or a similar method of calculation

According to Miedema et al. (2001), the following equation was found to be true for road traffic. This is the main noise source in the recordings performed for the present study. Due to lack of infrastructure to perform 24h recordings, the following relation will be used to determine Lden values from measured LAeq.

*Lden - LAeq,24h = 4 dB* (1)

### 2.2.3 A-Weighted Equivalent Level (LAeq)

Frequency filters serve to match meter readings with the sensitivity of the human ear and the relative loudness of various sounds. These are the simplest of the available rating metrics because they can be read directly on a typical sound level meter (SLM) with the respective filter.

The A-weighted filter, for example, is most commonly used for measuring ambient community noise. A-weighted sound level is most frequently encountered in the evaluation and rating of outdoor environmental noise, but it also has application indoors for assessing potential annoyance in presence of background noise and in specifying limits for human exposure to high-level noise. SPL measurements made with this filter are expressed as A-weighted decibels, or dBA.

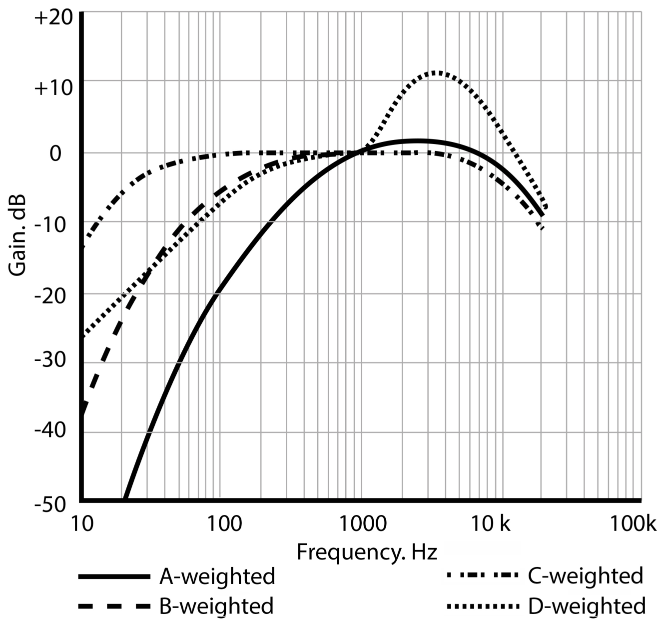



*Fig. 12 A, B, C & D weighting contour lines graph - IEC 61672:2003*

According to studies (Persson et al. (1985), Persson and Bjorkman (1988); Persson et al., 1990) the A-Weighted filter is relevant only over a limited spectrum of frequencies and underestimates annoyance for frequencies below about 200Hz. Due to the lack of more relevant and generally acknowledged filters for lower frequencies, values will be considered in Z-Weighted (no filter) S.P.L.

### 2.2.4 Percentile Levels

Minimum and maximum levels are poor descriptors for the background sound level. The dynamic range for the instantaneous sound level can vary from about 15 dBA to more than 40 dBA depending on the distance from dominating sources.
Miller (2008) concludes that audibility is closely related to spectral differences between the background noise and the disturbing sound, and also the instantaneous level. Percentile levels, i.e. the level that is exceeded a certain percentage of the time, may be a better indicator than an energy integrated index. Ln, where n may be anything from 1 to 99, is that noise level exceeded for n% of the measurement time. By definition of percentiles, L1 must be greater than or equal to L2, which must be greater than or equal to L3, etc. It is often the case that only a few Ln values are ever used.

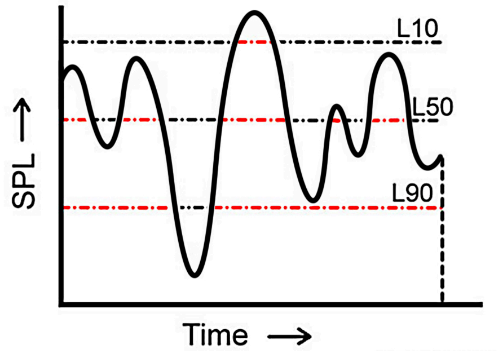



*Fig. 13 Percentile description - Noise Measurement Manual - Queensland, 2013*

L90 is generally considered to be representing the background or ambient level of a noise environment. L10 is the noise level exceeded for 10% of the time of the measurement duration. These higher sound pressure levels are probably due to spontaneous, sporadic or intermittent events. L50 is the noise level exceeded for 50% of the measurement duration. It represents the median of the fluctuating noise levels. Miller (2008) has concluded that the best representation of a “baseline” level to assess audibility of intruding sounds is the daytime median sound level, L50.

### 2.2.5 Noise Level Estimation

There are many methods of estimating Loudness using objective measurements in consideration to frequency spectrum analysis. No method is perfect. Zwicker‘s method makes use of several psychoacoustic principles in a calculation process to give an estimate of the „average person‘s“ impression of the Loudness of sound. It is still considered to offer the most elaborated results. Nevertheless this implies complicated procedures and is limited at low and high frequencies.

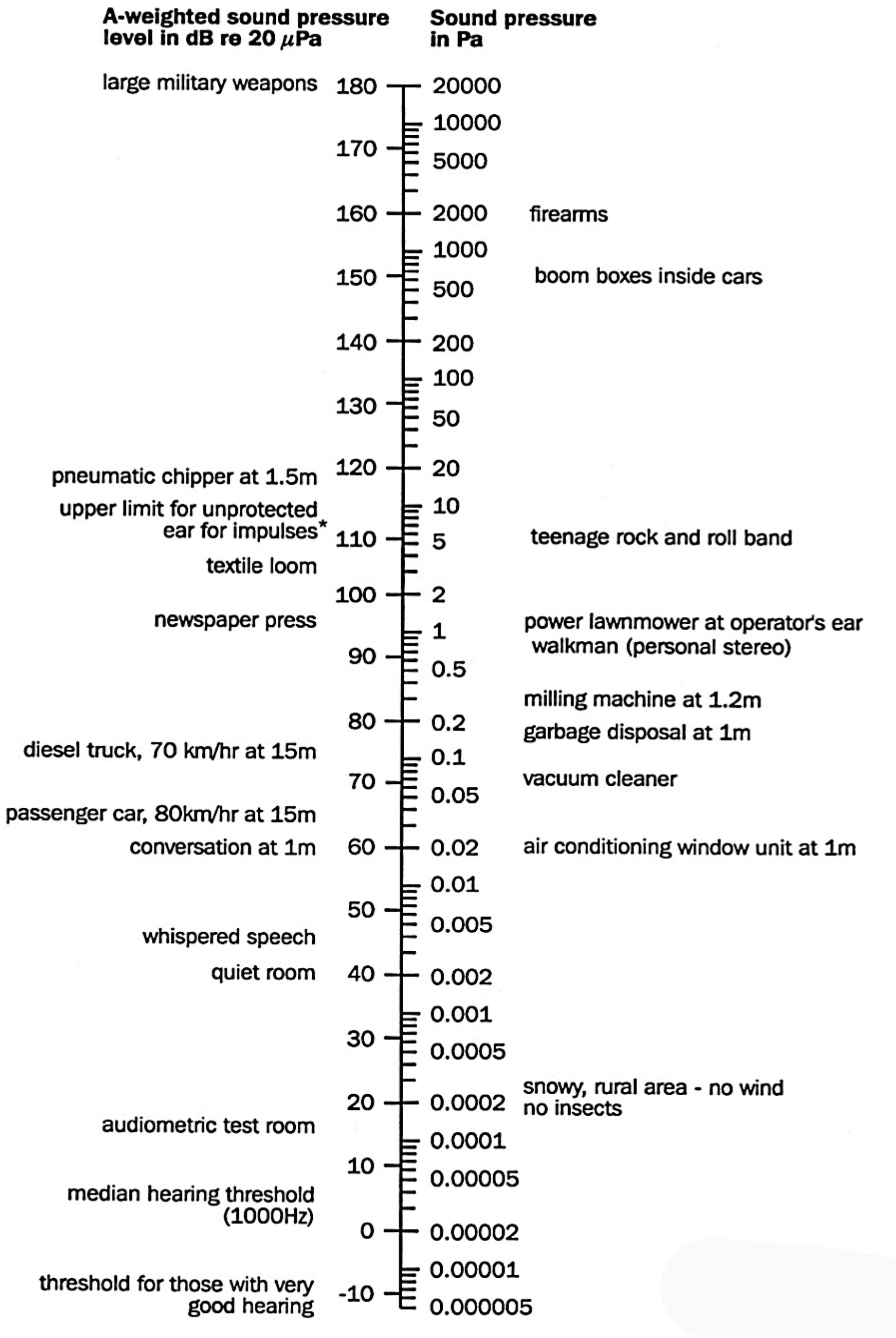



*Fig. 14 Sound levels produced by typical noise sources - C.H. Hansen, 2005*

Simpler single-number rating methods have been developed and are commonly used due to a greater practicality in analyzing great amounts of data. Currently there are a number of indoor noise criteria used to quantify the level of noise. A different directive accredits each of the many methods depending on: the region of the world where it is used; the scenario that it describes and the objective of the measurement. This study will focus on the methods most relevant to the scenarios at hand.

### 2.2.6 Noise Rating (NR)

According to the International Organization for Standardization (ISO) the Noise Rating (Kosten and Van Os,1962) is used as a graphical method for assigning a single number as speech interference rating to a noise spectrum. The method was originally developed for rating outdoor environmental noise, but today it is also used to rate background noise in rooms. Due to this, NR tends to be more permissive at low frequencies.

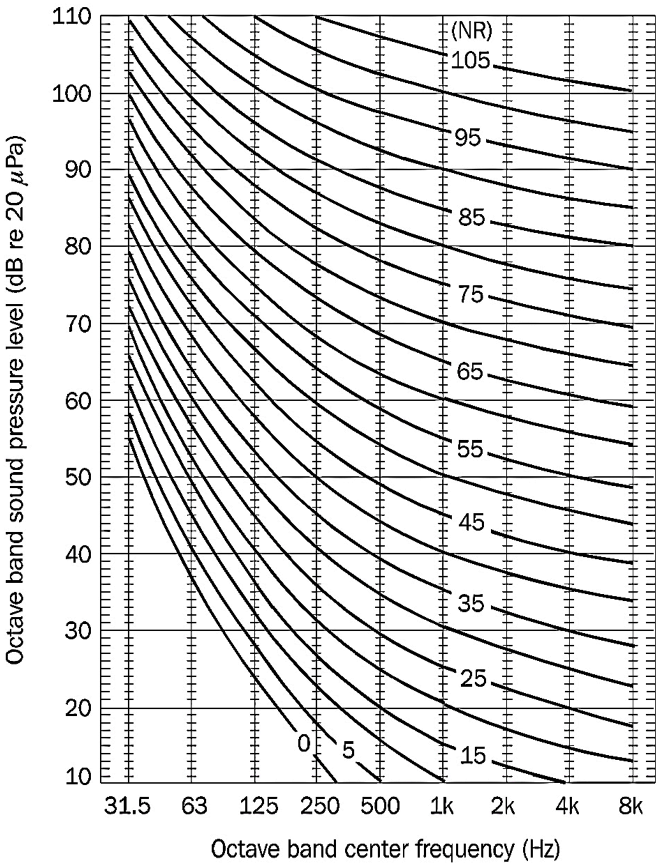



*Fig. 15 Noise Rating Contours - C.H. Hansen, 2005*

It can be used to specify the maximum acceptable level in each octave band of a frequency spectrum, or to assess the acceptability of a noise spectrum for a particular application. The NR (Noise Rating) of the spectrum corresponds to the value of the first NR contour that is entirely above the spectrum. As a result, two noise environments with the same NR-rating can have entirely different spectra.

### 2.2.7 Room Criterion (RC)

The Room Criterion (RC) Curves system was developed based on experience and ASHRAE-sponsored research (Broner 1994) for use in evaluating both structure- and airborne noise.

Apart from giving a more comprehensive description of noise, a major benefit of RC value is that its numerical rating gives the approximate speech interference level. The Room Criteria RC are defined in the standard ANSI S12.2-1995.

The RC method was revised to the RC Mark II method. This method uses curves nearly identical to those of the RC method and its means for rating a spectrum is the same. The method differs, however, in the way a sound quality descriptor is determined for a spectrum. This method defines a quality assessment index (QAI) that is calculated using the differences between the spectrum values and the neutral RC curve corresponding to the spectrum. This method is the outgrowth of experience by Blazier (1997) and others. Since then, RC Mark II system is considered to be the most relevant for indoor scenario.

The method relies on the determination of the mid-frequency average level and then plotting the perceived balance between high and low frequency sound and the desired mid-frequency levels are in the range of 25 to 50dB. Each RC criterion curve bears a rating number equal to the level at 1000 Hz. This is considered as a speech interference rating.

The letter is a qualitative descriptor that identifies the sound's perceived character: (N) for neutral, (LF) for low-frequency rumble, (MF) for mid-frequency roar, and (HF) for high-frequency hiss. A neutral environment is free of tonal exaggerations and will be judged as unobtrusive or bland if its spectrum follows the RC curve closely. A rumbly environment is one in which the measured values at and below 500Hz exceed the RC curve by more than 5dB at any octave. If the measured values at 1000Hz and above exceed the RC curve values by more than 3dB at any octave, the environment will be hissy.

