İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

AN ACOUSTICAL EVALUATION MODEL FOR OPEN PLAN OFFICES

M.Sc. Thesis by
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Department : Architecture

Programme : Environmental Control and Building Technology

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<u>İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ</u>

AÇIK PLANLI OFİSLER İÇİN AKUSTİK DEĞERLENDİRME MODELİ

YÜKSEK LİSANS TEZİ

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FOREWORD

I would like to express my deep appreciation and thanks for my advisor Asst.Prof. Dr. Nurgün Tamer Bayazit because of her great effort on me during my thesis period. She did more than anyone can imagine for leading and teaching me in the Master of Science period. She gave me the opportunity of study in Turkey and abroad. I also want to express my special thanks to Lau Nijs for his great support during studies and for giving me the opportunity of performing acoustical measurements of this study in Technical University of Delft, as an Erasmus student. The laboratory measurements of this study are performed in Technical University of Delft laboratories. I also want to thank Işın Meriç for being with me during all Master of Science period and sharing same processes. She showed me great patience and helped me with any problem. In addition I want to express my deep love, appreciations respect to my father and mother. They gave great support, for my good willing and success. Moreover I want to thank İrem Meydan for her incredible support, great help and sacrifices. This work is supported by ITU Institute of Science and Technology.

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Architect

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ABBREVIATIONS

AI	: Articulation Index
ALcons	: Articulation Loss of Consonants
ANSI	**:** American Standards Institute
dB	**:** Decibel
Hz	**:** Hertz
IL	: Insertion Loss
MDF	: Medium Density Fiberboard
RT	**:** Reverberation Time
SPL	: Sound Pressure Level
STI	: Speech Transmission Index
S-N	: Signal to Noise Level
WF	: Weighting Factor

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AN ACOUSTICAL EVALUATION MODEL FOR OPEN PLAN OFFICES

SUMMARY

In this study roles of the architectural and acoustical parameters, which influences acoustics of open plan offices are examined. The first point to be considered during the design process of the open plan offices is privacy. In this study, privacy measurement and calculation unit would be intelligibility. Articulation index would be the unit of intelligibility. During the laboratory studies performed for privacy in open plan offices, detecting effect of architectural parameters on required acoustical condition is aimed. To detect these effects, a workstation sample is modeled and measurements are performed in an anechoic chamber. During the scale model measurements, barrier height and ceiling absorption materials are changed. by use of this, influence of barrier height and ceiling absorption on intelligibility is researched. Measured insertion loss performances of barrier and ceiling combinations, are used for articulation index calculations. Signal to noise ratio is the primary unit which effects the articulation index. As the signal (speech) level increase and background noise level decreases, intelligibility of speech increases. As there may be many different signal and noise levels in every office, different signal and noise spectrums are used for calculations. As a result, open plan parameters which can effect privacy as barrier height, ceiling absorption, speech effort and background noise level values are all used in privacy calculations. Privacy margins are detected after the calculation of every combination of office parameters, articulation index results. Then a chart is prepared which monitors office parameter combinations and corresponding privacy margins. With this chart, open plan office designers, can decide ceiling absorption and barrier heights, by monitoring their interaction with signal to noise level.

AÇIK PLANLI OFİSLER İÇİN AKUSTİK DEĞERLENDİRME MODELİ

ÖZET

Bu çalışmada, mimari ve akustik parametrelerin açık planlı ofislerin akustiği üzerindeki etkileri araştırılmıştır. Açık planlı ofislerin akustik tasarımında gözetilmesi gereken birincil özellik mahremiyettir. Bu çalışmada mahremiyet ölçüm ve hesapları akustik anlaşılabilirlik üzerinden yapılacaktır. Anlaşılabilirliğin birimi olarakta anlaşılabilirlik endexi (Articulation Index) kullanılmıştır. Açık planlı ofislerdeki mahremiyet araştırmaları boyunca yapılan laboratuvar çalışmasında hangi parametrenin, gereken akustik gereksinimi nasıl etkilediği araştırılmıştır. Bu etkiyi bulabilmek için, açık planlı ofis çalışma ortamının ölçekli maketi hazırlanarak, anekoik laboratuar koşullarında, ölçümler gerçekleştirildi. Çalışma istasyonu maketi üzerinde yapılan ölçümlerde kullanılan, iki çalışanın arasında bulunan, bariyerin yüksekliği ve tavanın yutuculuğu değiştirilmiştir. Böylece bariyer yüksekliği ve tavan yutuculuğunun anlaşılabilirlik üzerindeki etkisi ölçülmüştür. Bu ölçümler sonucu elde edilen, bariyer ve tavan malzemesi kombinasyonlarının geçiş kaybı performansları Anlaşılabilirlik Endexi hesaplarında kullanılmıştır. Anlaşılabilirlik Endexini birincil olarak etkileyen konu olan sinyal gürültü oranıdır. Sinyalin (konuşmanın) basınç seviyesi yükseldikçe ve arka plan gürültü seviyesi de düştükçe konuşmanın anlaşılabilirliği artar. Açık planlı ofislerde, çok farklı konuşma ve gürültü oranları olabileceğinden yola çıkarak, Anlaşılabilirlik Endexi hesaplamalarında, farklı konuşma ve gürültü spektrumları kullanılmıştır. Böylece ofiste mahremiyeti etkileyebilecel parametrelerden olan, bariyer yüksekliği, asma tavan yutuculuğu, konuşma eforu, arka plan gürültüsü parametrelerinin hepsi mahremiyet hesaplarında dikkate alınmıştır. Anlaşılabilirlik Endexi hesapları tüm kombinasyonlar için gerçekleştirildikten sonra, mahremiyet aralıkları belirlenmiştir. Bu mahremiyet aralıklarını karşılayan bariyer yüksekliği, tavan yutuculuğu ve sinyal gürültü oranı değerleri sınıflandırılıp, hangi anlaşılabilirlik seviyesinin hangi şartlar altında sağlanabileceğini anlatan grafik hazırlanmıştır. Bu sayede açık planlı ofis tasarımcıları, bariyer yüksekliği, tavan yutuculuğu ve sinyal gürültü oranı etkileşimini görerek tavan malzemesi ve bariyer yüksekliği konularına daha rahat karar verebilirler.

1. INTRODUCTION

The aim of open planned environments is to hold more employees within a smaller area. As computers started to be used widely, paper works in offices are fewer. Therefore, every employee can work in a smaller area with same performance or even better. However, there may be some consequences of sharing same area with other employees. If these consequences examined trough the employee’s point of view, acoustical privacy is most important problem of open plan offices.

Throughout the historical development of open plan offices, as the opportunities of employees become better, performances of the workers increases [1]. So as the open plan offices becomes more private performance of the workers would increase. In this thesis, a chart to sustain acoustical privacy in open plan offices is searched.

Distraction of current work directly reduces the work performance, but there are also indirect effects of noise due to different coping mechanisms such as having extra breaks, arrangements of working schedule due to the noise, and noise management in the organization. Constant noises like ventilation and traffic very seldom cause complaints because they do not contain any information. Speech deteriorates work performance because it permanently loads the short-term memory. One cannot easily habituate to speech in offices because it is not of a steady nature [2]. Which means only intelligible speech causes distraction during the work.

According to the previous studies, speech heard from neighboring desks is the most distracting noise source in open plan offices. In the planning of the open plan offices, the aim is to provide efficient attenuation of speech and reduction of speech intelligibility between workstations so that the concentration of the worker will not be disturbed. There are some ways to attenuate the sound, such as using absorbing ceiling material and screens between adjacent workstations. A properly planned masking noise system can also used, if background noise level of the room is not sufficient to mask the speech [3].

1.1 Purpose of the thesis

Acoustical study affords in an open plan office are performed for employees to work in an acoustically satisfactory environment. Speech and office noise deteriorate work performance in open offices.

The main objective of this study is to help designers to check acoustical conditions of the open plan office designs. Architects or engineers can calculate acoustical privacy amount of their open plan office designs, but to be able calculate privacy levels in an open plan office, basic acoustical knowledge must known or acoustical consultancy is required.

According to the previous studies, acoustically satisfactory office means, acoustically private and less noisy working environment. Therefore, by performing some acoustical measurements in anechoic rooms, different variety of open plan offices are scale modeled and different acoustic conditions are measured. Via results of these measurements, some formulas and tables can be reached. These formulas and tables can give designers required ceiling absorption and barrier height within background noise level and signal level to sustain adequate level of privacy.

There are lots of studies has been accomplished about open plan office acoustics, due to the field conditions and unexpected diffractions there are lots of calculation methods invented about barrier attenuations in open plan offices.

In order to evaluate the influence of sound reflections from the ceiling on the acoustic performance of the screen, a mathematical model that includes the absorption coefficient must be used. Moreland et al. and Kurze have presented two different models but both assumed that the sound field in the room is diffuse [4, 5]. Both of the models are valid when ceiling and floor of the place are highly reflective. Kotarbinska treated the problem in a different way by using image source method to represent reflections [6]. Although this model is more general, only the averaged sound reflection coefficients of the floor and the ceiling were used in the model, which means that the effects of the floor reflection and ceiling reflections were not separated. In addition, the effects of mean absorption level of the room were not considered.

Many architectural effects change acoustical comfort of an open plan office. Such as height, width and absorption level of the barrier and diffraction over the screen and background noise level. Although most of these effects based on barriers, one more very important office component affects acoustical comfort in open plan offices is ceiling. In an open plan office, the ceiling, which is a sound reflective surface, always exists. Consequently, the sound energy may reach the receiver on the other side of the barrier via three different ways: diffraction at the edges, and reflection at the ceiling and transmission trough barrier. [6] As shown in the Figure 1.1

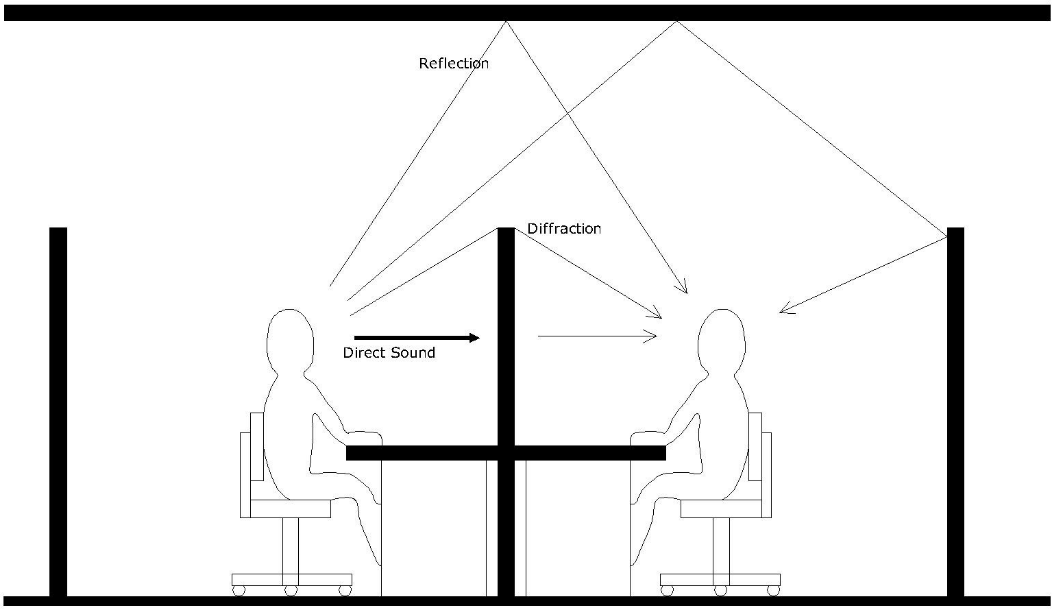

Figure 1.1 : Sound propagation in a workstation [2]

For an open plan office, the most important component, affecting the acoustical privacy is typically the ceiling reflection. As a result, it is suggested that the ceiling should be very absorptive [7].

In this study, a scale model of a working unit in an open plan office erected in an anechoic room, to measure acoustic effects of the edges, surfaces and other architectural components. Measurements are performed with different types of materials. As ceiling materials, MDF, wool and foam plastic is used to see the effect of ceiling absorption on measurements. Also different barrier height is used for same purpose.

Acoustical measurements of this study are mostly aimed to measure the level of privacy. Therefore, if amount of sound measured from the receiver side of the barrier is less, then the barrier and the screen used for that measurement is better.

To calculate the level of privacy, articulation Index is chosen as a unit. Therefore, after the measurements some calculations must be done to calculate the articulation index value of that office model. Within those calculations background noise level and speech effort of the source is integrated to the level of privacy.

In an open plan office, barrier height, usually expected to be as short as possible, because of the architectural purposes in order to avoid claustrophobic space. However, as the barrier height gets lower privacy level decreases. In addition, background noise level is expected to be as low as possible to avoid distraction of employees. Nevertheless, as the background noise level gets lower signal to noise level gets higher so, privacy level decreases again. Absorption level of the ceiling is another issue that have to be examined. Absorptive ceiling materials are much more expensive than the ones are not. But as the ceiling gets more absorptive, privacy level would increase.

These components (barrier height, background noise level and ceiling absorption) must be examined together to detect adequate level of privacy within an open plan office. These components must optimize.

To examine privacy level of the open plan environment and articulation index calculation, basic acoustical happenings in an open plan office must be described.

2. BASICS OF OPEN PLAN OFFICE

2.1 Sound Propagation in Open Plan Office

The acoustical design of an open-plan office can be complex because of the many different sound paths that need to be considered. Mainly, in addition to the direct sound, sound can be reflected from the ceiling, diffracted over the top of a separating panel, or transmitted through the panel. According to the mathematical calculations of propagation, that the most significant paths are those that reflect sound from the ceiling and diffract sound over the separating panel. It is therefore essential that the combination of ceiling absorption and separating panel height must be adequate in order to sustain acoustically comfortable office.

2.1.1 Direct Sound

If there are no obstacles between source and the receiver, the emitted sound, which reaches to the receiver without any reflection, is called direct sound.

Sound level, received directly by any occupants in an open plan office is related with sound level of the source, distance between source and the receiver and absorption of the room.

Figure 2.1 shows mean absorption of a room, changes the SPL received at a certain distance. According to the figure, direct sound (%100 absorptive) decreases to 35 dB at 15 meters. For 5 meters distance direct sound decreases to 45 dB, in %44 absorptive room SPL becomes 48 dB, in %22 absorptive room SPL becomes 50 dB, for %11 absorptive room SPL becomes 53 dB and for %5 absorptive room SPL is around 55 dB. As the reflection coefficient of a room increase, sound level in certain distance increases too. This means, absorption added to a room decreases sound level in a diffuse field [8].

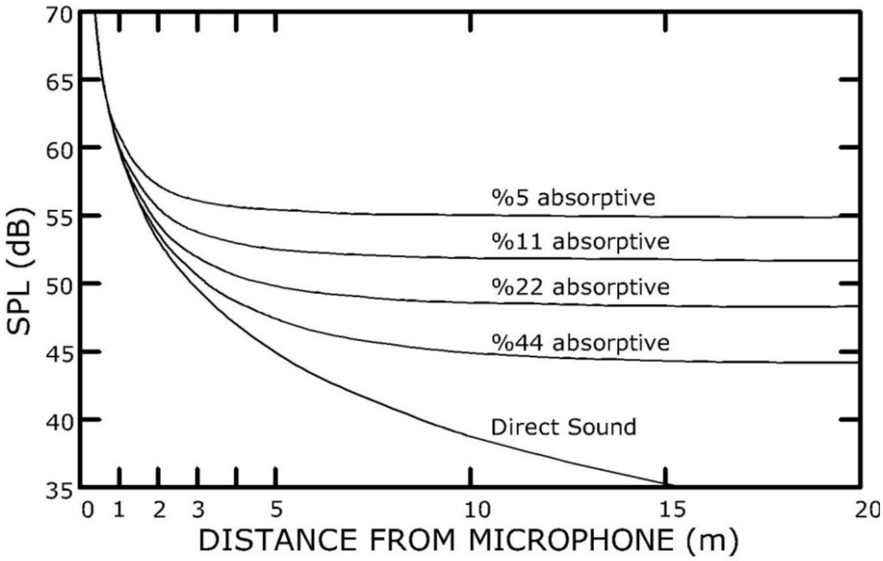

Figure 2.1 : SPL change according to the distance in different absorptive environments [8]

2.1.2 Reflection

When sound is activated in a room, sound travels radial in all directions. As the sound waves encounter obstacles or surfaces, such as walls, their direction of travel is changed, they are reflected.

Like the light/mirror analogy, the reflected wavefronts act as though they originated from a sound image. This image source is located the same distance behind the wall as the real source is in front of the wall. This is the simple case a single reflecting surface. In a rectangular room, there are six surfaces and the source has an image in all six sending energy back to the receiver. In addition to this, images of the images exist, and so on, resulting in a more complex situation.

A ray of sound may undergo many reflections as it bounces around a room. The energy lost at each reflection results in the eventual demise of that ray. The mid/high audible frequencies have been called the specular frequencies because sound in this range acts like light rays on a mirror. Sound follows the same rule as light, The angle of incidence is equal to the angle of reflection

The sound pressure on a surface normal to the incident waves is equal to the energy density of the radiation in front of the surface. If the surface is a perfect absorber, the pressure equals the energy density of the incident radiation. If the surface is a perfect reflector, the pressure equals the energy-density of both the incident and the reflected radiation. Thus the pressure at the face of a perfectly reflecting surface is twice that of a perfectly absorbing surface. At this point, this is only an interesting sidelight [9].

If an omnidirectional source is placed near a perfectly reflecting surface of infinite extent, the surface acts like a mirror for the sound energy emanating from the source. The intensity of the sound in the far field, where the distance is large compared to the separation distance between the source and its mirror image, is twice the intensity of one source.

Figure 2.1 shows this geometry in terms of the relationship between the sound power and sound pressure levels for a point source given in Equation 2.1[10].

$$Lp = Lw + 10\log(Q/4\pi r^2) + K \qquad \textbf{(2.1)}$$

Where;

Lp= sound pressure level

Lw= sound power level

Q = directivity

r = measurement distance

K = constant (0.13 for meters)

When the source is near a perfectly reflecting plane, the sound power radiates into half a sphere. This effectively doubles the Q since the area of half a sphere is $2\pi r^2$. If the source is near two perfectly reflecting planes that are at right angles to one another, such as a floor and a wall, there is just one quarter of a sphere to radiate into, and the effective Q is four [10].

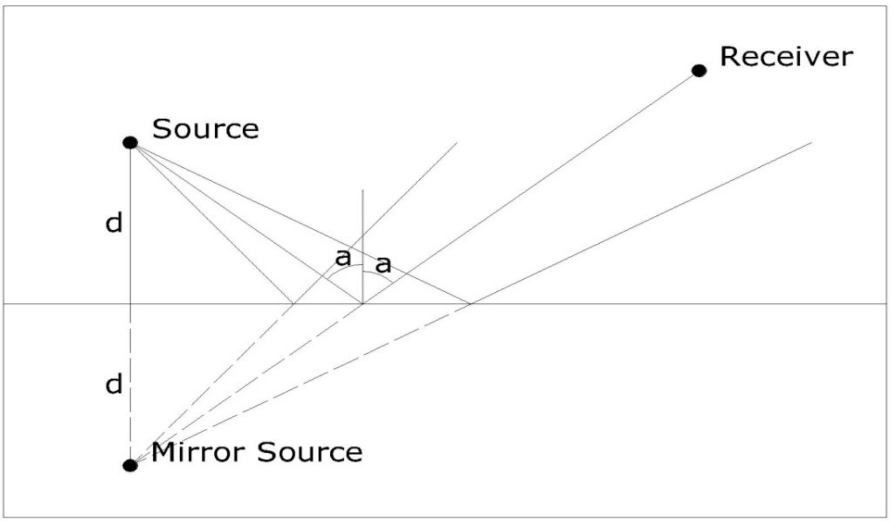

Figure 2.2 : Sound reflection mirror source method [11]

2.1.3 Diffraction

It is well known that sound travels around corners and around obstacles. Music reproduced in one room of a home can be heard down the hall and in other rooms. Diffraction is one of the mechanisms involved in this. The character of the music heard in distant parts of the house is different. In distant rooms, the bass notes are more prominent because their longer wavelengths are readily diffracted around corners and obstacles.

Wavefronts of sound travel in straight lines. Sound rays, a concept applicable at mid/high audible frequencies, are considered to be pencils of sound that travel in straight lines perpendicular to the wavefront. Sound wavefronts and sound rays travel in straight lines, except when something gets in the way. Obstacles can cause sound to be changed in its direction from its original rectilinear path. The process by which this change of direction takes place is called diffraction. It was demonstrated that light is not always propagated rectilinearly, that diffraction can cause light to change its direction of travel. In fact, all types of wave motion, including sound, are subject to diffraction.

The shorter the wavelength (the higher the frequency), the less dominant is the phenomenon of diffraction. Diffraction is less noticeable for light than it is for sound because of the extremely short wavelengths of light. Obstacles capable of diffracting (bending) sound must be large compared to the wavelength of the sound involved.

The effectiveness of an obstacle in diffracting sound is determined by the acoustical size of the obstacle. Acoustical size is measured in terms of the wavelength of the sound. In Figure 4, two types of obstructions to plane wavefronts of sound are depicted. In Figure 2.3A a heavy brick wall is the obstacle. The sound waves are reflected from the face of the wall, as expected. The upper edge of the wall acts as a new, virtual source sending sound energy into the “shadow” zone behind the wall by diffraction. The mechanism of this effect will be considered in more detail later in this chapter. In Figure 2.3B the plane wavefronts of sound strike a solid barrier with a small hole in it. Most of the sound energy is reflected from the wall surface, but that tiny portion going through the hole acts as a virtual point source, radiating a hemisphere of sound into the “shadow” zone on the other side.

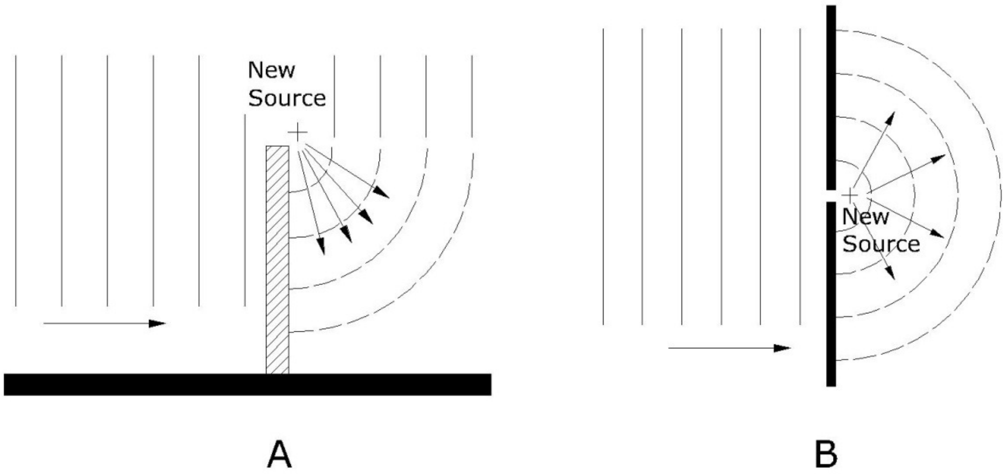

Figure 2.3 : Diffraction of sound waves through barrier [9]

(A) If the brick wall is large in terms of the wavelength of the sound, the edge acts as a new source, radiating sound into the shadow zone. (B) Plane waves of sound impinging on the heavy plate with a small hole in it sets up spherical wavefronts on the other side due to diffraction of sound [9].

2.1.4 Sound Transmission

The transmission of sound from one space to another through a partition is a subject of some complexity. In the simplest case, there are two rooms separated by a common wall having area Sw. If we have a diffuse sound field in the source room that produces a sound pressure Ps and a corresponding intensity which is incident on the transmitting surface, a fraction γ of the incident power is transmitted into the receiving room through the wall where it generates a sound pressure level.

If the receiving room is highly reverberant, the sound field there also will be dominated by the diffuse field component.

The equation for the transmission of sound between two reverberant spaces is [11];

$$Lr = Ls - \Delta LTL + 10\log\frac{Sw}{Rr} \qquad \textbf{(2.2)}$$

Where,

Lr = spatial average sound pressure level in the receiver room (dB)

Ls = spatial average sound pressure level in the source room (dB)

ΔLTL = reverberant field transmission loss (dB)

Sw = area of the transmitting surface (m^2)

Rr = room constant in the receiving room (m^2)

2.1.5 Attenuation

As sound waves propagate through any medium, the sound energy diminishes due to spreading, scattering, absorption, and sound transmission loss.

Spreading occurs as the sound expands in spherical waves. The sound level decreases as the distance from the source becomes larger. Scattering occurs as the wave direction changes through diffraction or reflection. Absorption occurs as the sound enters a porous material and gets trapped in the air pockets. The trapped sound energy is converted to other forms of energy. Sound transmission loss occurs when sound energy is converted into vibration energy within a material. Heavier, more massive materials attenuate sound more and, hence, have greater sound transmission loss values [12].

Barriers are the most commonly used way of controlling exterior and interior noise. Figure 2.4 shows a simple barrier geometry. When a plane wave encounters a barrier, the lower portion of it is cut off leaving the rest to propagate over the wall. The high and low-pressure regions of the wave impinge on the quiescent fluid in the shadow zone and propagate into it. In this manner the wave diffracts or is bent into the space behind the barrier. The greater the diffraction angle the greater the attenuation.