As it can be seen in the following figure, if one or more values fall in the shaded portion, vibrations are probable. Such vibrations may be felt and may cause light weighted structures furniture and objects to rattle audibly. As a result, there are also two subcategories of the low-frequency descriptor: (LFB), denoting a moderate but perceptible degree of sound-induced ceiling/wall vibration, and (LFA), denoting a noticeable degree of sound-induced vibration.

Despite the comprehensive description provided by the Room Criterion system, it is only relevant for indoor or quiet environments. As a result both NR shall be used extensively for measurement comparison in the present study. RC mark 2 will only be used complementary for specific scenarios.

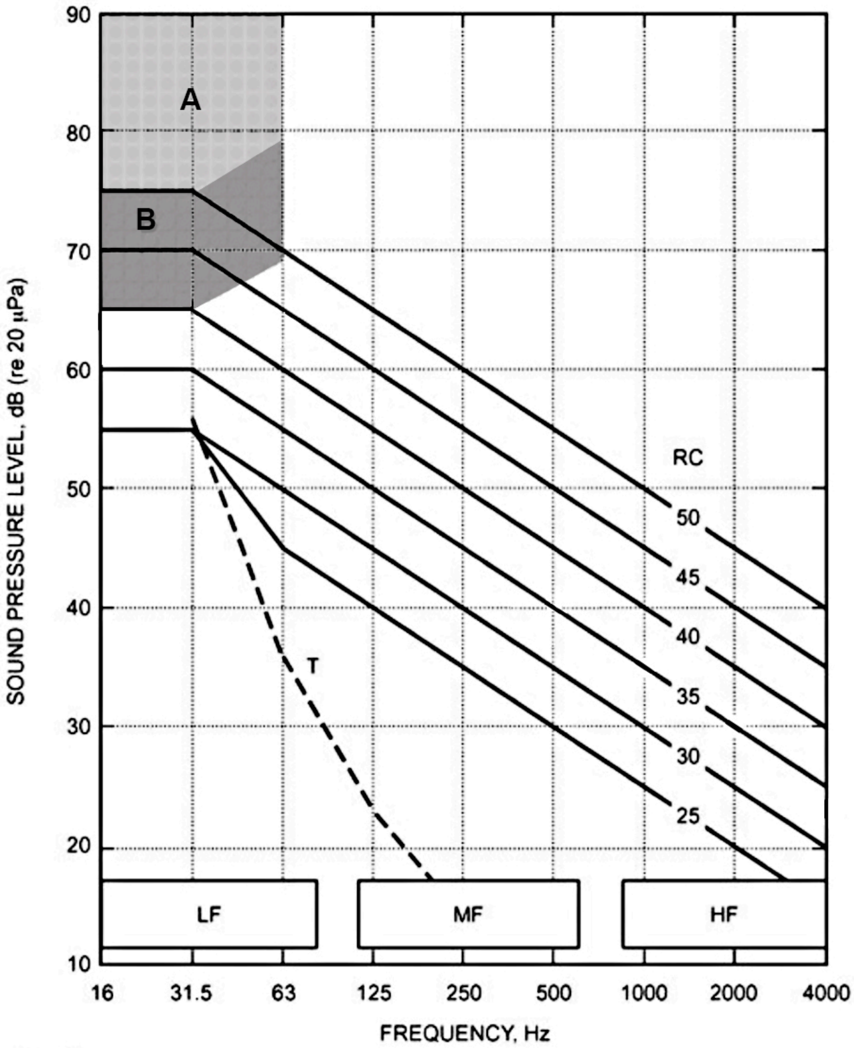



*Fig. 16 Room Criterion Contours - ASHRAE Handbook, 2015*

### 2.2.8 Waveform Description

Noise may be classified as steady, non-steady or impulsive, depending upon the temporal variations in sound pressure level. The various types of noise and instrumentation required for their measurement are illustrated in the table below. Noise characteristics classified according to the way they vary with time.

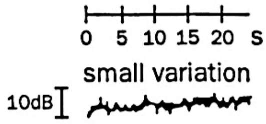
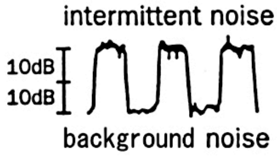
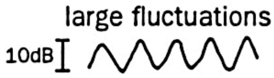
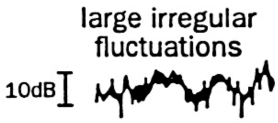
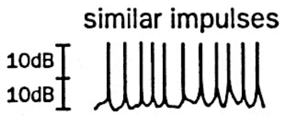
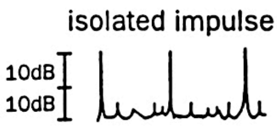
| | Characteristics | Type of Source |
|---|---|---|
|   | Constant continuous sound | Pumps, electric motors, gearboxes, conveyers |
|   | Constant but intermittent sound | Air compressor, automatic machineryduring a work cycle |
|   | Periodically fluctuating sound | Mass production, surface grinding |
|   | Fluctuating non-periodic sound | Manual work, grinding, welding, component assembly |
|   | Repeated impulses | Automatic press, pneumatic drill, riveting |
|   | Single impulse | Hammer blow, material handling, punch press, gunshot, artillery fire |

*Fig. 17 Noise Waveform Types and Characteristics - C.H. Hansen, 2005*

Constant noise remains within 5 dB interval for a long time. Steady noise is a noise with negligibly small fluctuations of sound pressure level within the period of observation. A noise is called non-steady when its sound pressure levels shift significantly during the period of observation. This type of noise can be divided into intermittent noise and fluctuating noise.

Constant noise, which starts and stops, is called intermittent. Intermittent noise is noise for which the level drops to the level of the background noise several times during the period of observation. The time during which the level remains at a constant value different from that of the ambient background noise must be one second or more. This type of noise can be described by: ambient noise level; level of the intermittent noise & average duration of the on and off period.

Fluctuating noise is a noise for which the level changes continuously and to a great extent during the period of observation. Fluctuating noise varies significantly but has a constant long-term average.

Impulse noise lasts for less than one second. It consists of one or more bursts of sound energy, each lasting less than about one second. Impulses are usually classified as type A and type B as described in the figure below (ISO 10843). Type A characterizes typically gun shot types of impulses, while type B is the one most often found in industry (e.g., punch press impulses). The characteristics of these impulses are the peak pressure value, the rise time and the duration (as defined in Figure 16) of the peak.

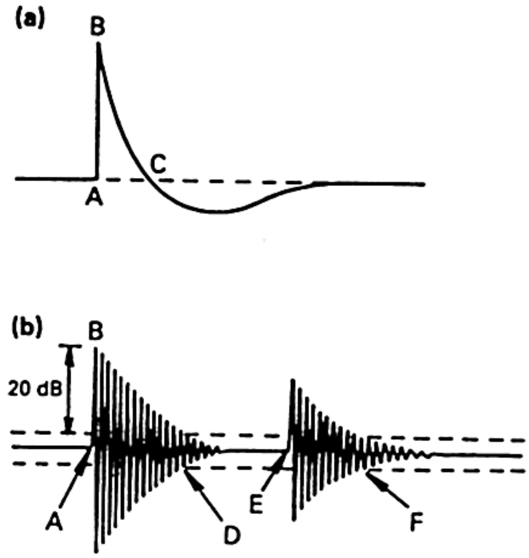



*Fig. 18 Ideal waveforms of impulse noise: (a) explosive generated (b) impact generated - C.H. Hansen, 2005*

## 2.3 Recording Parameters

### 2.3.1 Overview

The present study intends to analyze the physical aspects of field acoustical measurements in specific scenarios in the Vienna urban environment. As there is no optimal procedure to perform this, the makes use of each of the previously described methods. The results are to be evaluated, compared to each other and correlated to the existing E.N.D. strategic acoustical noise map estimations.

### 2.3.2 Equipment

The recordings were performed with a NORSONIC 140 sound level analyzer with a G.R.A.S. GS-40AN ½” condenser microphone. This allowed the sound level analyzer to record values for a wider frequency spectrum.

For a more extensive analysis of the specific environmental noise, each measurement implies S.P.L. readings with digital A & Z-Weighted filters of S.P.L. values every 1/8 of a second for each 1/3 Octave band.

### 2.3.3 Frequency intervals

The A-Weighted filter measurements are used to determine the measured $L_{den}$ , that is to be compared to the existing E.N.D. strategic acoustical noise map estimations.
The $L_{Aeq}$ contour line covers the frequency spectrum from 20Hz to 20kHz. This is in accordance to what is considered to be the human hearing spectrum. As it can be seen in the figure below, the A-weighted filter is less susceptible to noise in the lower spectrum under 1kHz.
The recorded Z-weighted measurement interval for the present analysis starts as low as the 0,4Hz and reaches up to 20kHz. The resulting $L_{eq}$ (sound pressure equivalent level) may describe more of the noise spectrum but it can be misleading.
Despite the fact the human body may be susceptible to sound at frequencies as low as 0,5Hz, it will mask excitations of noise of SPL lower then 70-80dB. These levels are relevant only in extreme case scenarios and not in the analyzed urban environment.

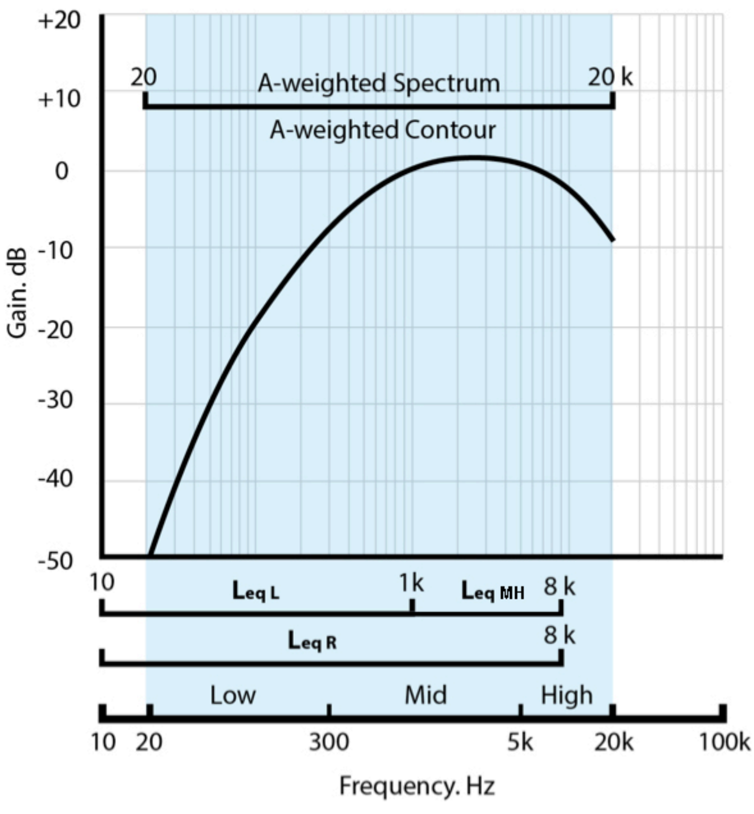



*Fig. 19 Reference spectrum ($L_{eqR}$) as well as low ($L_{eqL}$) and mid-high ($L_{eqMH}$) frequency ranges relative to the A-weighted frequency range*

As some people may be more susceptible then others, the lower limit of the studied frequency spectrum is 10Hz. This is generally considered the lowest possible frequency at which the human ear may record sound. The upper limit of the referenced frequency spectrum is 8kHz and is determined in accordance to the

intervals used to determine the NR and RC ratings. $L_{eqR}$ is the equivalent level of the referenced frequency spectrum (10Hz-8kHz). $L_{50R}$ values are determined for the same frequency interval.
To describe the role of low frequency noise in the overall acoustic environment an even narrower spectrum is required. This is to be noted as the low frequency equivalent level ($L_{eqL}$) and is to extend within the 10Hz-1kHz intervals. It is to be further compared to the rest of the referenced frequency spectrum 1kHz-8kHz ($L_{eqMH}$) as representing the medium-high interval.

### 2.3.4 Evaluation of Correlation

The root-mean-square deviation (RMSD) is a frequently used measure of the differences between values predicted by a model or an estimator and the values actually observed. The RMSD represents the sample standard deviation of the differences between predicted values and observed values. In the present study it will be used for evaluation of correlation between the different measured or determined values.

$$\mathrm{RMSD} = \sqrt{\frac{\sum_{t=1}^{n}(x_{1,t} - x_{2,t})^2}{n}} \tag{2}$$

### 2.3.5 Recording Conditions

The measurements were recorded between 21.01.2015 and 08.06.2015. Each recording lasted 1 hour. These were performed only on working weekdays, 3 times a day roughly within the intervals 06:00-09:00 (morning), 12:00-15:00 (noon) and 18:00-21:00 (evening). This is intended to cover the hours when most intense noise is produced and when people are most susceptible to acoustical disturbances.

In many of the recordings, construction sites were unavoidable. In this case the noise produced is atypical to the scenario but it cannot to be ignored. They also represent an unavoidable element of the urban acoustical environment.

A disturbance to the recording is only to be considered the direct result of the recording process (such as equipment adjustments or the squeaking of the floor) or unavoidable human activity. These are to be pointed out accordingly.

Due to the high sensitivity of the equipment, the recording weather conditions were particular. No recordings were performed during rain or outside air temperature under 0°C. Inside measurements were restricted to wind speeds down to 18km/h, while outside recordings were restricted even further to16km/h. It was observed that within these parameters measurements present no recording distortions.

Upon each measurement, adequate written and photographic add notations of the place together with an audio recording were taken. This was intended for easy correlation and identification between recorded S.P.L. values and context.