Barrier attenuation for a point source is calculated using the maximum Fresnel number, which is determined from the difference between the shortest propagation path that touches the edge of the barrier and the direct path through the barrier [13]. The geometry is given in Figure 2.4. The maximum Fresnel number N is;

$$N = \mp \frac{2}{\lambda} (A + B - r) \qquad \textbf{(2.3)}$$

Where, (A + B − r) is the minimum path length difference. The sign is positive in the shadow zone and negative in the bright zone. For a simple point source the barrier attenuation is [13];

$$\Delta Lb = 20 log \frac{\sqrt{2\pi N}}{tanh\sqrt{2\pi N}} + Kb \qquad \textbf{(2.4)}$$

Where;

ΔLb = barrier attenuation for a point source (dB)

A,B, r = minimum source to receiver distances over and through the barrier

N = maximum Fresnel number defined by Equation 5.10 ($-0.19 \leq N \leq 5$)

λ = wavelength of the frequency of interest

Kb = barrier constant which is 5 dB for a wall and 8 dB for a berm

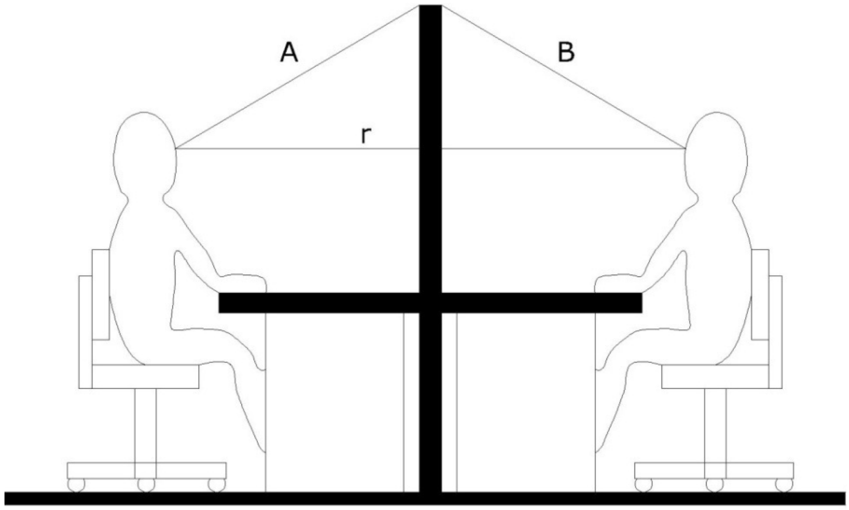

Figure 2.4 : Path length difference for a single barrier

When N is zero, that is when the line of sight between the source and the receiver is just broken by the top of the barrier, the theoretical attenuation afforded by a wall is 5 dB. For every 0.3 m of barrier above this line the barrier provides about one additional dB of attenuation at 500 Hz. This is a rough rule of thumb, which is useful for estimation purposes. Detailed attenuation calculations should be done for the actual source spectrum and barrier geometry. If the barrier has an unusual shape, such as a truncated triangle in section, the total path length across the top of the barrier must be calculated. For large values of N, the attenuation has a practical limit of 20 dB for walls and 23 dB for berms [13].

2.2 Elements of Open Plan Offices

Acoustic parameters are depended on frequencies and affect the privacy within daily occupancy. In an open plan office, if an employee wants to have a private call, he or she would lower their sound pressure level, or preferably would go to a more noisy part of the office to let background noise mask his or her speech and prevent others understand their speech. Open plan office parameters, which affect, privacy level of the open office is described below.

2.2.1 Masking System

When we listen to two or more tones simultaneously, if their levels are sufficiently different, it becomes difficult to perceive the quieter tone. We say that the quieter sound is masked by the louder. Masking can be understood in terms of a threshold shift produced by the louder tone due to its overlap within the critical band on the cochlea.

Tones mask upward in frequency rather than downward. The louder the masking tone the wider the range of frequencies it can mask. Masking by narrow bands of noise mimics that of pure tones and broad bands of noise mask at all frequencies.

Masking is an important consideration in architectural acoustics. It is of particular interest to an acoustician whether speech will be intelligible in the presence of noise. In large indoor facilities, such as air terminals or sports arenas, low-frequency reverberant noise can mask the intelligibility of speech. This can be partially treated by limiting the bandwidth of the sound system or by adding low-frequency absorption to the room. The former is less expensive but limits the range of uses. Multipurpose arenas, which are hockey rinks one day and rock venues the next, should have an acoustical environment that does not limit the uses of the space [10].

Sound masking system is a method of creating neutral background noise by adding simulated ventilation sound to the office. Background noise reduces the intrusion of intermittent noises by covering up (masking) more distracting speech sounds and by reducing the contrast between the quiet office and any noise.

Once installed, the sound masking system plays a neutral (not white or pink) background noise through speakers in the ceiling. The sound spectrum (range of frequencies emitted) and sound level are controlled to effectively mask most speech sounds without becoming a distraction.

It is not possible to use ventilation systems for sound masking because noise levels vary as ventilation requirements vary.

A good sound masking system balances the need for high frequencies to mask sound with the annoyance factor of excessive high frequencies. The sound level should be adjusted after the masking spectrum is found. Masking noise should have a maximum level of 48 dB(A). Generally, 45 dB(A) was most widely acceptable in open plan offices[12].

When an electronic masking system is used in an open office, it is usually advised that the staff be kept unaware of its existence. This avoids unnecessary problems with complaints from persons using the masking system as a focus for verbal sublimation of other unvoiced minor grievances. However, in this case, some information on the staff's reactions to various levels and spectrum shapes was desired and they were informed at the outset that a masking system would be in operation. They were told that it was believed that such a system would improve their working conditions and that their help was needed in ascertaining the best spectrum shape and optimum level of sound. Thus while the subjects were aware that their acoustic environment would vary they did not know just exactly how.

There are office workers for whom aural privacy is not a prime consideration. Their work does not demand a high degree of concentration so they are not disturbed by sounds from neighboring workstations. For the group considered here low background noise levels were preferred, so no masking system should be used. The acoustical ceiling material was not particularly absorbent (NRC=0.45) but since the loss of privacy caused by ceiling reflections was not important, it was not necessary to install more efficient material.

Faced with designing an office for a group such as this, the designer could economize on acoustical frills and concentrate on more important factors affecting user satisfaction. If the structure of the organization is such that the office may be occupied at a later date by a staff requiring a higher degree of privacy, then economics may necessitate the initial installation of high-quality ceiling boards, absorptive treatment of vertical surfaces, and the wiring for a masking system even if not immediately required [14].

2.2.2 Ceiling

The ceiling is the largest bare surface in an open-plan offices. It extends across the entire open-plan office, making it possible for sound to reflect into every workstation. Previous studies, gives some suggestions about the mean absorption level of the ceiling systems.

Even, mean absorption level of the ceiling is very high in an open plan office, light fixtures, baffles, air supply diffusers, return grilles, and any other ceiling elements can cause unwanted sound reflections. Spots that reflect sound directly from one cubicle to another must avoided, because non-absorbent elements mounted in the ceiling can compromise ceiling absorbency.

Absorptive floor covers is used to absorb reflections and reduce occupant noises, such as typing and squeaky chairs. In terms of surface area floor is as large as ceiling, also floor reaches to the all workstations. Sound propagation paths through the floor are generally blocked by partitions, such as desks, cabinets, and people, but covering the floor with an absorptive material can reduce the reflections that do get trough. Carpet and furniture also reduce any problems created by gaps between the floor and partitions. Gaps of up to 50 mm do not affect the AI rating when the floor is carpeted. Even gaps of 100mm are acceptable with carpeting [12].

2.2.3 Partition

Partitions block direct and transmitted sound. Sound transmission loss indicates a partition's ability to block sound. If the partition is not massive or heavy enough, it will not attenuate the sound passing through.

The higher the STC, the less sound will travel through the partition into the neighboring workstation. STC of 15 would give a good safety margin. Screens higher than 6 ft should have an STC of at least 20. STC 20 is an acceptable minimum [15]. Based on example situations, STC 15 does not provide adequate speech privacy, especially if there are other design problems in the room.

It is important to make sure that the partitions have no holes in them. Gaps for electrical cords and outlets must be covered to prevent noise from getting through holes.

Partitions can also block vertical diffraction paths if they are high. The higher the partitions, the quieter the sound becomes as it travels over. The minimum height of a barrier located in a workstation is1.7m [15]. In addition, partitions lower than 1.5m does not provide adequate speech privacy. However, partition heights greater than

2m offer smaller and smaller improvements [16]. Breaking the line of sight between occupants can provide acoustic privacy where it is needed most, either seated or standing.

Using very high partitions to isolate work areas from each other, instead of using them to create individual cubicles must be considered. Very high partitions not often used in open-plan offices because they can be aesthetically displeasing, and can block electric light and daylight.

Usage of absorbent ceiling and high partitions together to attenuate sound, gives the combination of the greatest effect on open-plan office acoustics. Changing the partition height by a small amount has a much greater effect on the AI rating when the ceiling is very absorbent.

Use absorbent partitions to attenuate reflected sound as it bounces off partitions. Partitions should have an SAA (sound absorption average) rating of at least 0.8 or be covered in a material with SAA 0.7. If a partition is covered on both sides with a material having SAA 0.7, it can be given a total SAA of O.8. SAA 0.9 for partitions is required[15].

If it is not possible to make all the partitions absorbent, then partitions between workstations and all parallel partitions must be absorbent to stop reflections bouncing off a back wall and over the partition. In that case, covering partition edges with absorptive material to attenuate some diffracted and reflected sound becomes necessary[12].

2.2.4 Lighting fixtures and placement

Light fixtures can reflect sound and make ceilings mean absorption level lower. Both the light fixture type and placement are important. Researchers investigated two positions for ceiling-mounted lighting: over the centre of the workstation and over the separating partition between two workstations

Flat lens lights (prismatic-lensed luminaires) are undesirable because they reflect sound. Researchers found that they created a hard surface that reflected sound easily from one workstation into the other when placed over the separating partitions. Over the centre of the workstations, the reflection paths are less direct. They only decrease mean absorption level of the ceiling material.

Open-grille lights (parabolic-louvered luminaires) scatter sound. Over separating partitions, they tend to scatter the sound away from the occupants. Over the centre of the workstation, they tend to scatter the sound directly towards occupants [15].

Indirect luminaires may reflect sound towards occupants, depending on their shape. Different shapes might create different effects, and smaller fixtures might reflect less sound[15].

2.2.5 Air Supply and Return Grilles

Placement of ceiling-mounted air supply diffusers and return grilles are very important. They can reduce ceiling absorption if they are misplaced. They can also create sound masking noise. Diffusers and grilles should not installed directly over workstations or in areas where they are likely to reflect sound into neighboring workstations [15].

2.2.6 Workstation design and orientation

The workstation design in an open-plan office should screen occupants from noise sources such as other workers, office equipments and corridors. This generally involves breaking sight lines between sources and receivers.

Large workstations increase speech privacy level and reduce acoustical distractions because sound diminishes over distance. Distance is especially important if the partitions are low.

Placement workstation openings should avoid reflection paths. Carefully arranging the workstation openings and making vertical surfaces absorbent reduces reflection paths.

Within workstations, workers should placed face away from each other, computers and telephones is better located in absorbent corners away from neighboring occupants. Speech sounds are directional and are much louder at the front of a person.

Sound reflected trough windows must considered. Additional panels should block reflections bouncing off windows that extend into multiple workstations. Window reflections can also be prevented by using parabolic louvers to scatter sound and maintain the view and sunlight provided by the window. Windows can also have recessed or tilted window baffles to reduce acoustic reflections; however, these window solutions involve significant renovation. Surfaces parallel to windows should be absorbent to stop reflections bouncing off windows and over the partitions.

2.3 Acoustical Measures

Privacy is primary acoustical measure in an open plan office. Main design goal in an open plan office is to sustain privacy within a less noisy environment.

There are several metrics currently enjoying use for the prediction of the intelligibility of speech in rooms: the Articulation Index (AI), the Articulation Loss of Consonants (ALcons), the Speech Transmission Index (STI), and the various signal-to-noise ratios including the Useful to Detrimental Energy Ratio ($U\tau$), the Useful to Late Energy Ratio ($C\tau$) and Speech Intelligibility Index (SII).

Much of the pioneering work in communication acoustics was done at Bell Laboratories, where engineers studied methods of improving the intelligibility of telephone conversations. Harvey Fletcher was one of these early pioneers. Fletcher proposed to quantify the speech distortion in telephone systems by relating it to articulation scores. He defined the “articulation,” which ranged from 0 to 1, as an overall measure of the intelligibility of speech transmitted through a system. One of Fletcher’s contributions was the discovery of the probabilistic nature of intelligibility, and indeed the definition of articulation is the probability of understanding an individual sound. If, for example, a syllable consists of a consonant-vowel-consonant (cvc) sequence, the probability of understanding the whole sequence would be the product of the probabilities of understanding each separate consonant or vowel. When this was combined with the realization that the probabilistic approach carried over into the analysis of separate frequency bands the basis for the Articulation Index was established. French and Steinberg formalized the method of measurement and Kryter published a method of calculating the expected speech intelligibility in rooms using the sum of weighted signal-to-noise ratios in third-octave frequency bands.

In 1986 Bradley published a study comparing the accuracy of various articulation metrics. Articulation Index (AI) is like virtually all other intelligibility prediction schemes in that it uses a signal-to-noise ratio as part of the calculation. The differences among the various schemes are how the terms "signal" and "noise" are defined. In AI calculations, the signal is the long-term rms average speech level (direct+reverberant) plus 12 dB, and the noise is the steady background noise level in each frequency band. AI is difficult to use as an intelligibility prediction methodology since it does not have a built-in way of accounting for reverberant noise. In the ANSI standard there is an empirical correction table for reverberation time but no way of dealing with the contribution of the reverberant field. Where an electronic masking system generates the steady background noise, AI yields good results in the assessment of privacy [17].

2.3.1 Articulation loss of consonants

Early researchers found that intelligibility was based on the recognition of consonants rather than vowels and developed metrics based on this concept. Maxfield and Albersheim examined the measured articulation loss- of-consonants data published by Steinberg and Knudsen and plotted them versus a steady-state direct-to-reverberant energy ratio. They found that the data did not lie along a straight line and subsequently developed the concept of a liveness factor, for use with microphone pickups, which they defined in Equation 5 [17],

$$L = \int_0^{\infty} Dr(t)dt/Dd \qquad \textbf{(2. 5)}$$

Where; Dr (t) is the reflected-energy density at any time, t, and Dd is the direct-field energy density.

In 1974 Peutz and Klein published a graphical method of accounting for the presence of noise. This was curve fitted by Bistafa and Bradley and in its continuous form is given in Equation 6 [17];

$$AL_{cons}= 9T_{60}\left(\frac{1}{1+(\frac{rl}{r})^2}\right) [1.071\ T_{60}^{-0.0285}]^{(25\text{-L sn})} + a \qquad \textbf{(2. 6)}$$

When the signal is less than 25 dB above the background noise there is a reduction in speech intelligibility, which becomes progressively worse as the signal level decreases. If the signal level is greater than 25 dB above the noise, there is no degradation due to background noise and the noise term is dropped. Here the signal level is the direct plus reverberant speech level, and the noise level is the steady background level having the same spectral shape as the speech level. Peutz and Klein did not include information on the spectrum of the background noise or the frequency at which the calculations are to be carried out. Standard practice is to use the 2000 Hz octave band.

In 1987, Davis and Davis recommended ALcons for general use in sound-system design, although in this form there is no single value of the directivity when multiple loudspeakers are used. Jacobs in 1985, experimenting with single high, medium, and low-Q loudspeakers, found a poor correlation between the predicted and measured intelligibility, particularly in highly reverberant rooms. His data indicated that ALcons underpredicted the speech intelligibility for low- and medium-Q loudspeakers and overpredicted with a high-Q device [17].

Bistafa and Bradley also found a poor correlation between ALcons predictions and those based on STI and U50 metrics [17]. They recommended that its use be limited to classrooms and small meeting rooms. This would seem to be a good approach. ALcons includes the reverberant field as part of the signal in a signal-to-noise ratio, but switches to a different formulation when the reverberant field dominates the direct field.

2.3.2 Speech transmission index

Researchers in optics, seeking to quantify the distortion of light received from stars, developed the optical transfer function, which was based on a mathematical formulation called the modulation transfer function (MTF). Houtgast, Steeneken, and Plomp (1980) reasoned that stars are the spatial equivalent of an acoustical impulse source and this approach could be useful in evaluating distortion in rooms.

With the MTF we have a quantity that mimics the behavior of speech, and can be physically measured with a properly constructed instrument. The missing link is the relationship between MTF and speech intelligibility.

speech transmission index (STI), is similar to an articulation index or a percentage loss of consonants, in that it is a direct measure of speech intelligibility. All three are numerical schemes used to quantify the intelligibility of speech.

Steeneken and Houtgast (1980, 1985) developed an algorithm for transforming a set of m values into a speech transmission index (STI) by means of an apparent signal-to-noise ratio expressed as a level. This level is the signal-to-noise ratio that would have produced the modulation reduction factor, had all the distortion been caused by noise intrusion, irrespective of the actual cause of the distortion[10].

$$L_{SNapp} = 10 \log \frac{m}{1-m} \qquad \textbf{(2. 7)}$$

Where,

L_{SNapp} = apparent signal to noise ratio (dB)

m = modulation reduction factor

$$L_{Snapp}^{AVG} = \sum_{i=1}^{7} wi\ (\text{LSnapp}) \qquad \textbf{(2.8)}$$

Where,

L_{Snapp}^{AVG} =average apperent signal to noise ratio (dB)

Wi= weighting factor for octave bands

Then,

$$STI = [L_{Snapp}^{AVG}+15] / 30 \qquad \textbf{(2.9)}$$

The research done by Houtgast and Steeneken established a way of measuring speech and intelligibility using an electronically generated test signal rather than a group of human subjects. Their calculation method is useful in evaluating rooms for an omnidirectional source, but does not include consideration of loudspeaker directivity, so necessary to the design of reinforcement systems. Once the method has been established as equivalent to other measures of intelligibility without amplification, the measurement system can be used to evaluate installed sound systems [17].

2.3.3 Signal to Noise Ratios (C_τ and U_τ)

In 1935 two researchers, F. Ainger and M. J. O. Strutt, reported on the property of the ear that combines early-reflected sounds with the direct sound so as to increase the apparent strength of the whole. They suggested an energy ratio formula to quantify the effects of background noise and room acoustics on intelligibility. They called this ratio impression, which they defined in Equation 10[17];

$$Q = \frac{Ed+Ee}{El+En} \quad \textbf{(2.10)}$$

Ed= Direct Field Energy (N m)

Ee=Early part of the reflected energy (N m)

El=Late portion of the reflected energy (N m)

En=Constant noise energy (N m)

In the 1950s, Thiele published one of the earliest attempts at relating early to total sound energy ratio to intelligibility, which he called the definition, D. He considered the useful energy to be the direct plus the reflected energy that arrives within 50 msec of the direct sound. The definition can be written as Equation 11 [17].

$$D_{50}=\frac{1+(\frac{rl}{r})^2-e^{-069/T60}}{1+(\frac{rl}{r})^2} \quad \textbf{(2.11)}$$

Definition does not account for the contribution of the background noise to the detrimental energy. It represents another early attempt to quantify speech intelligibility in terms of room acoustics. Bradley (1986) used variations of the *Q* metric in his study of speech intelligibility in classrooms. These included the useful-to-detrimental noise ratio [17].

$$U\tau = 10 \ \log [\frac{R\tau}{(1-R\tau)+10^{-0.1LSN}} \quad \textbf{(2.12)}$$

Where $R\tau$ is the ratio between the early and the total energy;

$$R\tau = E_e / (E_e + E_l) \quad \textbf{(2.13)}$$

and the early-to-late signal-to-noise ratio;

$$C\tau = 10\log [\frac{R\tau}{1-R\tau}] \quad \textbf{(2.14)}$$

which is obtained by setting the second term in the denominator of Equation 12 equal to zero.

When these expressions are evaluated using the diffuse-field impulse response and a cutoff time of 50 msec we obtain[17].

$$U_{50} = 10\log\left[\frac{1+\left(\frac{rl}{r}\right)^2 - e^{-\frac{0.69}{T60}}}{e^{-\frac{0.69}{T60}} + 10^{0.1(Ln-Lr)}}\right] \quad \textbf{(2.15)}$$

$$C_{50} = 10\log\left[\frac{1+\left(\frac{rl}{r}\right)^2 - e^{-\frac{0.69}{T60}}}{e^{-\frac{0.69}{T60}}}\right] \quad \textbf{(2.16)}$$

2.3.4 Weighted Signal to Noise Ratios (C^{α}_{τ} and U^{α}_{τ})

Early to late ratios were also the basis of work by Lochner and Berger in the Afrikaans language. These authors identified and separated the early sound energy, arriving at less than a certain time after the direct sound, from the later reflected sound. In their system the early arrivals are weighted and integrated over the time period and compared to the sound energy arriving after that time. They defined a useful-to-late energy ratio as [17],

$$C^{\alpha}_{t} = 10\log\frac{\int_0^t \alpha(t)w(t)dt}{\int_t^{\infty} w(t)dt} \quad \textbf{(2.17)}$$

where *α(t)* is the average fraction of the energy of an individual reflection that is integrated into the useful early energy sum. This weighting term depends on the amplitude of the reflected energy, relative to the direct sound and the time of arrival. The *α(t)* term was included because the un weighted method proved highly sensitive to individual reflections arriving just before or just after the cutoff time. The weighting factor was set to one at a start time and to zero at the finish time, and decreased linearly between them. Various algorithms have been used as a weighting function. Among them are as follows [17],

$$\begin{aligned} \alpha(t) &= 1 && \text{for } 0 \le t < t_1 \\ \alpha(t) &= (t_2 - t)/(t_2 - t_1) && \text{for } 0 \le t < t_1 \qquad \textbf{(2.18)} \\ \alpha(t) &= 0 && \text{for } t > t_2 \end{aligned}$$

With

t1 = 0.035 s and

t2 = 0.095 s.

For a diffuse field and a 95 ms cutoff time, Lochner and Burger's useful-to-detrimental ratio is given in Equation 2.19 [18],

$$U^{\alpha}{}_{95} = 10log\left[\frac{1+\left(\frac{rl}{r}\right)^2+1.21T60(e^{-\frac{1.31}{T60}}-e^{-0.48/T60}}{e^{-1.31/T60}+10^{0.1(Ln-Lr)}}\right] \quad \textbf{(2.19)}$$

The useful-to-late ratio $C^{\alpha}{}_{95}$ can be obtained by setting the noise term in the denominator equal to zero.

In 1986, Bradley also worked with a simple metric, namely the A-weighted steady-average speech level (55 dBA at 1 m for a normal voice and 63 dBA for a raised voice in this study), based on anechoic measurements of speech. He calculated the direct plus reverberant-field level and used it to test intelligibility for various background-noise levels. The results were very similar to those found with more complicated metrics, and its ease of use makes it attractive. It is interesting to note that these data support his assertion that signal-to-noise ratios significantly less than 15 dB yield very satisfactory intelligibility.

Bradley published intelligibility versus U_{80} values in his study of classrooms in 1986. Bradley worked with several cutoff times: 35, 50, 80, and 95 msec. He found later in 1998 that the differences using cutoff times between 50 and 95 msec are not great, for example, $C_{80}(A) \cong C_{50}(A)+ 2$ [17].

Bradley, in his comparison of several methods of predicting speech intelligibility in rooms, examined metrics in three categories: ALcons , STI, and the various signal to noise ratios. His studies were carried out using a Fairbanks rhyme test, which gives a result similar to that obtained with nonsense syllables. He found that there was close agreement between STI and the early-to-late ratios, but poor correlation between ALcons and the other metrics. Jacobs, using loudspeakers of differing directivities, found a similar result with ALcons , yielding errors on the order of 20% in intelligibility. In his work the use of STI lead to a slight (5%) under prediction of intelligibility, whereas a weighted signal to noise ratio, yielded an over prediction of the same order of magnitude. Bistafa and Bradley found a linear relationship between STI and U_{50}, as given in Equation 2.20 [17].

$$U_{50} \cong 31STI - 16 \quad \textbf{(2. 20)}$$

Indicating that these metrics are essentially equivalent. A similar relation was deduced for Lochner and Burger's signal-to-noise ratio is given [17].

$$U^{\alpha}{}_{50} \cong 1,25\ U_{50} + 3,4 \quad \textbf{(2.21)}$$

The research cited in this section was done with single, as opposed to distributed, loudspeakers and is best utilized in analyzing rooms with unamplified talkers or single-source reinforcement systems. The complications introduced by multiple loudspeakers with different directivity characteristics and delay times are not addressed here.

2.3.5 Articulation index

AI is a frequency-weighted signal to noise ratio measure. Moreover, it is well related with speech intelligibility scores. Thus, establishing speech privacy criteria in terms of maximum allowed AI values is preferred [18]. Articulation index range is between zero and one. As zero articulation means a confidential privacy, one articulation index means no privacy. ANSI gives the calculation method of AI [16]. AI calculation is sum of weighted signal to ratios in each third octave bands. These octave bands are weighted according to the importance to the ear.

AI calculations can be performed even the spectrum of the background noise is not flat and is different from that of speech. It also accounts in part for the masking of speech by low frequency noise. AI uses the peak levels generated by speech as the signal level and the energy average background levels as the noise [19].

Articulation index is equally useful in the calculation of privacy as it is for intelligibility. The numeric value of AI shows how intelligible the speech is, if that value subtracted from one then privacy value would be found. Both are ultimately dependent on signal to noise ratio. Table 2 shows relationship between degrees of AI and privacy.

Table 2.1: Articulation index values corresponding privacy levels and intelligibility levels. [16]

AI	% Sentence Understood	Intelligibility	Privacy
AI>0.4	>90	Very good	No privacy
0.4>AI>0.2	80	good	Poor privacy
0.2>AI>0.1	50	fair	Marginal privacy
0.1>AI>0.05	20	poor	Normal privacy
AI<0.05	0	Very poor	Confidential privacy

0.2 AI can be very reasonable design goal. Even it is not perfectly privacy but does represent a significant improvement over doing nothing, which would result in intelligibility scores close to %100 [18]. According to the table 2, 0.2 AI located in marginal privacy interval.

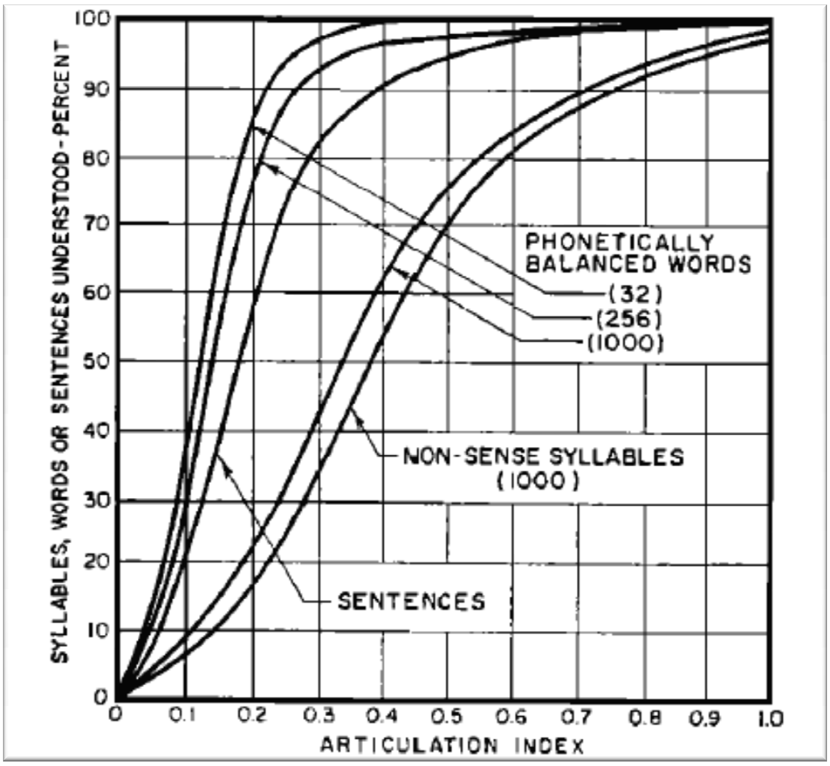

Figure 2.5 : Approximate relationship between articulation index and intelligibility scores of different kind of texts read by skilled talkers [19].