# 3 RESULTS

## 3.1 Measured values and END indicated intervals

In the following tables and charts Fig.20-26, a comparison is made between the END indicated intervals and $L_{den}$ deduced from measured $L_{Aeq}$ values. The resulting contour lines are further compared to the NR.

Only 2 of the estimated 5 locations have $L_{den}$ levels above 75dB (Fig.22). Each of these was recorded in close proximity of high road traffic. The noisiest locations are situated within high residential neighbourhoods of Vienna (Meidling and Hernals). The highest $L_{den}$ level of these was recorded in Meidling at boulevard level under the railway bridges. The measured value here is 77,63dB.

$L_{den}$ recording at both locations in the proximity of the airport are under the END estimated levels. By nature, air traffic noise has a strong temporary presence with scarce irregular repetitions. The effects of this can better be seen in the morning and evening NR recorded values next to the airport (Fig.23). These ratings drop drastically compared to the afternoon measured values due to the lower air traffic flow and the very low background noise.

While the recordings in the proximity of Stadt Mitte Station correlate to the END indicated 70-75dB interval, measurements at Marxergasse 13 are significantly lower. The recorded $L_{den}$ level is 65,1dB. This is close to 5dB lower then the END estimated interval (Fig.23).

Also lower but less so, the measured $L_{den}$ value in Resselpark is 58,44dB. As a result, it is situated under the END 60-65dB estimated interval (Fig24).

In contrast, by approaching areas with lower estimated $L_{den}$ intervals, measured levels tend to be higher then the respective estimated intervals (Fig.24-26). This is better seen in the case of the measurements performed at Längenfeldgasse 31 and Schmeltzbruckenrampe 2. Values in these cases are higher then the END indicated interval of 65-70dB (Fig.24). Similarly, the recorded $L_{den}$ at Leo-Slezak-Gasse 6 is 68dB, thus higher then the 60-65dB END interval (Fig.25).

Finally, this is also the case of both locations indicated to have $L_{den}$ values within the 55-60dB interval. Recorded values at Henriettenplatz and Donau-City-Strasse 11 are very similar to eachother, just above 61dB (Fig.26).

| Scenario | Time of day | NR | $L_{den}$(dB) | END $L_{den}$(dB) |
|---|---|---|---|---|
| | | | | |
| **Meidling** Outside/Under train bridges Längenfeldgasse | Morning | 67,1 | 77,63 | >75 |
| | Noon | 65,7 | | |
| | Evening | 65,7 | | |
| **Alserstrasse** Outside/U-bahn prox. | Morning | 64,2 | 76,12 | >75 |
| | Noon | 62,5 | | |
| | Evening | 63,4 | | |
| **Tangente Highway/ Katherinnengasse** Outside/Highway prox. | Morning | 62,1 | 71,75 | >75 |
| | Noon | 61,5 | | |
| | Evening | 60,9 | | |
| **DonauCity** Outside/Kaisermühlentunnel Exit | Morning | 61,2 | 70,84 | >75 |
| | Noon | 60,6 | | |
| | Evening | 58,8 | | |
| **Schwechat** Outside/Railway, Highway prox. Mannswörther Straße 188 | Morning | 60,3 | 70,74 | >75 |
| | Noon | 60,3 | | |
| | Evening | 58,4 | | |
| **Stadt Mitte** Outside/U&S-bahn prox. Stadt Mitte | Morning | 56,9 | 74,13 | 70-75 |
| | Noon | 61,0 | | |
| | Evening | 61,2 | | |
| **Mariahilferstrasse Outer Ring** Outside/Bulevard Mariahilferstrasse 172 | Morning | 61,4 | 72,52 | 70-75 |
| | Noon | 59,0 | | |
| | Evening | 59,6 | | |
| **Tangente Highway /Baumgasse 89** Outside/Highway prox. | Morning | 59,6 | 69,75 | 70-75 |
| | Noon | 58,0 | | |
| | Evening | 57,3 | | |
| **Schwechat** Outside/Airport prox. | Morning | 46,3 | 68,35 | 70-75 |
| | Noon | 58,8 | | |
| | Evening | 53,1 | | |

*Fig. 20 Measured NR & $L_{den}$ in relation to END indicated intervals*

| Scenario | Time of day | NR | Lden(dB) | END Lden(dB) |
|---|---|---|---|---|
| **Stadt Mitte** Outside/Block prox. Marxergasse 13 | Morning | 54,8 | 65,10 | 70-75 |
| | Noon | 52,2 | | |
| | Evening | 53,0 | | |
| **Meidling** Outside/block Längenfeldgasse 31 | Morning | 62,5 | 73,65 | 65-70 |
| | Evening | 62,1 | | |
| **Mariahilferstrasse Outer Ring** Outside/Railway prox. Schmelzbrückenrampe 2 | Morning | 61,3 | 72,84 | 65-70 |
| | Noon | 60,2 | | |
| | Evening | 58,8 | | |
| **Karlsplatz** Outside/U-bahn prox. Otto Wagner Pavillion | Morning | 56,2 | 68,46 | 65-70 |
| | Noon | 58,8 | | |
| | Evening | 54,0 | | |
| **Mariahilfestrasse Inner Ring** Outside/Block prox. Gerngross Center | Morning | 55,1 | 67,35 | 65-70 |
| | Evening | 51,6 | | |
| **Alserstrasse** Outside/Block prox. Leo-Slezak-Gasse 6 | Morning | 56,9 | 68,04 | 60-65 |
| | Noon | 54,8 | | |
| | Evening | 54,2 | | |
| **Tangente Highway /Baumgasse** Outside/Block prox. | Morning | 50,6 | 62,89 | 60-65 |
| | Noon | 53,0 | | |
| | Evening | 49,5 | | |
| **Karlsplatz** Outside/Park Resselpark | Noon | 48,6 | 60,20 | 60-65 |
| | Evening | 45,8 | | |
| **Mariahilferstrasse Outer Ring** Outside/Park Henriettenplatz | Morning | 47,4 | 61,39 | 55-60 |
| | Noon | 50,9 | | |
| | Evening | 45,0 | | |
| **DonauCity** Outside/Over tunnel Donau-City-Straße 11-13 | Morning | 48,5 | 61,11 | 55-60 |
| | Noon | 48,2 | | |
| | Evening | 43,7 | | |

*Fig. 21 Measured NR & $L_{den}$ in relation to END indicated intervals*

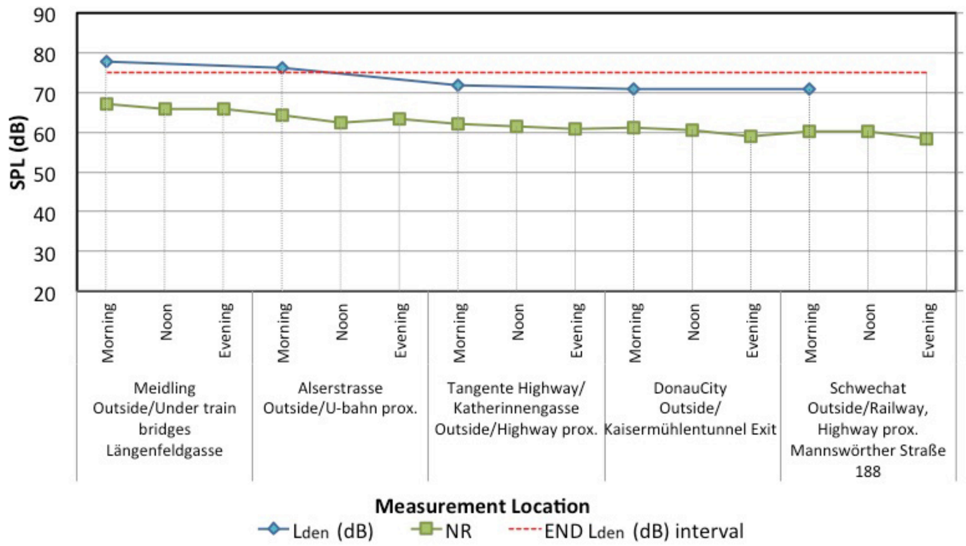



*Fig. 22 Measurement determined $L_{den}$ & NR values in areas where estimated END interval is >75dB*

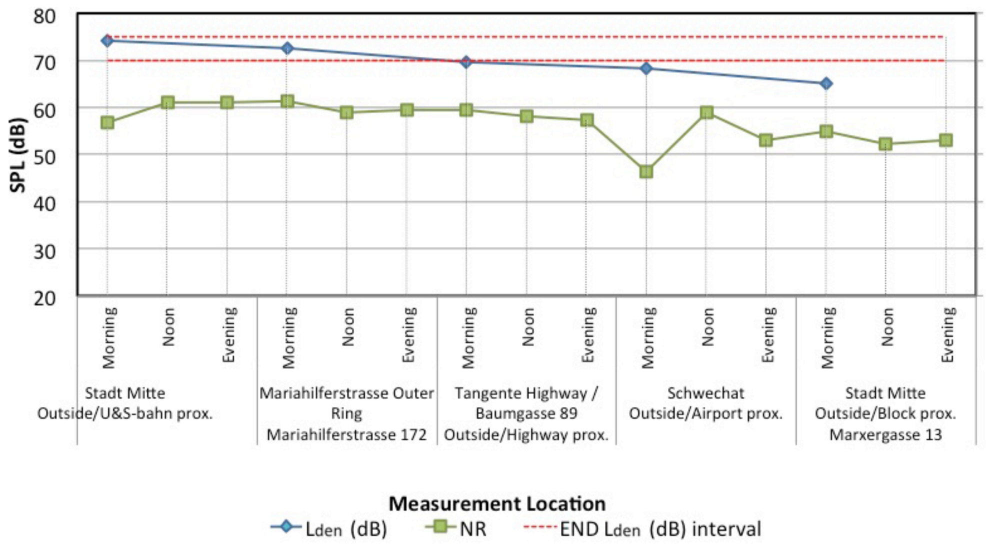



*Fig. 23 Measurement determined $L_{den}$ & NR values in areas where estimated END interval is 70-75dB*

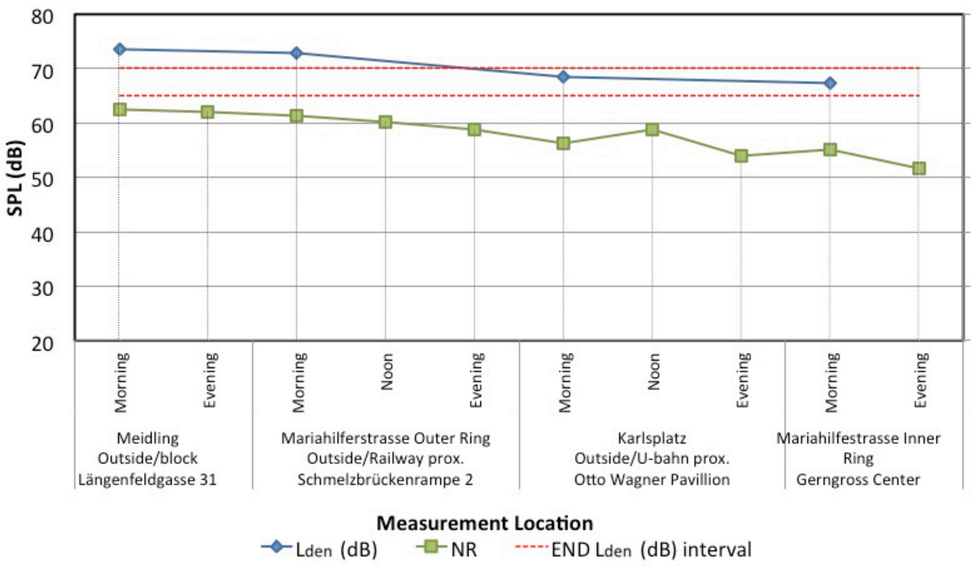



*Fig. 24 Measurement determined $L_{den}$ & NR values in areas where estimated END interval is 65-70dB*

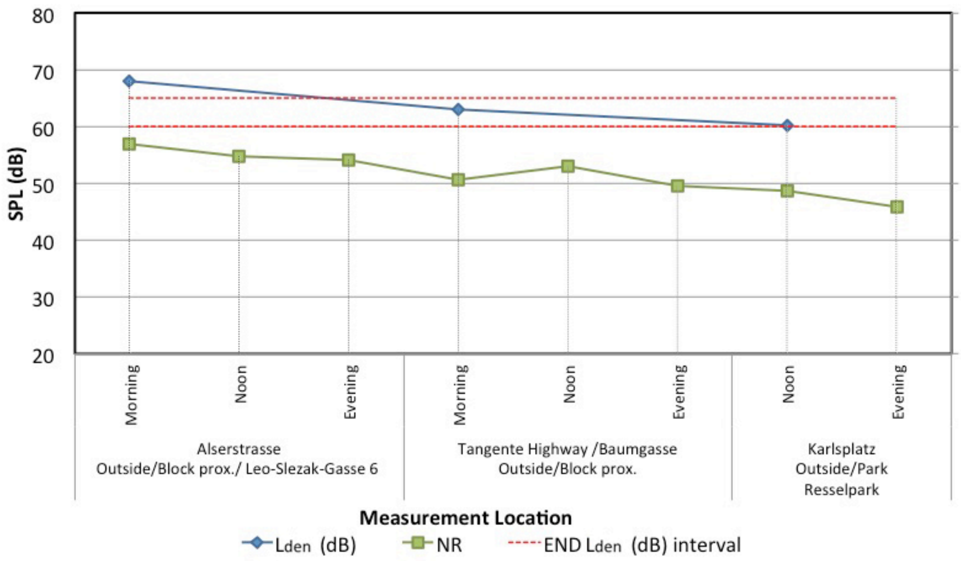



*Fig. 25 Measurement determined $L_{den}$ & NR values in areas where estimated END interval is 60-65dB*