Figure 2.5 shows the approximate relationship between articulation index and intelligibility for skilled talkers and listeners. The numbers in parentheses gives the size of the test vocabulary. [20]

Figure 2.6 shows the relationship between AI and percentage of mean speech intelligibility of sentences. Privacy levels are shown with different colors.

It is normally assumed that a good acoustical environment in an open plan office requires adequate speech privacy between adjacent workstations. Speech privacy depends on the speech source level or speech effort of the talker, the attenuation of speech sounds between the talker and the listener, and on the level of ambient noise at the listener [20].

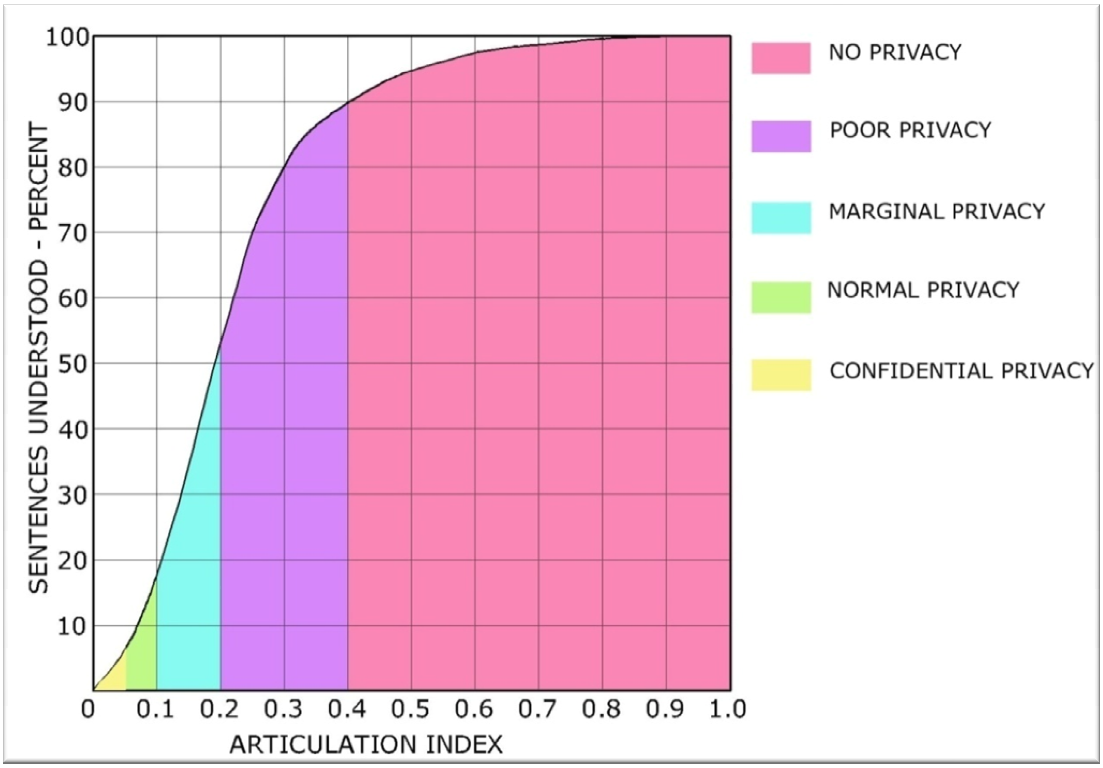

Figure 2.6 : Relationship between AI and percentage of mean speech intelligibility of sentences. [19]

Articulation index formula given in Equation 2.22.

(2.22)

In open plan offices, architectural components affect the articulation index values. Ceiling absorption, barrier height, lighting type and placement is very important according to the articulation index.

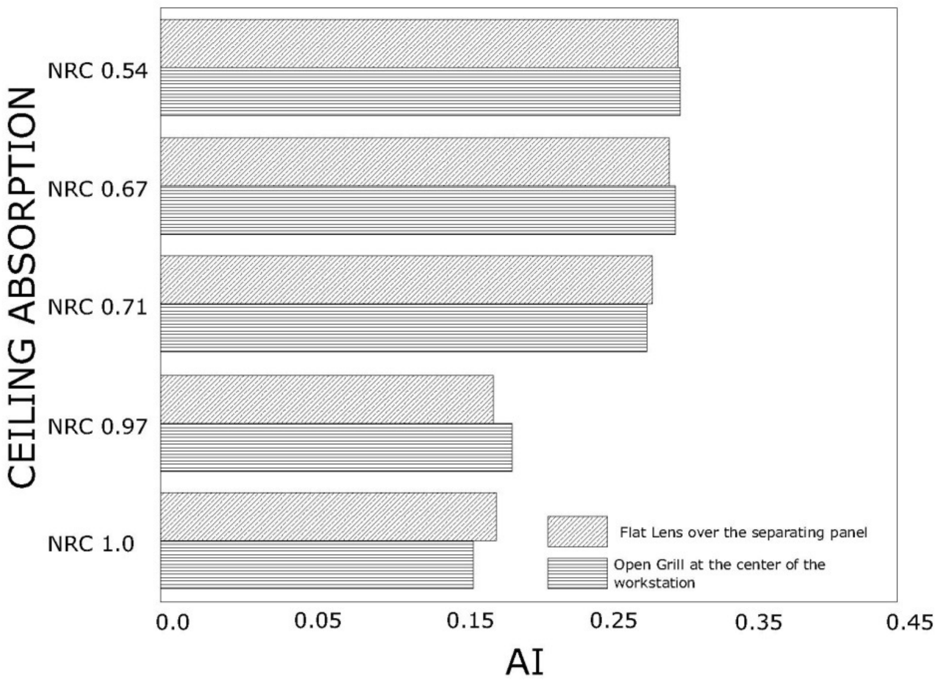

Figure 2.7 : Mean AI values for five ceiling absorption values for both open grille lights over the centre of each workstation and a flat lens light over the separating panel.

The 2.74 m by 2.74 m workstations were constructed of 1.52 m high panels faced with 50 mm absorbing foam [12].

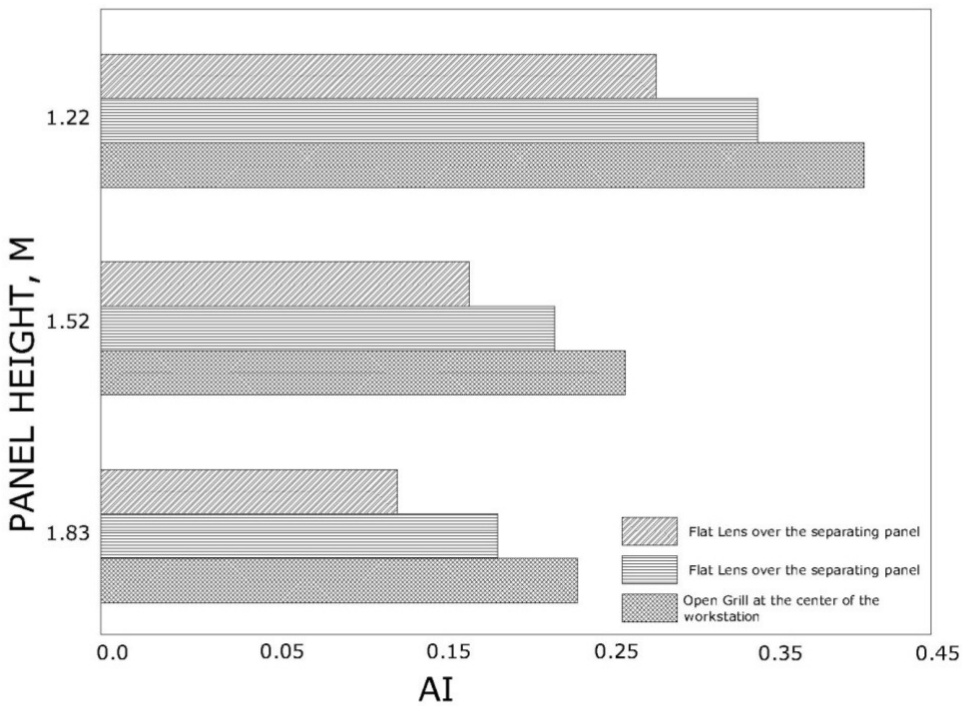

Figure 2.8 : Mean AI values for 3 workstation panel heights and for 3 different workstation plan sizes.

The ceiling tile was H-B at a ceiling height of 2.74 m and there was a flat lens light over the separating screen [12].

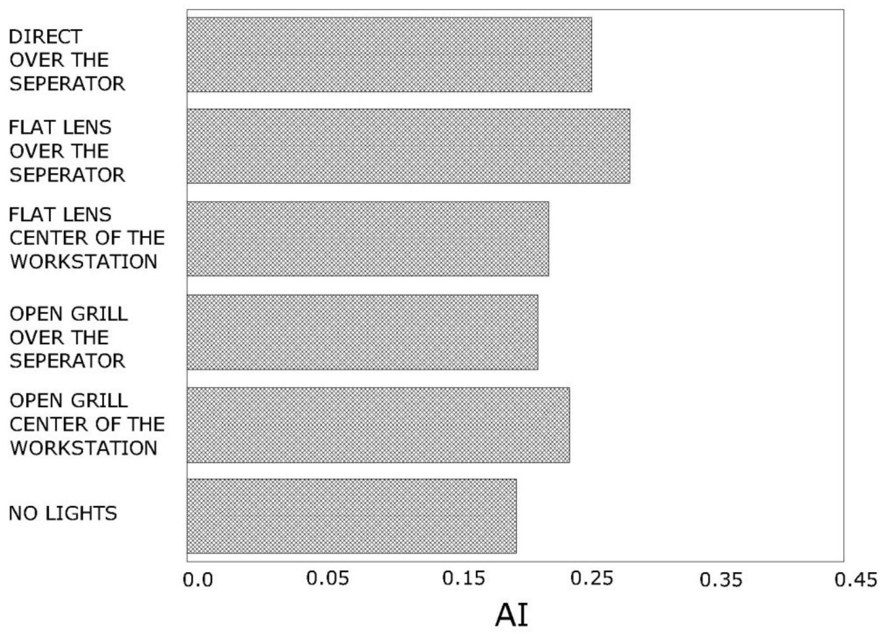

Figure 2.9 : Mean AI values for 6 lighting configurations (including no lights)

Lightings with H-B ceiling tiles at a ceiling height of 2.44 m. The 2.74 m by 2.74 m workstations were constructed of 1.52 m high panels faced with 50 mm absorbing foam [15].

2.3.6 Noise reduction coefficient

As we are defining absorption performances of the materials, it is not always easy to define them with absorption coefficients in every octave bands. Noise reduction coefficient is used to get a general idea of the effectiveness of a particular material. For critical calculations, octave band absorption values must be used.

Absorptive materials, such as acoustical ceiling tile, wall panels, and other porous absorbers are often characterized by their noise reduction coefficient, which is the average diffuse field absorption coefficient over the speech frequencies, 250 Hz to 2 kHz, rounded to the nearest 0.05 [21].

$$NRC= \frac{1}{4}(\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}) \qquad \textbf{(2.23)}$$

2.3.7 Sound transmission class

Although transmission loss data in third-octave or full-octave bands are used for the calculation of sound transmission between adjacent spaces, it is convenient to have a single-number rating system to characterize the properties of a construction element.

The shape of the STC curve is based on a speech spectrum on the source-room side so this rating system is most useful for evaluating the audibility of conversations, television, and radio receivers. It is less accurate for low-frequency sounds such as music or industrial noise, where energy in the bass frequencies may predominate [11].

2.3.8 Signal to noise level

Acoustical intelligibility evaluations are frequency depended. Every frequency has its own particular weighting factor because thresholds of every frequency are different. While calculating the intelligibility score of any situation, weighting factor of each frequency is multiplied by background noise level subtracted from signal level of that particular frequency. By this measure, background noise level is added to the calculation of intelligibility. To calculate signal to noise level, Equation 2.24 is used in every frequency.

$$S\text{-}N = SPL_{signal} - SPL_{noise} \qquad \textbf{(2.24)}$$

2.3.9 Insertion loss

The difference between emitted sound pressure level and measured pressure level from the receiver point is called Insertion loss. In an open plan environment, some amount of the sound pressure is absorbed by air and ceiling, some amount of pressure is lost while transmitting trough the barrier.

$$IL = SPL_{source} - SPL_{receiver} \qquad \textbf{(2.25)}$$

2.4 Acoustical Comfort Conditions

The degree of acoustic comfort in an open-plan office is related to the combined effects of unwanted background noise and a desired level of speech privacy. Speech privacy is related to the levels of intruding speech sounds, from adjacent workspaces, relative to general ambient noise levels. Because of the lack of full-height partitions, adequate speech privacy is difficult to obtain. While increasing the ambient noise level will increase speech privacy, too much noise will not lead to optimum acoustic comfort [22].

What are the acoustic conditions like in real open-plan offices? Researchers have been measuring the sound levels in open-plan offices since the 1960's with the hopes of properly addressing the acoustic problem. Over this period there have been substantial changes in office equipment that have changed the level and the nature of sounds in offices, most notably the change from typewriters on the desks of clerical staff to computers on every desk. Keighley in 1966, for example, found that in the UK, office noise levels varied from 60 – 79 dB(A). Levels have dropped since that time.