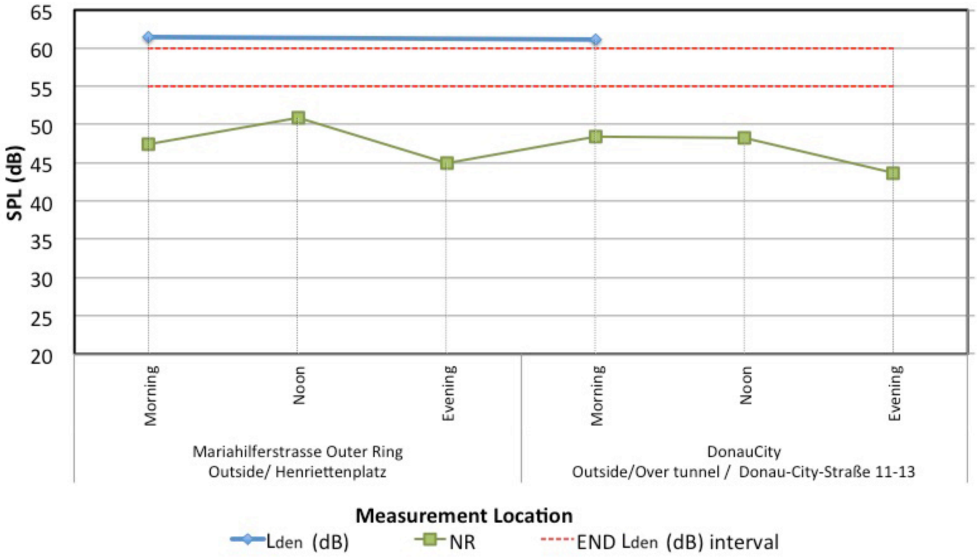



*Fig. 26 Measurement determined $L_{den}$ & NR values in areas where estimated END interval is 55-60dB*

## 3.2 The role of low frequency noise in the referenced spectrum

The present chapter intends to portray the role played by low frequency noise in the recorded acoustical environment.

In the tables and charts (Fig.27-33) contained in this chapter, the referenced equivalent level ($L_{eqR}$) is to be separated in two distinct components: low ($L_{eqL}$) and mid-high ($L_{eqMH}$).

It can be seen that the low frequency component is higher then the mid-high equivalent level in all measurements. The low frequency equivalent levels are generally situated above the END indicated interval.

In two instances, as exception to this rule, $L_{eqL}$ is found to be lower then 75dB, the minimum indicated $L_{den}$ (Fig.29). These values were recorded in both instances in the evening and in the proximity of highway tunnel exits. These locations are Katherinengasse (in proximity of the Tangente Highway) and at Kaisermühlentunnel exit (in proximity of Donaucity).

In two more instances, the values are situated within the END indicated interval. These are the cases of the morning recording at The International Airport and the noon and evening recordings at Marxergasse 13 (Fig.30).

At the same time, the majority of the mid-high equivalent level values are below this interval. In few instances the $L_{eqMH}$ values situate within the END indicated interval. These are the cases of the measurements performed at Längenfeldgasse 31 and the morning and noon recordings at Schmeltzbruckenrampe 2 (Fig.31). The same can be said also about the morning recordings at Leo-Slezak-Gasse 6 (Fig.32) and the measurements performed at noon in Herietenplatz (Fig.33).

| Scenario | Time of day | LeqR(dB) | LeqL (dB) | Leq MH(db) | END Lden(dB) |
|---|---|---|---|---|---|
| | | | | | |
| **Meidling** Outside/Under train bridges Längenfeldgasse | Morning | 85,11 | 84,97 | 71,94 | >75 |
| | Noon | 83,52 | 83,36 | 70,80 | |
| | Evening | 83,77 | 83,61 | 70,93 | |
| **Alserstrasse** Outside/U-bahn prox. | Morning | 82,45 | 82,36 | 67,95 | >75 |
| | Noon | 83,56 | 83,50 | 66,71 | |
| | Evening | 82,69 | 82,62 | 67,20 | |
| **Tangente Highway/ Katherinnengasse** Outside/Highway prox. | Morning | 78,07 | 77,91 | 65,89 | >75 |
| | Noon | 75,85 | 75,63 | 65,29 | |
| | Evening | 74,30 | 73,99 | 64,87 | |
| **DonauCity** Outside/Kaisermühlentunnel Exit | Morning | 76,02 | 75,73 | 65,90 | >75 |
| | Noon | 75,72 | 75,45 | 65,30 | |
| | Evening | 74,28 | 74,03 | 63,49 | |
| **Schwechat** Outside/Railway, Highway prox. Mannswörther Straße 188 | Morning | 76,65 | 76,44 | 65,10 | >75 |
| | Noon | 76,75 | 76,57 | 64,80 | |
| | Evening | 75,23 | 75,03 | 63,41 | |
| **Stadt Mitte** Outside/U&S-bahn prox. Stadt Mitte | Morning | 78,07 | 78,00 | 61,57 | 70-75 |
| | Noon | 80,68 | 80,56 | 66,05 | |
| | Evening | 79,96 | 79,87 | 65,30 | |
| **Mariahilferstrasse Outer Ring** Outside/Bulevard Mariahilferstrasse 172 | Morning | 79,45 | 79,30 | 66,34 | 70-75 |
| | Noon | 80,21 | 80,13 | 64,16 | |
| | Evening | 80,07 | 79,97 | 64,97 | |
| **Tangente Highway /Baumgasse 89** Outside/Highway prox. | Morning | 78,61 | 78,52 | 63,79 | 70-75 |
| | Noon | 77,47 | 77,38 | 62,52 | |
| | Evening | 75,63 | 75,52 | 61,50 | |
| **Schwechat** Outside/Airport prox. | Morning | 72,59 | 72,58 | 49,94 | 70-75 |
| | Noon | 75,75 | 75,55 | 63,87 | |
| | Evening | 74,99 | 74,91 | 59,02 | |

*Fig. 27 Measured $L_{eqR}$, $L_{eqL}$ & $L_{eqMH}$ in relation to END indicated intervals*

| Scenario | Time of day | $L_{eqR}$(dB) | $L_{eqL}$ (dB) | $L_{eq\,MH}$(db) | END $L_{den}$(dB) |
|---|---|---|---|---|---|
| | | | | | |
| **Stadt Mitte**<br>Outside/Block prox.<br>Marxergasse 13 | Morning | 76,07 | 76,01 | 59,39 | 70-75 |
| | Noon | 72,52 | 72,44 | 56,88 | |
| | Evening | 70,64 | 70,53 | 56,91 | |
| **Meidling**<br>Outside/block<br>Längenfeldgasse 31 | Morning | 80,95 | 80,80 | 67,84 | 65-70 |
| | Evening | 76,83 | 76,54 | 66,69 | |
| **Mariahilferstrasse Outer Ring**<br>Outside/Railway prox.<br>Schmelzbrückenrampe 2 | Morning | 84,32 | 84,26 | 66,97 | 65-70 |
| | Noon | 81,76 | 81,69 | 65,49 | |
| | Evening | 80,06 | 79,98 | 63,97 | |
| **Karlsplatz**<br>Outside/U-bahn prox.<br>Otto Wagner Pavillion | Morning | 77,00 | 76,92 | 61,19 | 65-70 |
| | Noon | 77,04 | 76,85 | 63,78 | |
| | Evening | 74,60 | 74,50 | 59,73 | |
| **Mariahilfestrasse Inner Ring**<br>Outside/Block prox.<br>Gerngross Center | Morning | 79,12 | 79,07 | 61,01 | 65-70 |
| | Evening | 73,57 | 73,49 | 57,50 | |
| **Alserstrasse**<br>Outside/Block prox.<br>Leo-Slezak-Gasse 6 | Morning | 78,07 | 78,00 | 61,57 | 60-65 |
| | Noon | 75,89 | 75,82 | 59,46 | |
| | Evening | 75,54 | 75,46 | 59,38 | |
| **Tangente Highway /Baumgasse**<br>Outside/Block prox. | Morning | 72,55 | 72,50 | 55,13 | 60-65 |
| | Noon | 70,14 | 69,96 | 57,97 | |
| | Evening | 69,17 | 69,08 | 54,15 | |
| **Karlsplatz**<br>Outside/Park<br>Resselpark | Noon | 72,14 | 72,08 | 54,37 | 60-65 |
| | Evening | 71,63 | 71,60 | 51,95 | |
| **Mariahilferstrasse Outer Ring**<br>Outside/Park<br>Henriettenplatz | Morning | 71,05 | 71,00 | 52,85 | 55-60 |
| | Noon | 72,41 | 72,35 | 55,64 | |
| | Evening | 69,07 | 69,03 | 50,20 | |
| **DonauCity**<br>Outside/Over tunnel<br>Donau-City-Straße 11-13 | Morning | 72,59 | 72,58 | 49,94 | 55-60 |
| | Noon | 72,54 | 72,50 | 53,39 | |
| | Evening | 69,39 | 69,37 | 47,36 | |

*Fig. 28 Measured $L_{eqR}$, $L_{eqL}$ & $L_{eqMH}$ in relation to END indicated intervals*

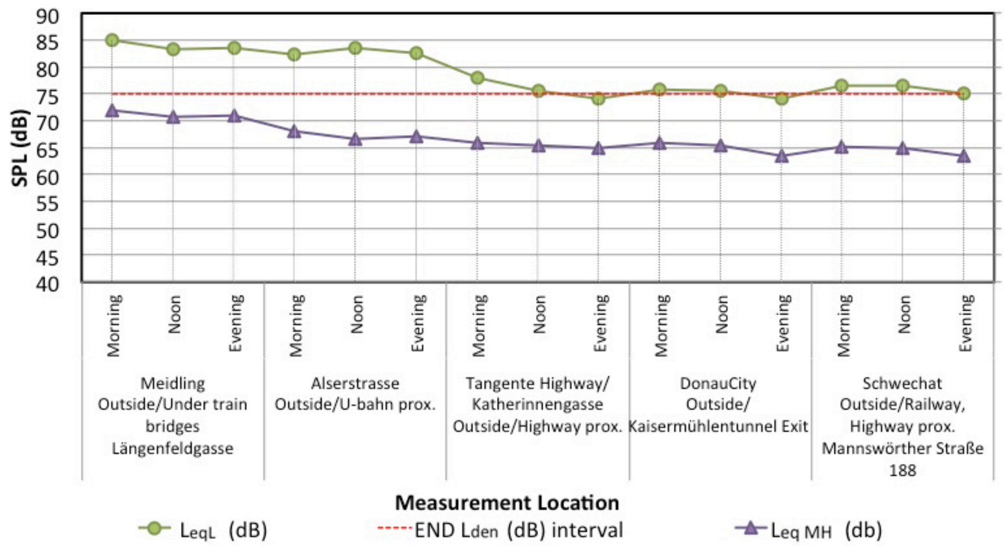



*Fig. 29 Measured $L_{eqL}$ & $L_{eqMH}$ values in areas where estimated END interval is >75dB*

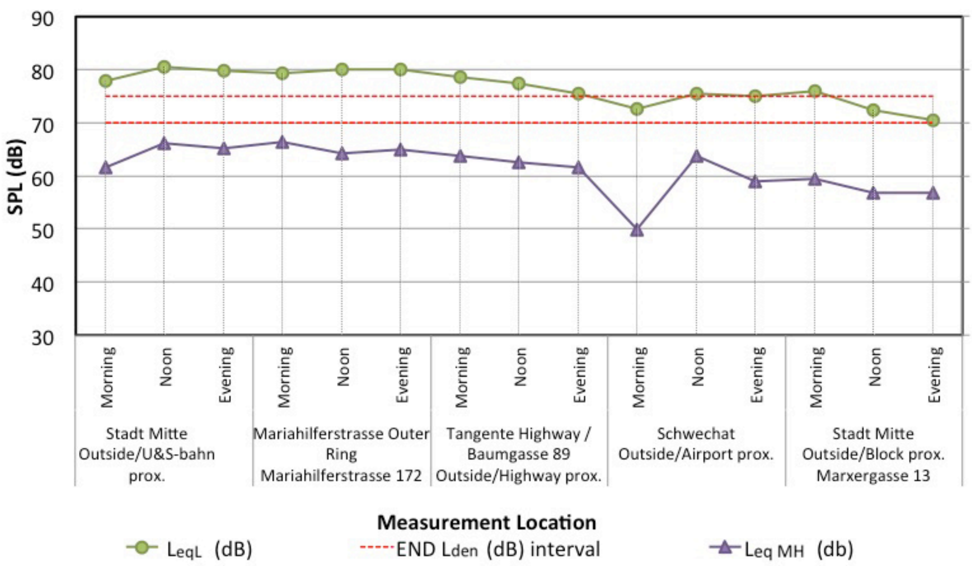



*Fig. 30 Measured $L_{eqL}$ & $L_{eqMH}$ values in areas where estimated END interval is 70-75dB*

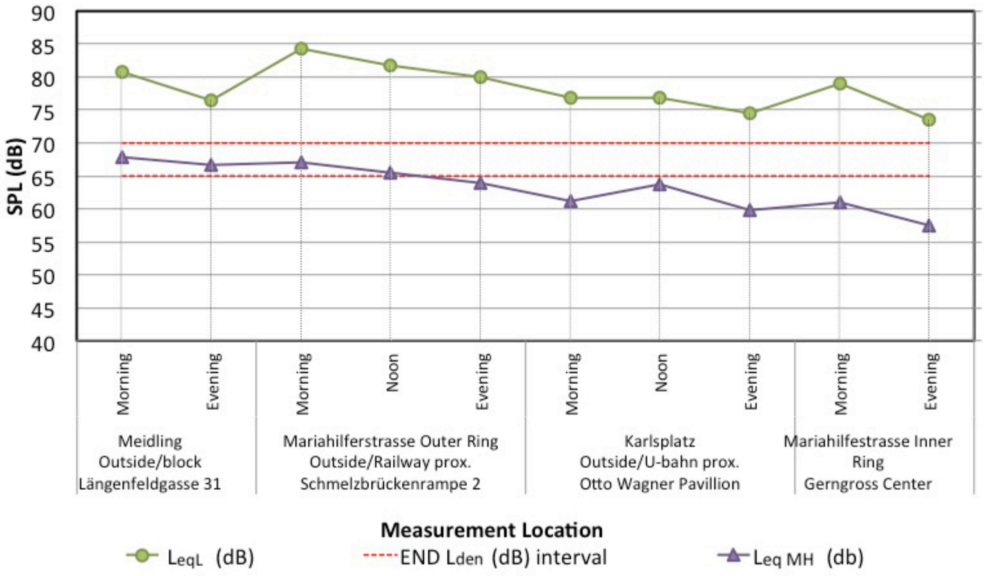



*Fig. 31 Measured $L_{eqL}$ & $L_{eqMH}$ values in areas where estimated END interval is 65-70dB*

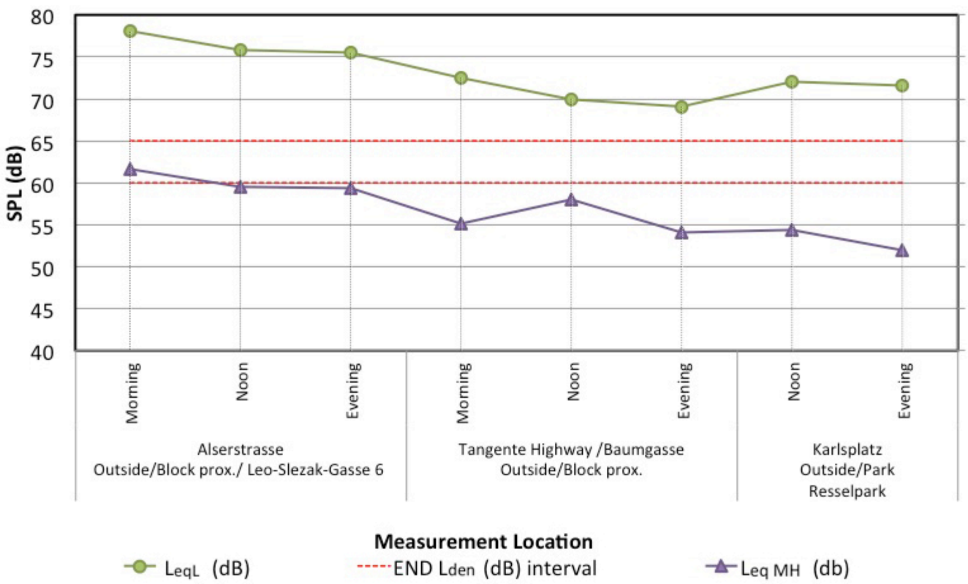



*Fig. 32 Measured $L_{eqL}$ & $L_{eqMH}$ values in areas where estimated END interval is 60-65dB*

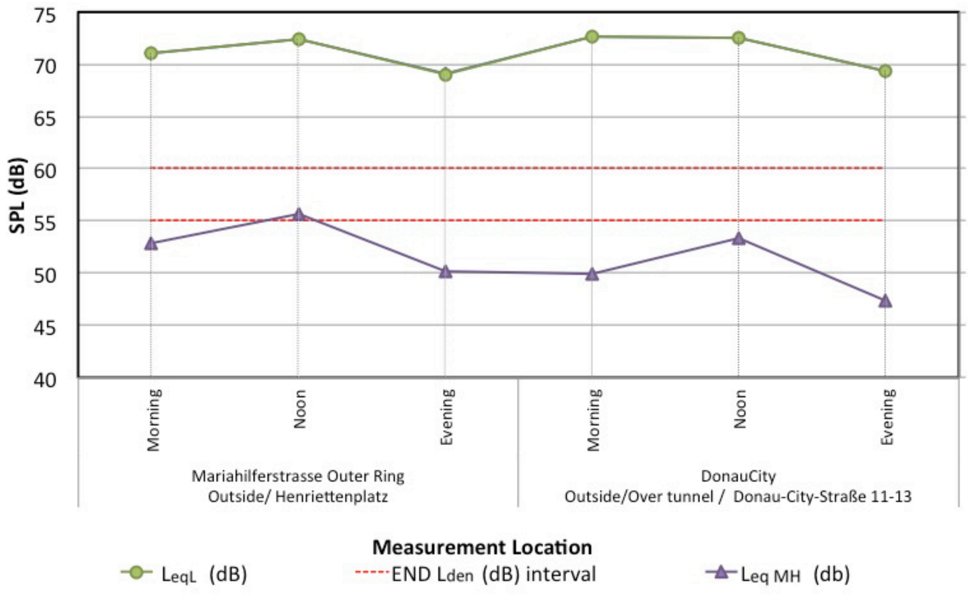



*Fig. 33 Measured $L_{eqL}$ & $L_{eqMH}$ values in areas where estimated END interval is 55-60dB*

## 3.3 Spatial sound distribution

In the present chapter as the tables and charts Fig. 36-45 are analysed, the objective is to gain a better image of the noise distribution in each of the chosen locations. The different recording points for each chosen location are portrayed descending from the noisiest to what are considered to be the most quiet. Thus, the different values of $L_{eqL}$, $L_{50R}$ and NR are compared. $L_{50R}$ is portrayed as a daytime median level for the 10Hz-8kHz referenced frequency spectrum.

Clear similarities can be found between $L_{50R}$, $L_{eqL}$ measured values. More then this, the NR contour line is found to be much lower but to follow roughly the same path. This is true for both indoor and outdoor recordings.

In two exceptional cases do $L_{50R}$ values drop so low as to be closer to NR then $L_{eqL}$. These measurement were taken indoors, in the evening, at Resimannhof 13 (Fig.41); the other outside, at noon, in the proximity of the International Airport (Fig.45). Similar in both cases is that the road and rail traffic are not dominant sources of noise.

| Location | Scenario | Time of day | $L_{eqL}$(dB) | $L_{50R}$(dB) | NR | RC |
|---|---|---|---|---|---|---|
| | | | | | | |
| **Karlsplatz** | Inside/Closed Windows **TUWien/Boecklsall** | Morning | 54,17 | 52,86 | 28,8 | RC=27 / QAI-10.8H |
| | | Noon | 55,83 | 52,16 | 22 | RC<25 |
| | | Evening | 53,45 | 51,42 | 26 | RC<25 |
| | Inside/Open Windows **TUWien/Boecklsall** | Morning | 61,74 | 60,94 | 37,1 | RC=35 / QAI-11.2H |
| | | Noon | 61,08 | 60,09 | 41,3 | RC=38 / QAI-14.7H |
| | | Evening | 59,38 | 58,59 | 37,4 | RC=34 / QAI-9.8H |
| | Inside/Basement | Morning | 55,37 | 47,65 | 34,6 | RC=35 / QAI-15.6H |
| | | Noon | 55,90 | 51,61 | 33,1 | RC=33 / QAI-14.6H |
| | | Evening | 51,62 | 46,67 | 30 | RC=29 / QAI-15.9H |
| | Outside/Park **Resselpark** | Noon | 72,08 | 71,50 | 48,6 | RC-46 / QAI-9.3H |
| | | Evening | 71,60 | 70,97 | 45,8 | RC-44 / QAI-5.9H |
| | Outside/U-bahn prox. **Otto Wagner Pavillion** | Morning | 76,92 | 75,59 | 56,2 | RC>50 / LFB |
| | | Noon | 76,85 | 75,42 | 58,8 | RC>50 / LFB |
| | | Evening | 74,50 | 72,65 | 54 | RC>50 |
| **Alserstrasse Station** | Inside/Closed Windows **Leo-Slezak-Gasse 6 / 3rd floor** | Morning | 63,03 | 57,71 | 26,1 | RC<25 |
| | | Noon | 60,80 | 55,78 | 25,9 | RC<25 |
| | | Evening | 59,13 | 52,94 | 25,9 | RC<25 |
| | Inside/Basement **Leo-Slezak-Gasse 6** | Morning | 62,14 | 57,71 | 31,5 | RC=28 / QAI-9.1H |
| | | Noon | 64,47 | 56,34 | 32,6 | RC=32 / QAI-4.6N |
| | | Evening | 57,66 | 54,48 | 29,8 | RC=25 / QAI-10.7H |
| | Outside/Block prox. **Leo-Slezak-Gasse 6** | Morning | 78,00 | 75,26 | 56,9 | RC>50 / LFB |
| | | Noon | 75,82 | 73,81 | 54,8 | RC>50 / LFB |
| | | Evening | 75,46 | 73,58 | 54,2 | RC>50 / LFB |
| | Outside/U-bahn prox. **Währinger Gürtel 11** | Morning | 82,36 | 79,83 | 64,2 | RC>50 / LFB |
| | | Noon | 83,50 | 81,17 | 62,5 | RC>50 / LFB |
| | | Evening | 82,62 | 80,43 | 63,4 | RC>50 / LFB |
| **Stadt Mitte** | Inside/Closed Windows **Marxergasse 13 / Loft-Roof** | Noon | 56,91 | 53,79 | 29 | RC<25 |
| | | Evening | 58,39 | 54,40 | 29,6 | RC<25 |
| | Inside/Open Windows **Marxergasse 13 / Loft-Roof** | Morning | 58,77 | 60,50 | 36,2 | RC=35 / QAI-11.2H |
| | | Noon | 60,78 | 58,20 | 37,5 | RC=36 / QAI-13.3H |
| | | Evening | 61,20 | 58,17 | 36,8 | RC=35 / QAI-13.5H |
| | Outside/Block prox. **Marxergasse 13** | Morning | 76,01 | 71,19 | 54,8 | RC>50 / LFB |
| | | Noon | 72,44 | 68,70 | 52,2 | RC>50 |
| | | Evening | 70,53 | 64,81 | 53 | RC>50 |
| | Outside/U&S-bahn prox. **Stadt Mitte** | Morning | 78,00 | 75,26 | 56,9 | RC>50 / LFB |
| | | Noon | 80,56 | 78,27 | 61 | RC>50 / LFB |
| | | Evening | 79,87 | 79,83 | 61,2 | RC>50 / LFB |
| **Mariahilfestrasse Inner Ring** | Inside/Closed Windows **Gerngross Center** | Morning | 59,93 | 55,65 | 29,9 | RC=25 / QAI-8.8H |
| | | Evening | 53,60 | 49,28 | 29,2 | RC=25 / QAI-11.9H |
| | Inside/OpenWindows **Gerngross Center** | Morning | 69,78 | 66,02 | 48,5 | RC=47 / QAI-13.7H |
| | | Evening | 65,73 | 57,76 | 44 | RC=43 QAI-11.8H |
| | Outside/Block prox. **Gerngross Center** | Morning | 79,07 | 76,22 | 55,1 | RC>50 / LFB |
| | | Evening | 73,49 | 67,55 | 51,6 | RC>50 / LFB |
| **Schwechat** | Outside/Airport prox. | Morning | 72,58 | 66,82 | 46,3 | RC-43 / QAI-7.9H |
| | | Noon | 75,55 | 63,87 | 58,8 | RC>50 |
| | | Evening | 74,91 | 70,87 | 53,1 | RC>50 / LFB |
| | Outside/Railway, Highway knot Mannswörther Straße 188 | Morning | 76,44 | 75,53 | 60,3 | RC>50 / LFB |
| | | Noon | 76,57 | 75,45 | 60,3 | RC>50 / LFB |
| | | Evening | 75,03 | 73,01 | 58,4 | RC>50 |