In 1973, Nemecek and Grandjean carried out an extensive study of 15 landscaped offices in Switzerland. Fifteen-minute noise measurements were made repeatedly in various points of each of the offices with a Bruel and Kjaer sound level meter. The mean noise level varied from 48 to 53 dB(A) with frequent peaks averaging 8 to 9 dB(A) above the mean level.

In an effort to understand the spectral and temporal characteristics of sound in the office environment, Moreland found that between 9 a. m. and 4 p. m. , the average sound level in seven open-plan offices was 44.9 dB(A), ranging from 42.9 dB(A) to 48.4 dB(A). Noise samples were collected every 2 minutes between the hours of 7 a. m. and 7 p. m. , with a Rion model SA 25 one-third octave band spectrum analyser, and Bruel and Kjaer type 4165 and 2615 microphones.

Offices were among the sites visited by Landström, Kjellberg, and Soderberg (the survey included industrial control rooms, which are not relevant here and not discussed). A-weighted levels average 53.3 dB(A) in offices. In Hong Kong, the mean was slightly higher: Tang and Wong surveyed workstations in 6 air-conditioned, landscaped offices, and found that the average L_{eq} levels in the six offices ranged from 52 to 58 dB(A). Articulation Index values ranged from 0.69 to 0.75 indicating extremely low acoustical privacy conditions. Results from questionnaires revealed that the majority of disturbing noise sources consisted of human speech, followed by air conditioners, office machinery, and traffic, respectively.

AI and SII values depend on speech effort as well as background noise levels. Field measurements of speech levels are few, but Warnock and Chu collected speech recordings from 118 participants in nine offices. Participants wore head-sets with microphones attached and were told to speak as naturally and freely to another person in their workstation as they normally would. Each individual speech recording lasted 1 minute. Background noise measurements were also measured at each of the 9 offices, in various locations throughout the working day. Average male and female voice levels in open-plan offices were 51.3 dB(A) and 50.6 dB(A) respectively corrected to 0.9 m in front of the speaker (the measurements were taken at a shorter distance). The average sound level across all nine offices was 46 dB(A).[23]

The acoustical design of an open-plan office should attempt to minimize the intelligibility and disturbance of unwanted speech from nearby workstations. The success of the design can be assessed in terms of signal-to-noise ratio type measures such as the Articulation Index (AI) or its newer replacement the Speech Intelligibility Index (SII). In Europe the use of Speech Transmission Index (STI) has been proposed for evaluating open-plan offices.

Subjective studies, have confirmed conventional recommendations that the combination of speech from an adjacent workstation and ambient noise levels should correspond to AI≤0.15. While increased ambient noise levels can better mask unwanted speech sounds and lead to reduced AI ratings, too much noise is disturbing and causes people to talk louder. An ambient/masking noise level of 45 dBA is recommended as an optimum compromise for open-plan offices [12].

Open-plan offices must be designed to have appropriate ambient/masking noise levels and should attenuate the propagation of speech as much as possible to ensure adequate speech privacy. The most important two elements of the design are a highly sound absorbing ceiling, to minimize reflected sound, and adequate height workstation panels to block speech propagation to adjacent workstations. Figure 2.11 shows combinations of these two parameters that will meet the design criterion of AI≤0.15. The study of these graph is performed at 2m to 2m dimensioned closed workstation.

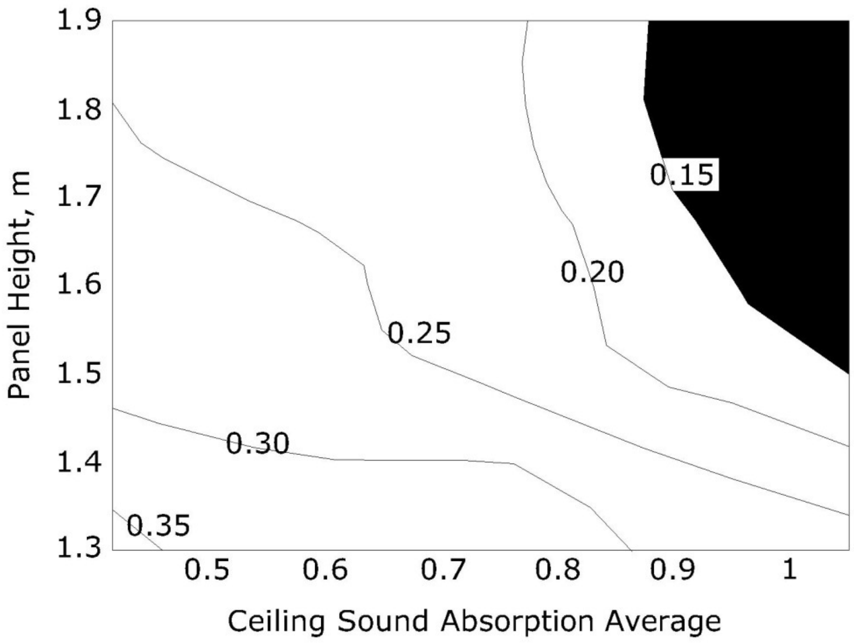

Figure 2.10 : Different ceiling absorption levels and barrier heights with corresponding Articulation index values. [15]

2.4.1 Speech privacy

Speech privacy is related to the levels of intruding speech sounds, from adjacent workspaces, relative to general ambient noise levels. Because of the lack of full-height partitions, adequate speech privacy is difficult to obtain [14, 24]. Increasing the ambient noise level would increase speech privacy but too much noise will not lead to optimum acoustic comfort [22, 25]. Ambient noise would also destruct employees. That is why researches had performed studies about destruction levels of background noise levels for an office.

So, required acoustical needs in an open plan office can be examined in two titles, decreased speech transmission to the other workers, which is called privacy and less noise to distract employees.

To sustain less noisy environment one of the fundamental acoustical requirements is having the reverberation time as short as possible, otherwise sound reflection trough surfaces would increase the noise level received at the open plan environment. So, highly absorptive materials, especially ceiling, should be used to avoid disturbing noise in open plan offices. Actually, the use of the absorptive materials helps with the privacy too.

If an occupant wants to make private phone calls or some private speech with team members, reflective surfaces can make it impossible even there are sound barriers are installed [10].

Acoustical degrees of privacy can evaluated in some ways but most common classification can defined as Table 2.2.

Table 2.2: Degrees of acoustical privacy [25]

DEGREE of PRIVACY	ACOUSTICAL CONDITION	POSSIBLE SUBJECTIVE RESPONSE
Confidential Privacy	Cannot converse with others. Cannot understand speech of others. May not be aware of presence of others. May not hear activity sound of others. Confidential conversation possible. No distractions.	Complete privacy. Sense of isolation. No privacy complaints expected.
Normal Privacy	Difficult to converse with others. Occasionally hear the activation sounds of others. Aware of presence of others. Speech and machines are auditable but not distracting. Confidential conversation possible only under special conditions.	Sense of privacy. Some isolation. No privacy complaints expected.
Marginal Privacy	Possible to converse with others. By raising voice. Often hear activity sounds and speech of others. Aware of each other's presence. Conversations of others occasionally understood.	Sense of community. Sense of privacy weakened. Some privacy complaints expected.
Poor Privacy	Possible to converse with others at normal voice levels. Activity sounds, speech, and machines will be continually heard. Continually aware of each other's presence. Frequent distractions.	Sense of community. Loss of privacy. Some loss of territory. Privacy complaints expected.
No Privacy	Easy to converse with others. Machine and activity sounds clearly audible. Total distraction from other tasks.	Sense of community. Sense of intrusion on territory. No sense of privacy. Many privacy complaints expected.

3. A MODEL FOR THE EVALUATION OF PRIVACY IN OPEN PLAN OFFICES

3.1 Method of Evaluations

To investigate how design and acoustic parameters affect the privacy, scale model method is preferred within this study. Other calculation methods can also be preferred but most of them do not count side diffractions of the barrier or some other parameters.

In the beginning of the 1930's first scale models were built to investigate all acoustical properties of concert halls, because acoustics of a concert hall was very hard to predict from architectural drawings. Sound propagation depends on the relation between the wavelength of sound and the actual dimensions within the acoustical environment. Therefore, if the dimensions of a hall are scaled down in a model, the wavelength should be scaled down with the same factor. Since wavelength and sound frequency are inversely proportional, the frequency should be scaled up with the same factor [26].

The frequencies of the human ear range from 20 to 20 000 Hz and, for instance, frequencies 200 to 200 000 Hz should be used on a 1/10 scale.

Since AI calculations requires frequency range between 200 to 5000 Hz, source and the microphone should be sensitive within the range 2 000 to 50 000 Hz for 1/10 scale model.

3.1.1 Designing the scale model

In this scale model, an open plan condition is considered. Two employees are designed to sit against each other with a sound barrier between them. Different height barriers with different absorptive suspended ceiling types are chosen. The drawings of the model are shown in Figures 3.1, 3.2, and 3.3.

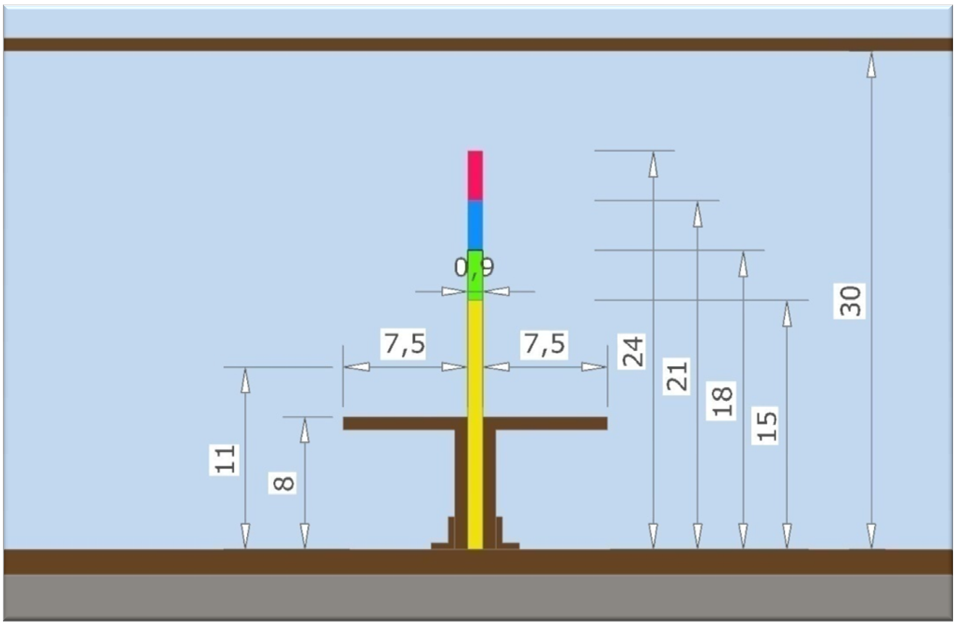

Figure 3.1 : Section of the scale model

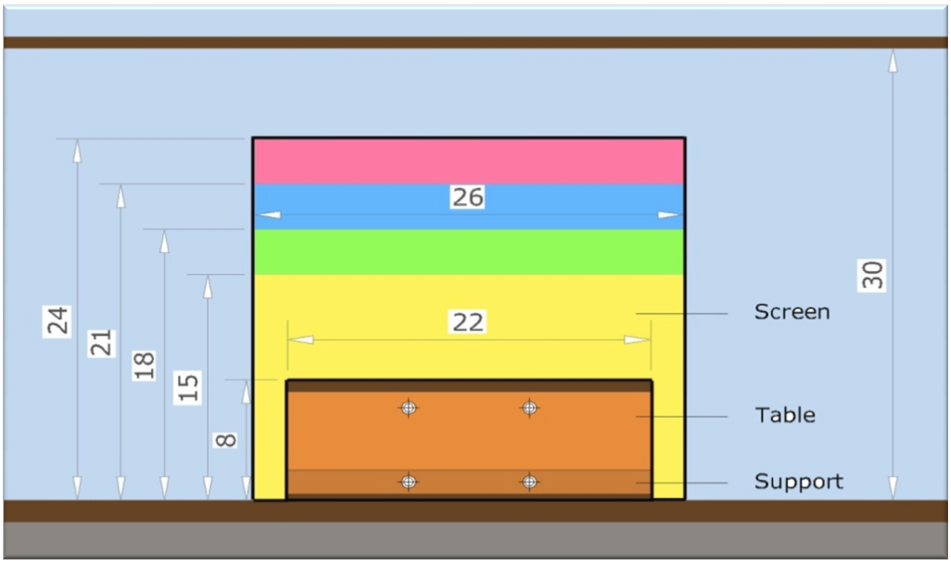

Figure 3.2 : Elevation of the scale model

Figure 3.1 and 3.2 shows installation of the scale model. Possible effects of 150, 180, 210 and 240 cm height barriers are measured within 3 meters height ceiling. Height of the table is 8 cm (represents 80 cm). Ears and mouth of the employees are predicted as 110 cm height.