*Fig. 34 Measured values $L_{eqL}$ , $L_{50R}$ , NR and RC in each of the chosen locations*

| Location | Scenario | Time of day | $L_{eqL}$(dB) | $L_{50R}$(dB) | NR | RC |
|---|---|---|---|---|---|---|
| Mariahilferstrasse Outer Ring | Inside/Closed Windows **Arnsteingasse 25 / 2nd floor** | Morning | 57,57 | 45,40 | 20 | RC<25 |
| | | Noon | 61,98 | 52,69 | 20,7 | RC<25 |
| | | Evening | 62,99 | 52,07 | 23 | RC<25 |
| | Inside/Open Windows **Arnsteingasse 25 / 2nd floor** | Morning | 69,04 | 65,40 | 43 | RC=41 / QAI-8.5H |
| | | Noon | 69,94 | 62,81 | 41,9 | RC=41 / QAI-8.5H |
| | | Evening | 67,96 | 58,52 | 38,2 | RC=36 / QAI-7H |
| | Outside/Park **Henriettenplatz** | Morning | 71,00 | 66,69 | 47,4 | RC-46 / QAI-9H |
| | | Noon | 72,35 | 68,71 | 50,9 | RC-50 / QAI-11.1H |
| | | Evening | 69,03 | 63,35 | 45 | RC-43 / QAI-7.8H |
| | Outside/Bulevard **Mariahilfer Strasse 172** | Morning | 79,30 | 77,63 | 61,4 | RC>50 / LFB |
| | | Noon | 80,13 | 76,69 | 59 | RC>50 / LFB |
| | | Evening | 79,97 | 76,75 | 59,6 | RC>50 / LFB |
| | Outside/Railway prox. **Schmelzbrückenrampe 2** | Morning | 84,26 | 79,96 | 61,3 | RC>50 / LFB |
| | | Noon | 81,69 | 77,83 | 60,2 | RC>50 / LFB |
| | | Evening | 79,98 | 77,72 | 58,8 | RC>50 / LFB |
| Meidling | Inside/Closed Windows **Reismannhof 13 / 2nd floor** | Morning | 48,42 | 43,09 | 25,7 | RC=25 / QAI-14.1H |
| | | Noon | 53,78 | 46,85 | 35 | RC=32 / QAI-13.4H |
| | | Evening | 55,09 | 46,43 | 45 | RC=39 / QAI-28.3H |
| | Outside/block **Längenfeldgasse 31** | Morning | 80,80 | 77,85 | 62,5 | RC>50 / LFB |
| | | Evening | 76,54 | 73,12 | 62,1 | RC>50 / LFB |
| | Outside/Under train bridges **Längenfeldgasse** | Morning | 84,97 | 82,53 | 67,1 | RC>50 / LFB |
| | | Noon | 83,36 | 80,80 | 65,7 | RC>50 / LFB |
| | | Evening | 83,61 | 81,28 | 65,7 | RC>50 / LFB |
| Tangente Highway/ Bridge | Inside/Closed Windows **Baumgasse 79** | Morning | 64,44 | 60,53 | 29 | RC<25 |
| | | Noon | 62,10 | 56,76 | 30,1 | RC=25 / QAI-10.3H |
| | Outside/Block prox. **Baumgasse 79** | Morning | 72,50 | 68,36 | 50,6 | RC-48 / QAI-9.6H |
| | | Noon | 69,96 | 66,82 | 53 | RC>50 |
| | | Evening | 69,08 | 63,60 | 49,5 | RC-47 / QAI-11.1H |
| | Outside/Highway prox. **Baumgasse 89** | Morning | 78,52 | 77,25 | 59,6 | RC>50 / LFB |
| | | Noon | 77,38 | 76,52 | 58 | RC>50 / LFB |
| | | Evening | 75,52 | 73,77 | 57,3 | RC>50 / LFB |
| Tangente Highway/ Tunnel exit | Inside/Closed Windows **Katherinnengasse 9** | Morning | 50,75 | 49,30 | 27,5 | RC=26 / QAI-15.4H |
| | | Noon | 52,20 | 49,53 | 31,7 | RC=29 / QAI-15.9M |
| | | Evening | 51,32 | 49,24 | 28,7 | RC=28 / QAI-15.9H |
| | Outside/Highway prox. **Katherinnengasse 9** | Morning | 77,91 | 77,31 | 62,1 | RC>50 / LFB |
| | | Noon | 75,63 | 75,30 | 61,5 | RC>50 |
| | | Evening | 73,99 | 73,59 | 60,9 | RC>50 |
| DonauCity | Outside/Over tunnel **Donau-City-Straße 11-13** | Morning | 72,58 | 70,37 | 48,5 | RC-45 / QAI-12.6H |
| | | Noon | 72,50 | 65,35 | 48,2 | RC-48 / QAI-10.7H |
| | | Evening | 69,37 | 66,38 | 43,7 | RC-41 / QAI-6.2H |
| | Outside **Kaisermühlentunnel Exit** | Morning | 75,73 | 75,28 | 61,2 | RC>50 |
| | | Noon | 75,45 | 74,94 | 60,6 | RC>50 |
| | | Evening | 74,03 | 73,21 | 58,8 | RC>50 |

*Fig. 35 Measured values $L_{eqL}$ , $L_{50R}$ , NR and RC in each of the chosen locations*

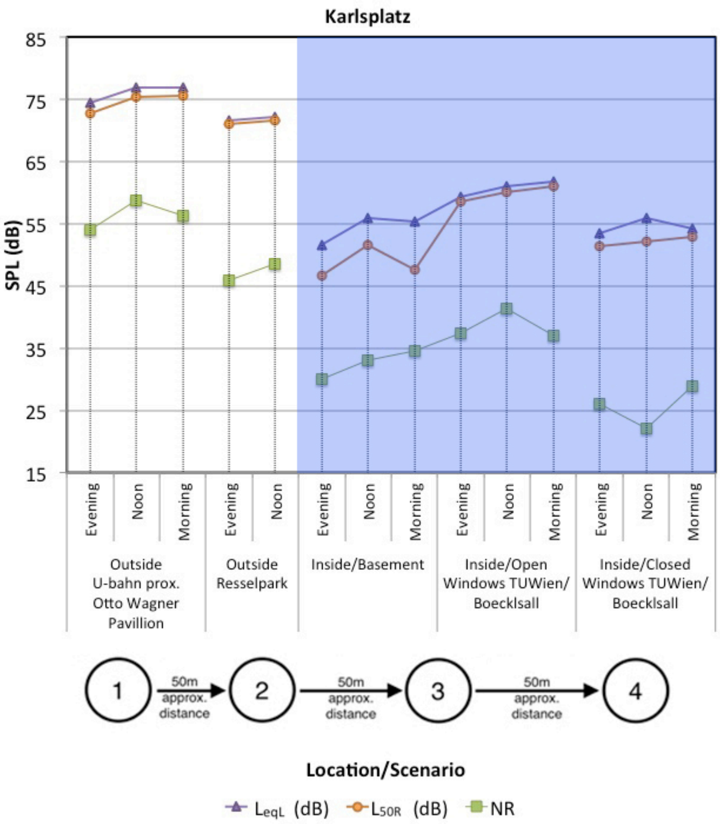



*Fig. 36 Measured values $L_{eqL}$, $L_{50R}$ and, NR in Karlsplatz*

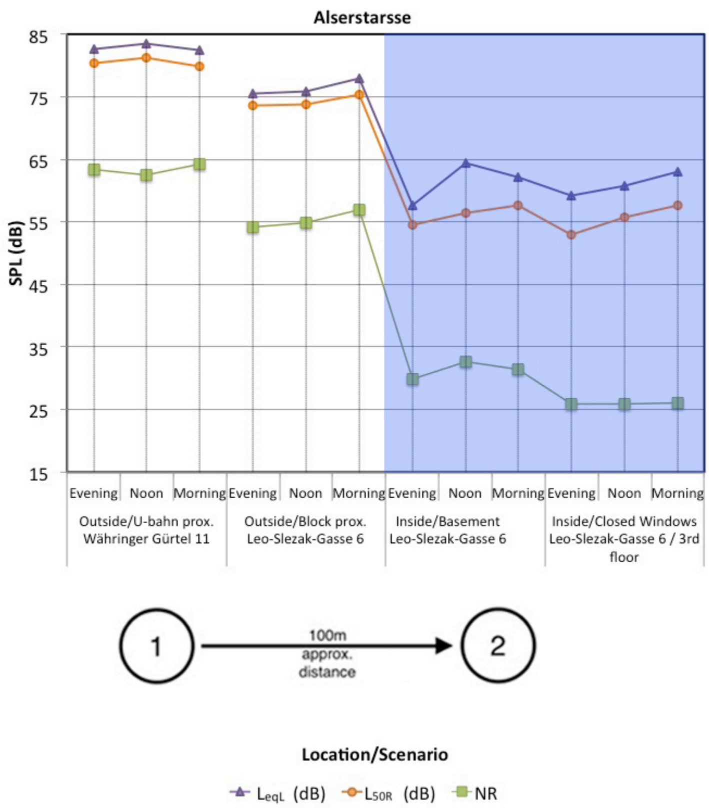



*Fig. 37 Measured values $L_{eqL}$, $L_{50R}$ and, NR in proximity of Alserstrasse Station*

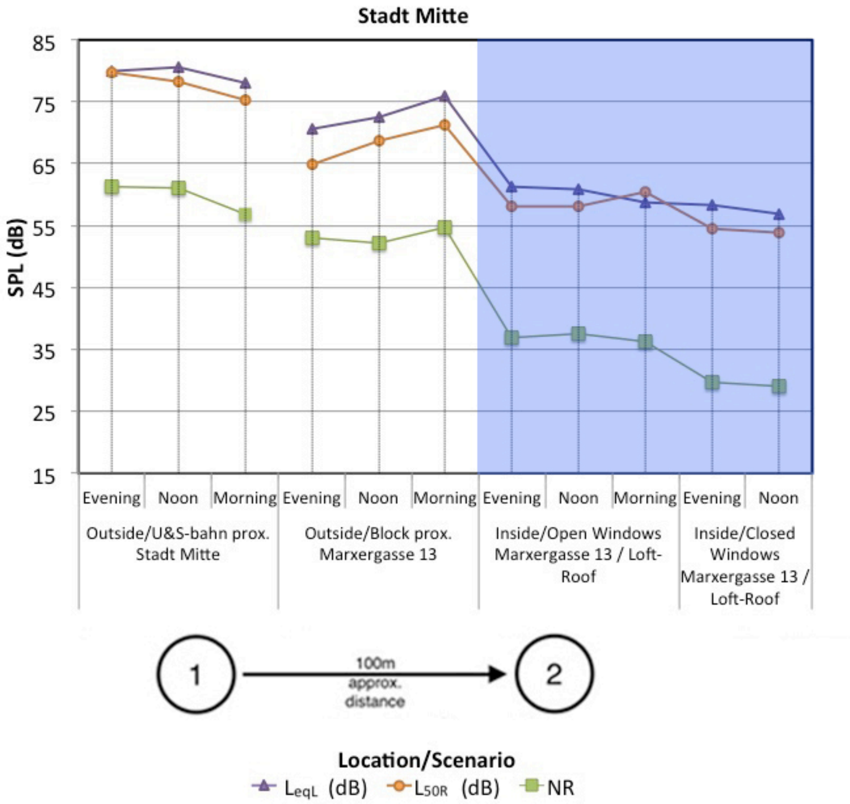



*Fig. 38 Measured values $L_{eqL}$, $L_{50R}$ and, NR in proximity of Stadt Mitte Station*

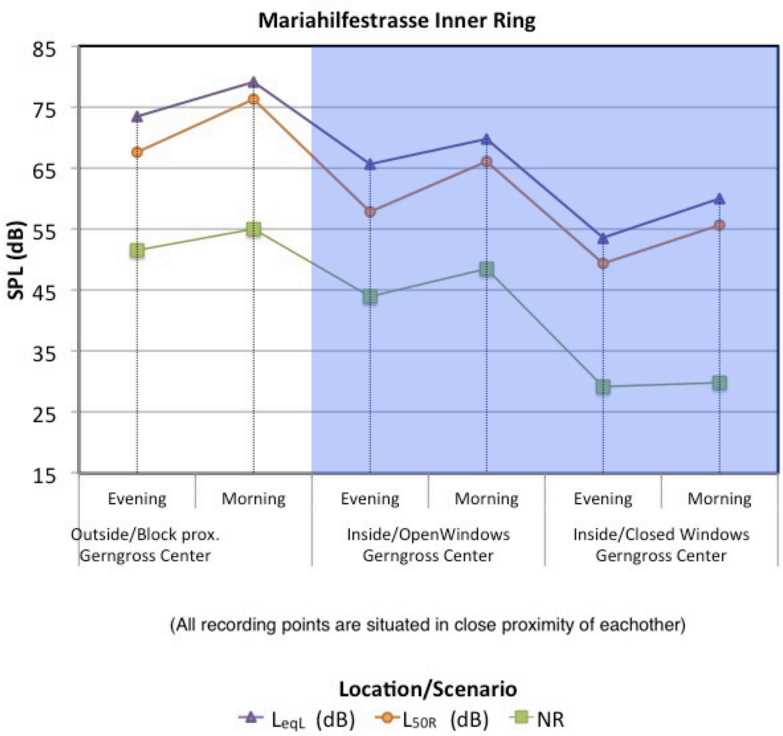



*Fig. 39 Measured values $L_{eqL}$, $L_{50R}$ and, NR in Mariahilferstrasse Inner Ring*

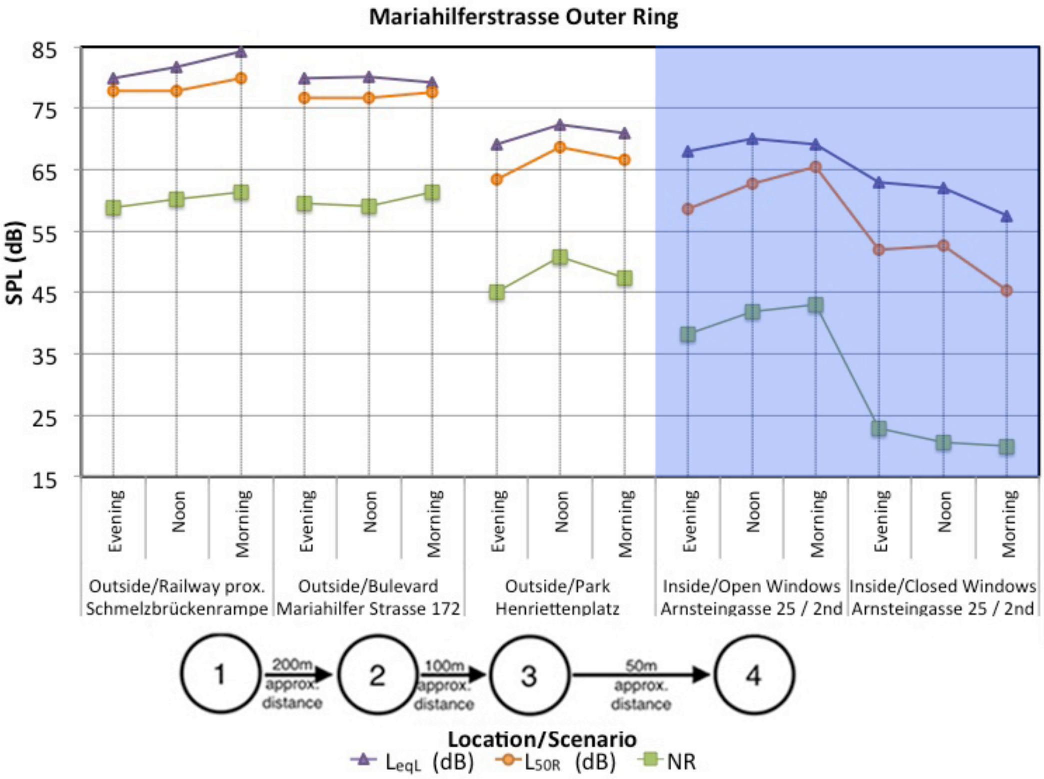



*Fig. 40 Measured values $L_{eqL}$, $L_{50R}$ and, NR in Mariahilferstrasse Outer Ring*

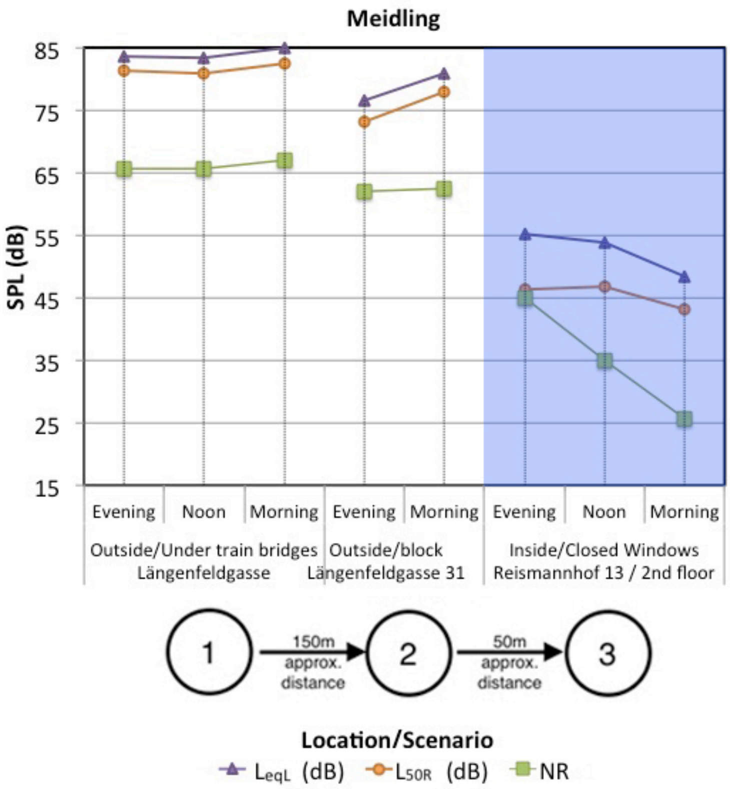



*Fig. 41 Measured values $L_{eqL}$, $L_{50R}$ and, NR in proximity of Meidling Station*

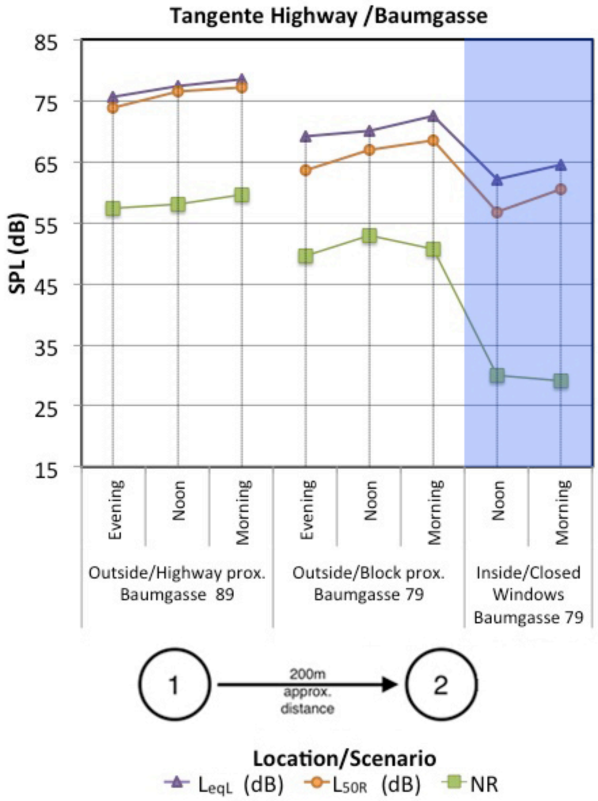



*Fig. 42 Measured values $L_{eqL}$, $L_{50R}$ and, NR at Baumgasse (in prox. of Tangente Highway)*

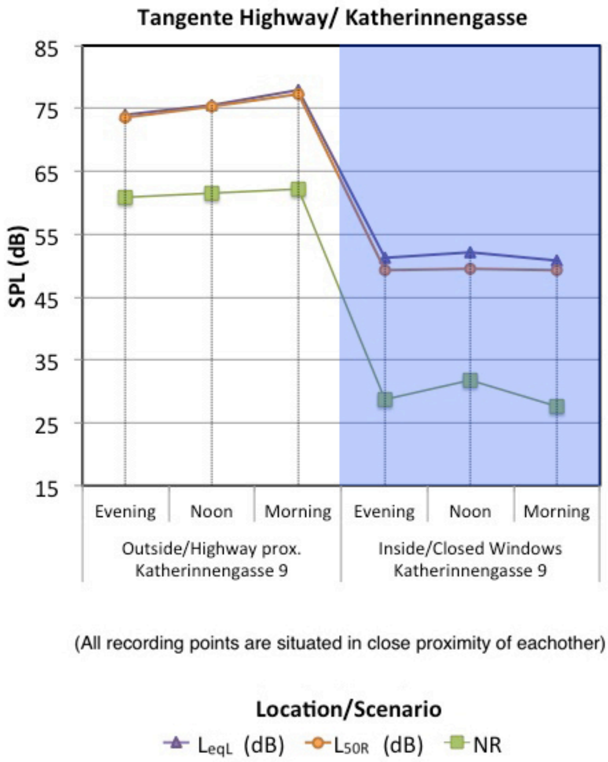



*Fig. 43 Measured values $L_{eqL}$, $L_{50R}$ and, NR at Katherinnengasse(in prox. of Tangente H.w.)*

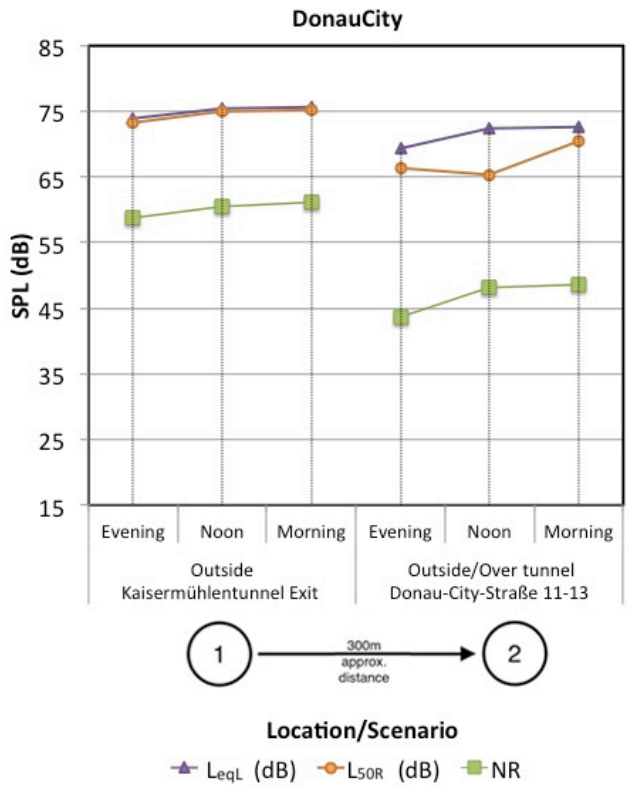



*Fig. 44 Measured values $L_{eqL}$, $L_{50R}$ and, NR in Donaucity*

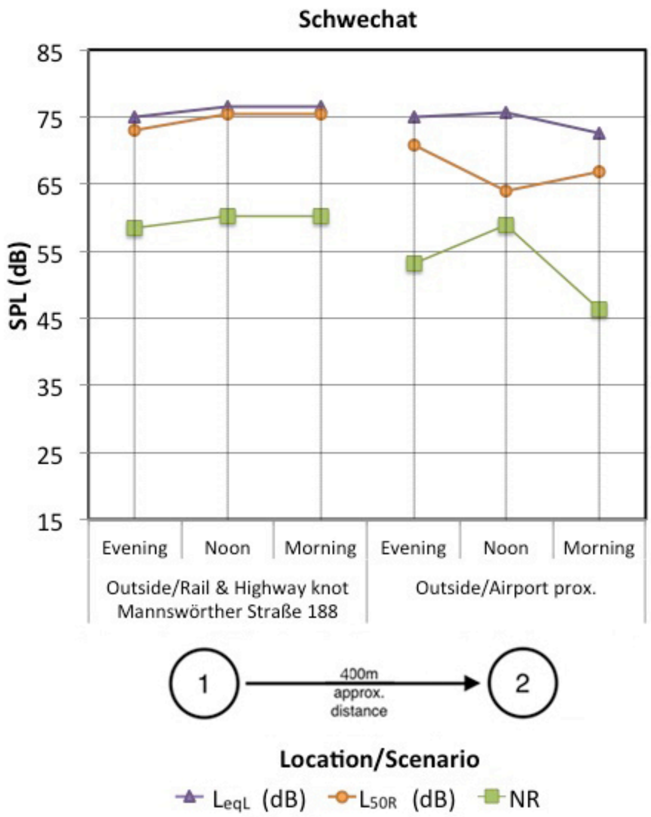



*Fig. 45 Measured values $L_{eqL}$, $L_{50R}$ and, NR in Schwechat (in airport proximity)*

# 4 DISCUSION

## 4.1 Overall Observations

According to the measurements performed, the greatest source of noise in the city of Vienna is road traffic. This is uniform in its distribution and affects the entire city. Noise due to road traffic has been shown to reach critical average values over 70dB even in central areas of the city. In some cases peak values may even exceed 100dB. Most of the average top noise levels were recorded in the morning. This is due to the high car traffic at this time interval. The constant flow of a great diversity of vehicles involved in road traffic and alternating rates of movement determines an irregular waveform pattern.

In places where movement is regulated by traffic lights, an apparent rhythm in the noise waveform pattern occurs over a long period of time. The pattern remains though irregular at a closer inspection. The apparent rhythm is only attributed to start and stop stages of vehicle motion. As these reinitiate movement, higher noise peaks are implied, especially in the lower spectrum.

U-bahn and tram traffic noise also have a strong effect on the acoustical environment of the city. Similar to road traffic, the urban rail network is fairly uniform in its distribution throughout the city. The noise waveform pattern is irregular and with strong peaks.

Although only slightly distinguishable, rail and air traffic noise can be perceived at several points throughout the city. Outside the direct affected areas, noise produced by these sources has very little effect on the overall acoustical environment.

Landscape and urban planning, were shown to greatly influence of noise propagation. In dense urban environment, noise was shown to decay significantly in short distances up to 100m. In open field this may be perceived even at 400m.

Vienna offers a great variety of noise containing, deflecting and dispersing solutions. They range from elevated and excavated pathways to noise walls and vegetation. As expected and shown by the recordings at Alserstrasse, Karlsplatz, Stadtmitte Station and Donaucity, tunnelling proves to be the most efficient solution for noise containment.

## 4.2 Measurement Correlative Observations

### 4.2.1 The relationship between measured values and E.N.D. noise map estimations.

Assuming the mid-point of the 5 dB intervals to represent E.N.D. estimates, the root-mean-square deviation of the measurements from E.N.D. values amount to 2.2 dB. As such, E.N.D. maps appear to provide a reasonable general overview of the urban noise circumstances. However, measurement results at individual locations can considerably deviate from E.N.D. data.