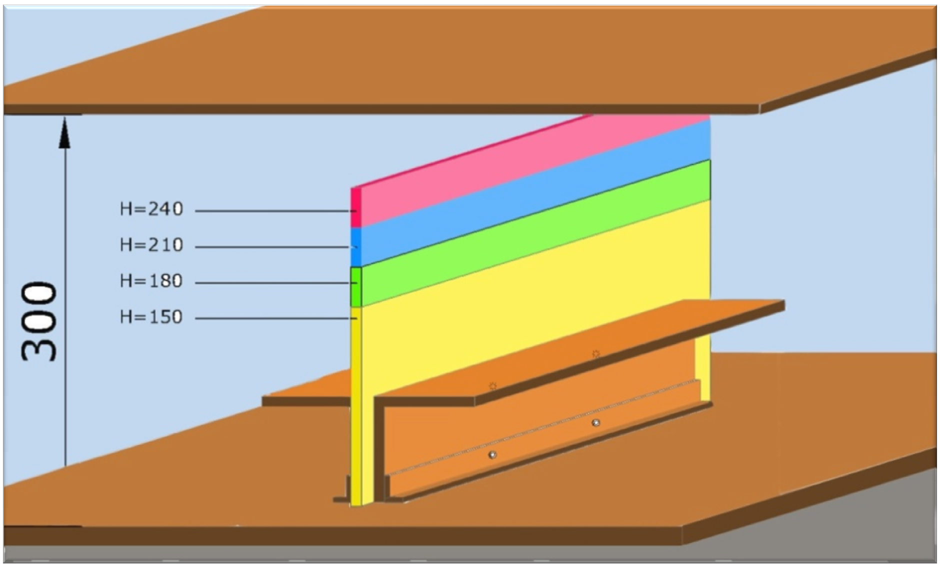

Figure 3.3 : Perspective of the scale model

Figure 3.3 shows perspective view of scale model. To measure effects of different ceiling absorption coefficients of three ceiling types are carried out. MDF, foam plastic and wool ceilings are measured to detect how AI would be changed according to the absorption of the ceilings.

3.1.2 Sound pressure level measurements of the scale model

The measurements of tests are performed in an anechoic chamber. Continuous sound source is used. First process was to measure background noise level of the anechoic chamber in octave bands.

For the model measurements firstly sound source and the microphone are placed properly and then, sound level of the source is measured. Then different height barriers and different absorptive ceilings are installed and sound pressure levels are measured from receiver side of the workstation model. During these measurements, six different barrier heights with four different absorptive ceiling types. Via these measurements, effect of different ceiling types are used with different height barriers on receiver are measured. Performance of insertion loss values of barriers with different ceilings is measured. For example, 180 cm height barrier with wool ceiling has better results than 150 cm height barrier with MDF ceiling. All measurements are performed in octave bands for detailed evaluations.

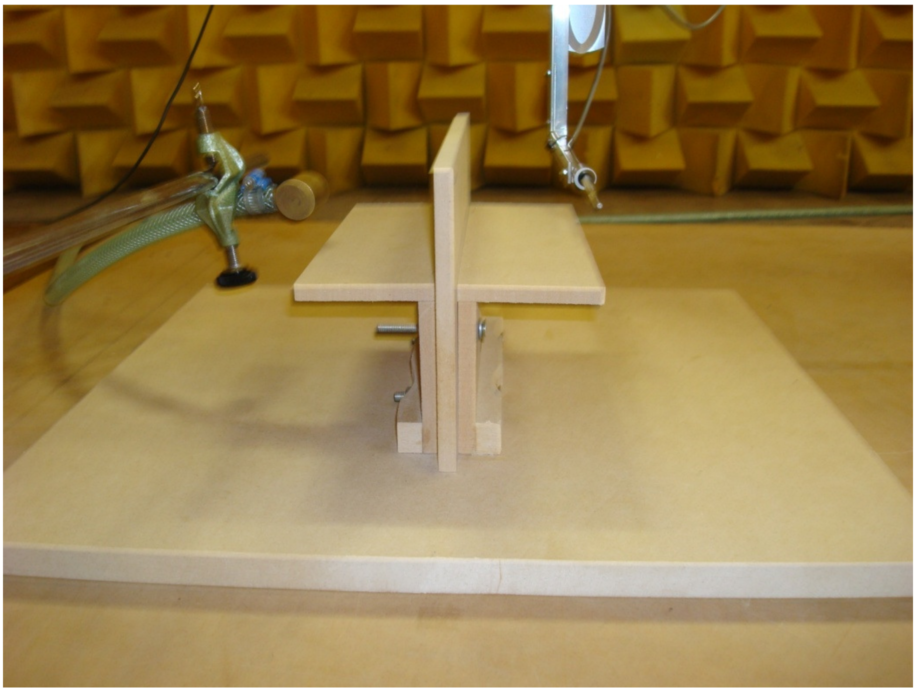

Figure 3.4 : Photo of the test environment in anechoic chamber

Figure 3.4 shows the test environment. For the material of the model, MDF is used for its high reflective properties and its common usage in offices. A reflective model is used to see worst results because of the increasing specialities on ceiling reflections and barrier diffractions.

Figure 3.5 : Setup of measurement in anechoic chamber

Graph shows how SPL changes with different ceiling materials and with their different absorption coefficient values. As expected high ceiling, absorption causes a reduction of SPL at the receiver side. The absorption coefficients of these ceiling materials are listed from most absorptive to most reflective, wool on MDF, foam plastic on MDF and MDF. If the subject was outdoor barriers, then without ceiling condition should be considered but in an open plan office ceiling reflection takes an important role. Figure 3.6 shows that, if the ceiling material changed foam plastic to wool, SPL at the receiver part, would be reduced by 6 dB.

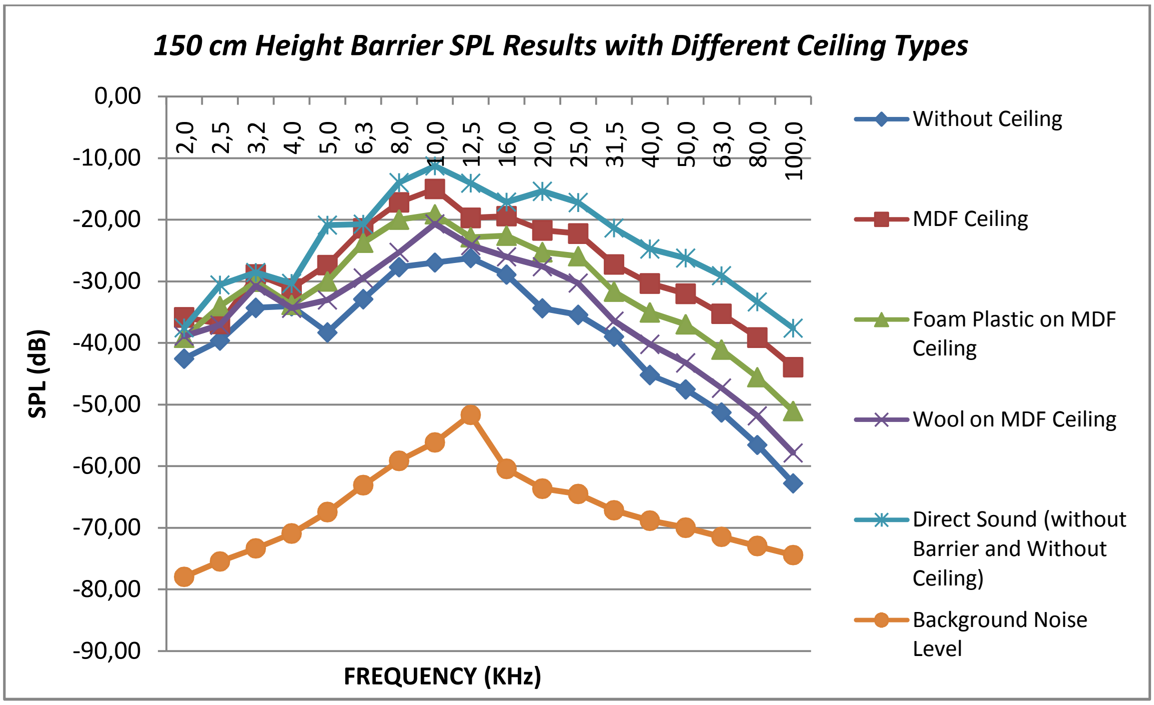

Figure 3.6 : 150 cm height barrier sound pressure level results with different ceiling types.

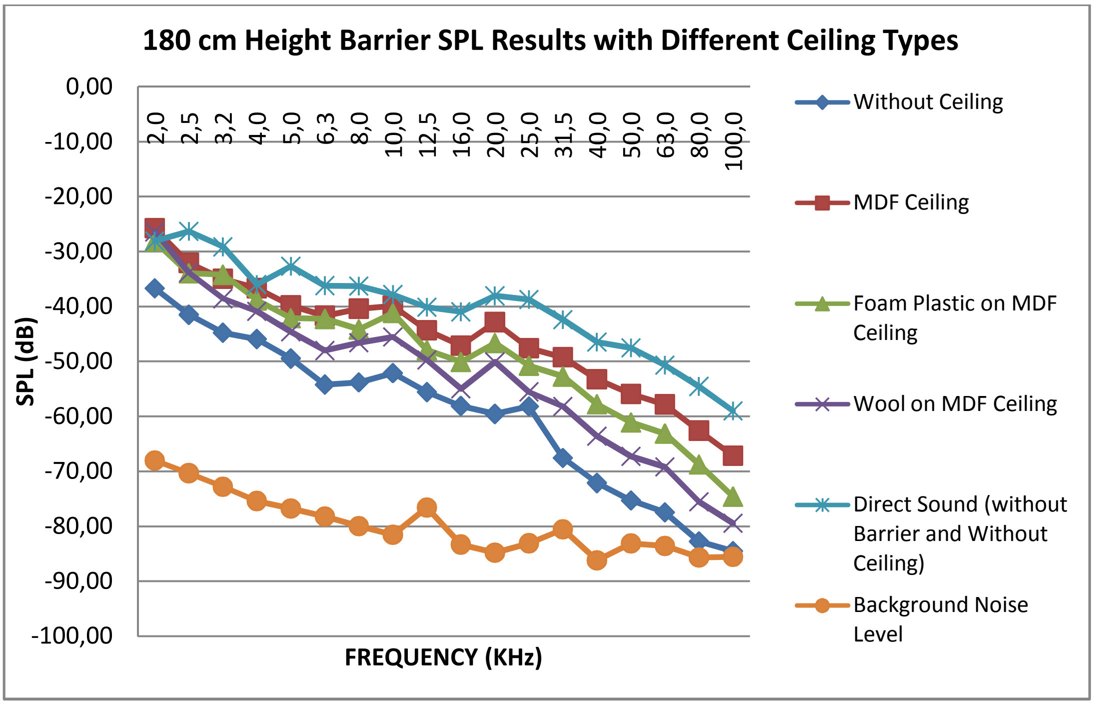

Figure 3.7 : 180 cm height barrier sound pressure level results with different ceiling types.

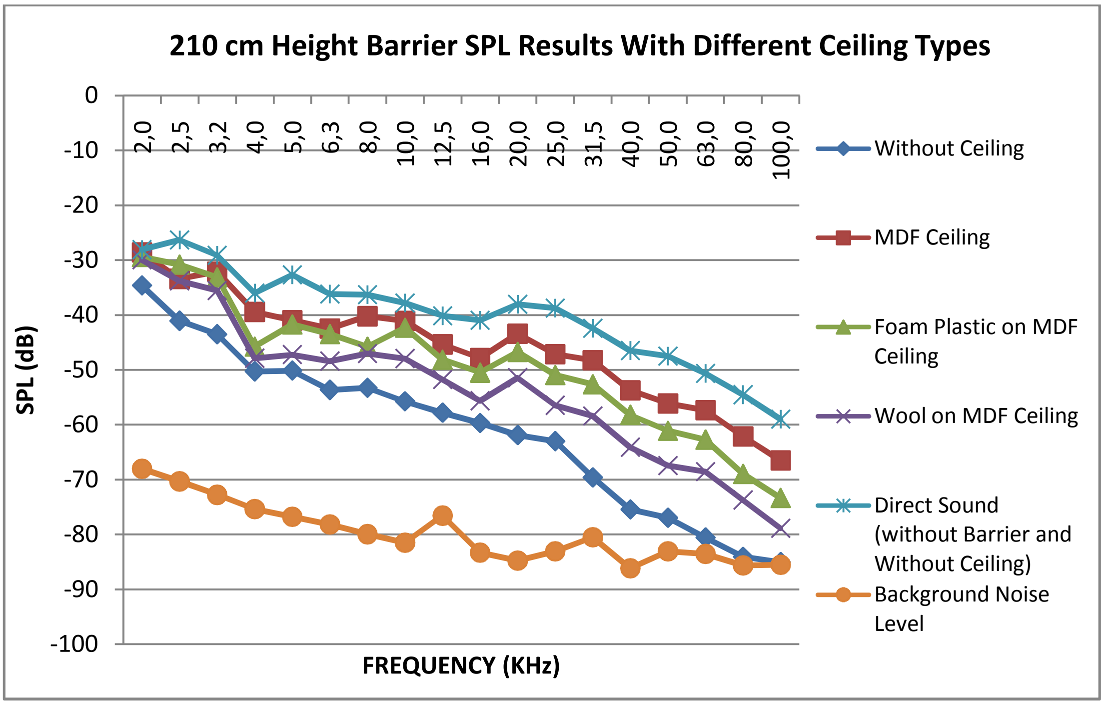

Figure 3.8 : 210 cm height barrier sound pressure level results with different ceiling types.