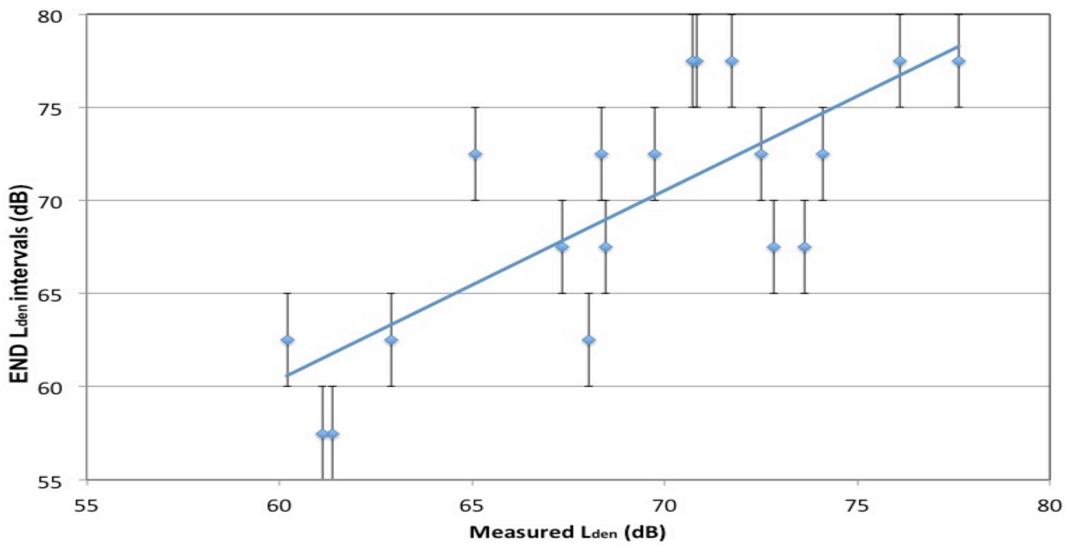



*Fig. 46 The relationship between measurement-inferred $L_{den}$ levels and E.N.D. values (expressed in terms of 5 dB intervals)*

### 4.2.2 The relationship between measurements in the low frequency spectrum and overall noise levels.

To investigate the low frequency component in the measurements, consider the two components of $L_{eqR}$, namely $L_{eqL}$ and $L_{eqMH}$.. As Fig. 47 suggests, there is a clear congruence between these components, even though, in numeric terms, $L_{eqL}$ values are considerably higher. In this case, the root-mean-square deviation (RMSD) between $L_{eqL}$ and $L_{eqMH}$ is 15.3 dB. This suggests that $L_{eqR}$ is largely influenced by $L_{eqL}$, as the RMSD between the two is 0.14 dB.

Thus, it can be seen that the low frequency equivalent levels have a consistent and significant presence. Even as the human ear is less sensitive to these frequencies, such an intensity level difference cannot be ignored. Especially for people who are susceptible to such noise.

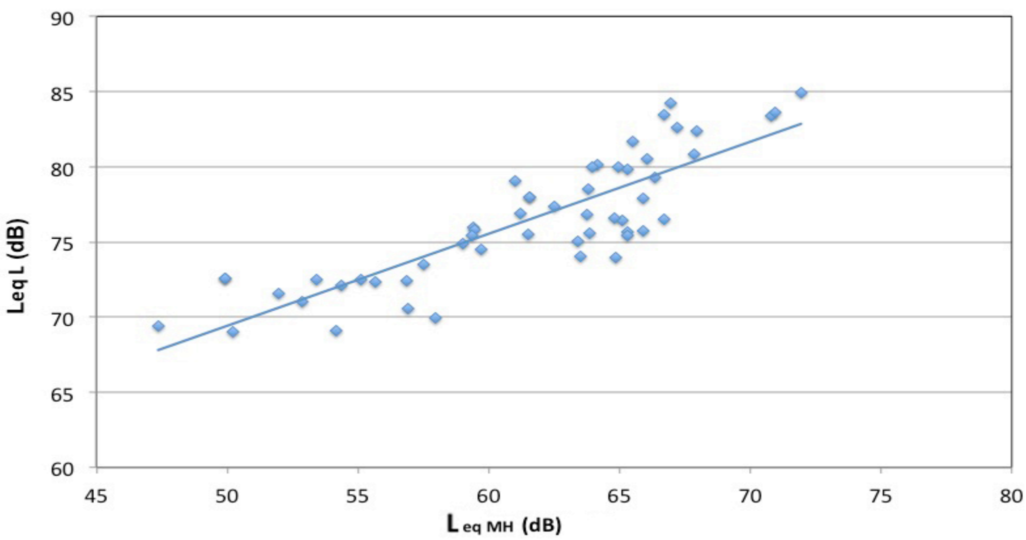



*Fig. 47 Correlation between $L_{eqL}$ & $L_{eqMH}$*

### 4.2.3 Noise distribution in the acoustical environment of the chosen locations.

As illustrated in the following charts (Figure 48-49), the noise difference between outside and indoors with open and closed windows measurements was investigated using $L_{eqL}$, $L_{50R}$ and NR.

The differences between outdoor and indoor with open windows values (Figure 48) are found to be consistent and small independent of the location and rating system. The highest difference was recorded in the case of the measurements performed at Marxergasse 13 (in the proximity of the Stadtmitte Station). This may be due to the height at which the loft apartment is situated. The clearest difference appears to be in the NR values.

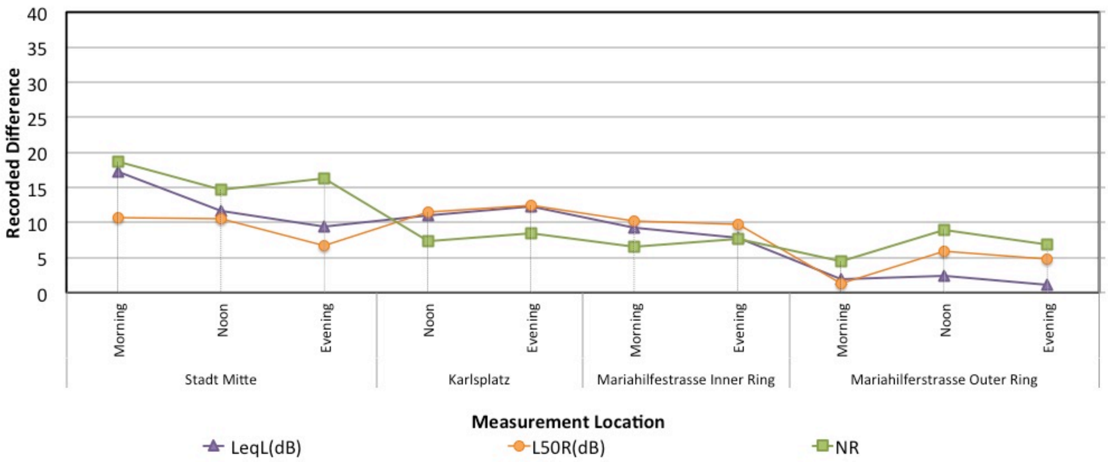



*Fig. 48 Recorded $L_{eqL}$, $L_{50R}$ and NR differences between outside and indoor with open windows measurements*

Also when comparing the closed window scenario values with the outdoor measurements (Figure 49), NR differences appear to be the highest in most of the cases. The difference in the quality assessment index of NR values remains though relatively consistent between 20 and 35. Low frequency levels are even less reduced, as the difference coefficient may drop as low as 8 dB in the case of the recordings performed at Baumgasse 79 (in the proximity of the Tangente Highway elevated section). As in previous chart, the $L_{eqL}$ & $L_{50R}$ difference contours are relative similar. This implies a strong presence of low frequency noise and influence over the overall median sound level.

The highest differences were recorded when indoor measurements were performed in apartments facing an inner courtyard (Reismannhof 13 and Katharinengasse 9). The most significant perceived noise difference was recorded at Katharinengasse 9 in direct proximity to the Tangente highway tunnel exit. Noise outside of this apartment is very high. By simply facing the windows away from the source, noise is significantly reduced.

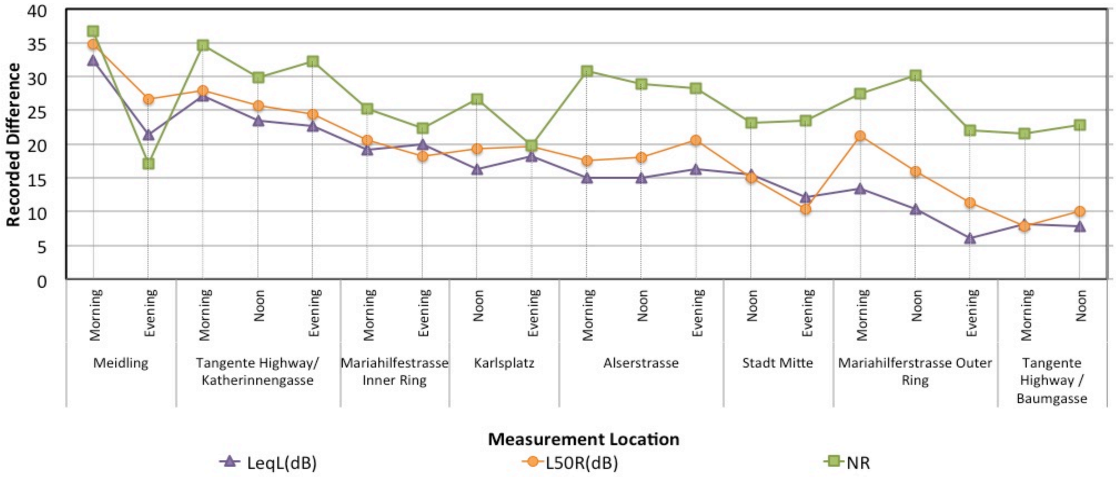



*Fig. 49 Recorded $L_{eqL}$, $L_{50R}$ and NR differences between outside and indoor with closed windows measurements*

### 4.2.4 The relationship between $L_{50R}$ and NR.

As Figure 50 suggests, $L_{50R}$ correlates highly with NR. The former values are consistently about 17 dB higher than the latter. Should future – more extensive – studies confirm this trend, it could suggest a useful and relatively effective way of assessing noise exposure in urban locations: $L_{50R}$ values are fairly easy to obtain empirically. Note that the correlation between $L_{50R}$ and NR appears to be particularly high when road and/or rail traffic constitute the dominant noise sources. As such, outliers in Fig. 50 correspond to locations where such noise sources were much less present.

It has been observed that the outliners were recorded in relative absence of road or rail traffic background noise. Such representative examples are the recordings performed in the proximity of the Airport or above the Kaisermühlentunnel in Donaucity.

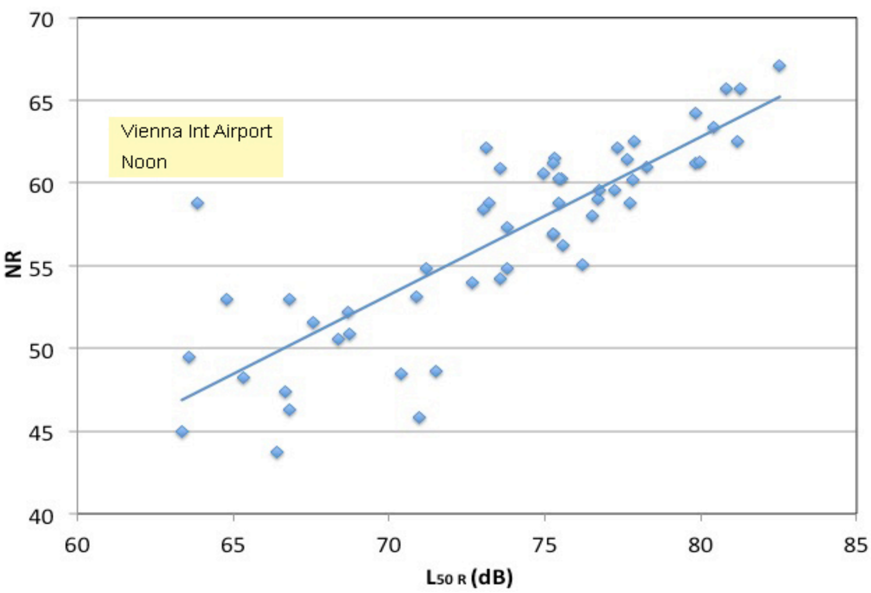



*Fig. 50 Correlation between $L_{50R}$ & NR*

# 5 CONCLUSION

## 5.1 Overview

The main objective of the present contribution was to determine the degree to which noise level measurements in the urban context agree with corresponding information in the E.N.D. maps. Moreover, the relationship between the low-frequency segment of the acoustical exposure to the broad-band data was investigated, based on measurements in the city of Vienna, Austria. Likewise, the correlation between measurement-based $L_{50R}$ and NR was studied.

In case of Vienna, the main sources of noise are road and rail traffic. Some of the highest values recorded are the result of temporary work sites that are present throughout the city of Vienna.

In general, the measured $L_{den}$ values agree relatively well with the E.N.D. data, but deviations at individual locations can be significant. Numeric values of the measured low frequency levels ($L_{eqL}$) are considerably higher than the $L_{eqMH}$ levels. As such, the overall sound levels ($L_{eqR}$) appear to be numerically dominated by the low frequency component of the acoustical exposure.

Further results suggest that $L_{50R}$, which is relatively simple to measure, may be a reliable indicator of the acoustical exposure situation, as it correlates well with corresponding NR data. In the specific case of our measurements in the city of Vienna, $L_{50R}$ values were found to be consistently 17dB higher than the corresponding NR values.

## 5.2 Recommendations

A more in depth research of the human perception of noise in specific scenarios throughout the city is recommended. Recordings over 24h would improve the accuracy of the results of the present study.

This would imply also a study of the psychological aspects of noise perception in correlation to registered complaints and volunteer controlled environment and field measurements.

This would further help develop noise prevention strategies that are adequate to specific real scenarios.

# 6 INDEX

## 6.1 List of Figures

## 6.2 List of Equations

# 7 LITERATURE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