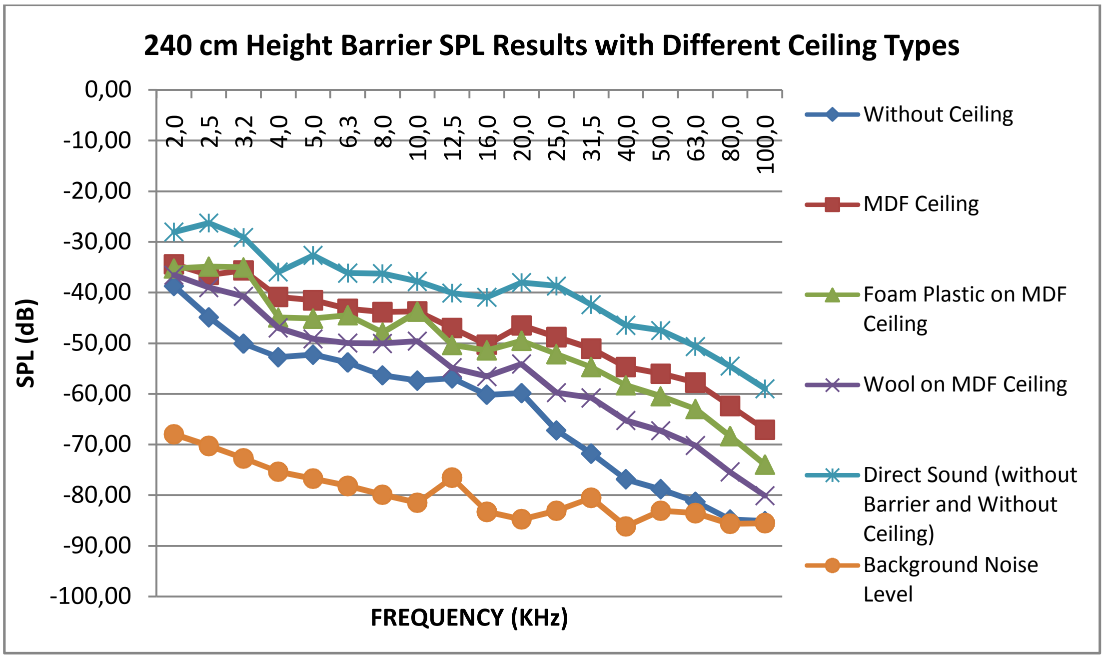

Figure 3.9 : 240 cm height barrier sound pressure level results with different ceiling types.

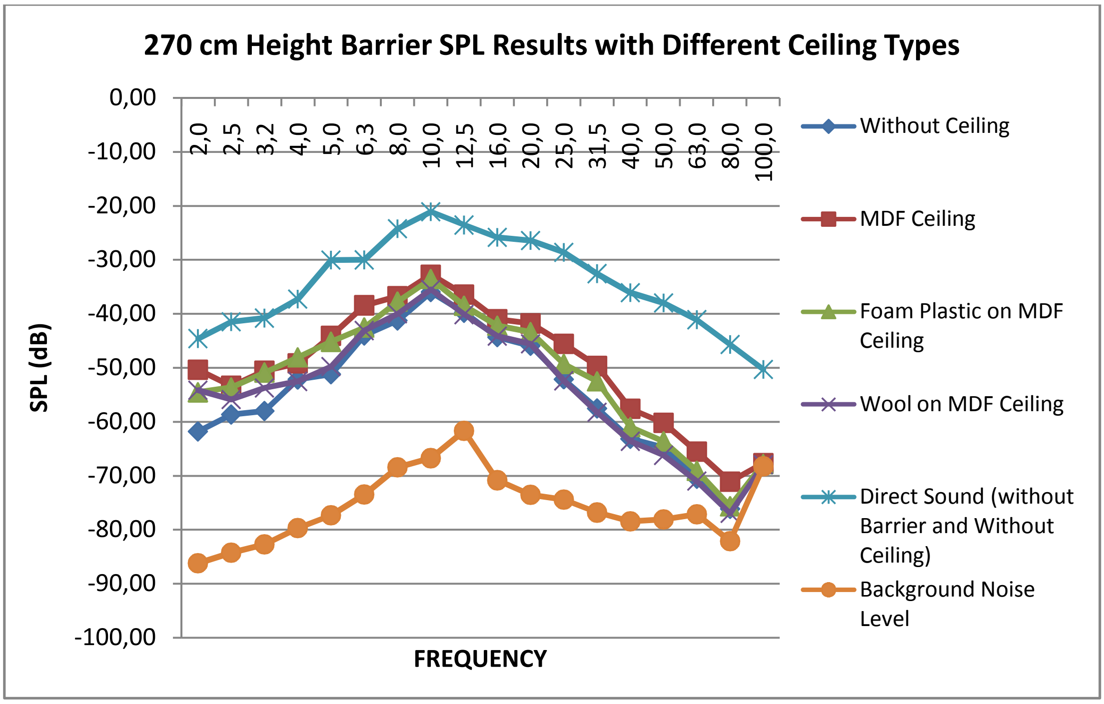

Figure 3.10 : 270 cm height barrier sound pressure level results with different ceiling types.

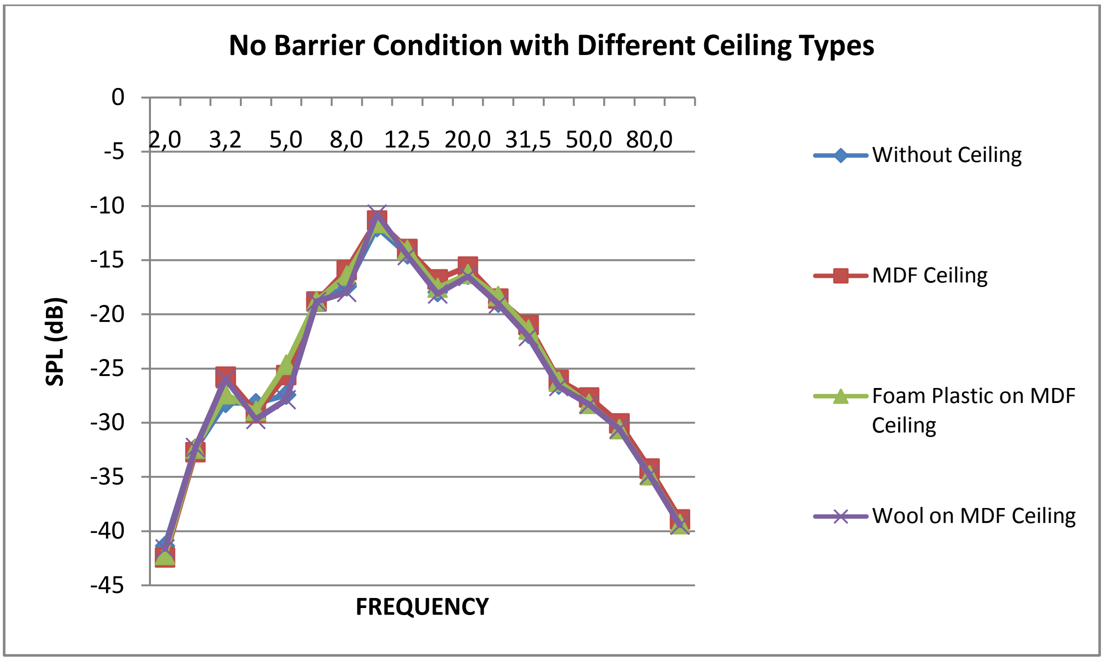

Figure 3.11 : No barrier condition sound pressure level results with different ceiling types.

3.1.3 Absorption coefficient measurements of ceiling types

Absorption levels of ceiling types has to be measured to detect numeric effect of absorption on privacy. To define the absorption coefficients of materials, another setup is prepared in anechoic chamber. Figures 3.12, 3.13 and 3.14 show the drawings of the set up positions and distances.

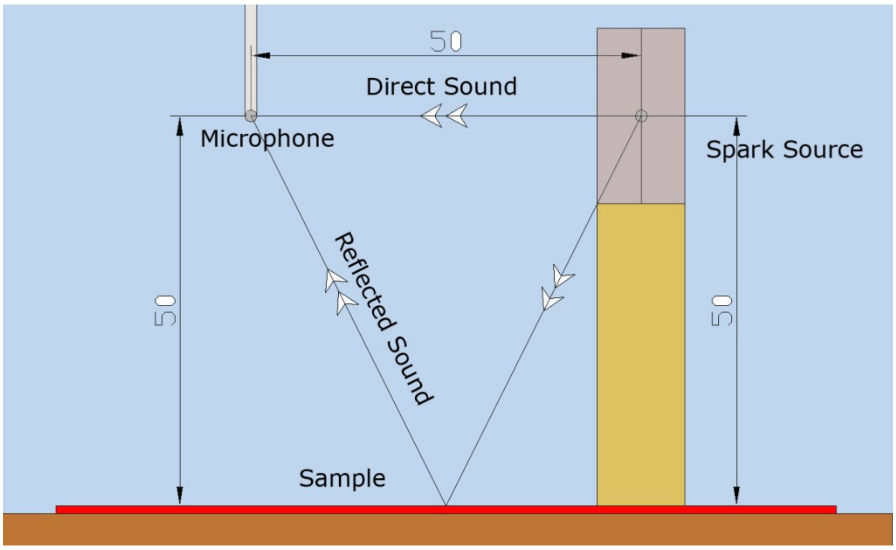

Figure 3.12 : Front elevation of the set up

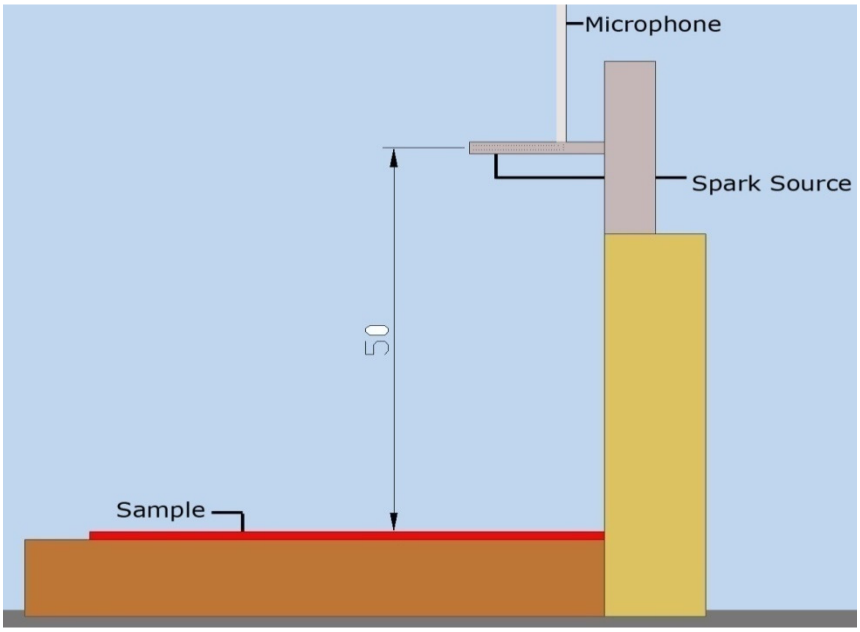

Figure 3.13 : Side elevation of the set up

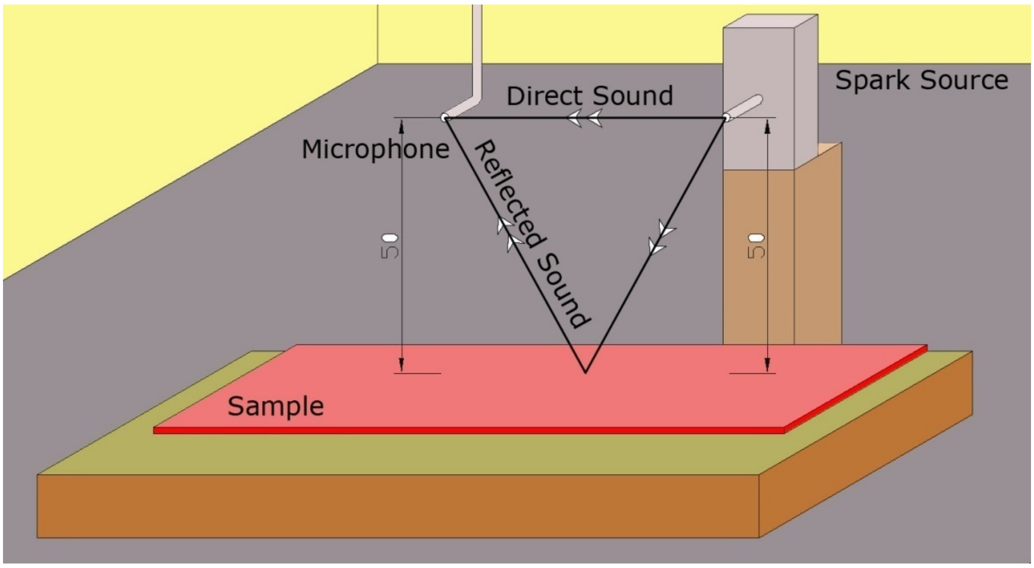

Figure 3.14 : Perspective of the set up

Even though there are many ways to measure absorption coefficients, this measurement performed by Tone-Burst Method is choosen for measurement purposes. The general definition of the method is based on to the difference between pressure level of direct sound and sound reflected trough the sample of material. The sound pressure difference between direct and reflected sound is because of the absorption of the material and the air. As the air absorption is a constant value, a few calculations show absorption coefficients of the material.

Figure 3.15 : Photos of Wool on MDF and Foam on MDF ceiling types.

The Tone-Burst Method uses spark sources. As it sparks short sound signals emits. As the signal travels through the room, signal goes directly to the microphone and through the material. Sound reflected through material has a time delay so via the software we can compute both of signals received by microphone. Figure 3.16 and 3.17 show average SPL of direct and reflected sound of MDF and Foam plastic on MDF.

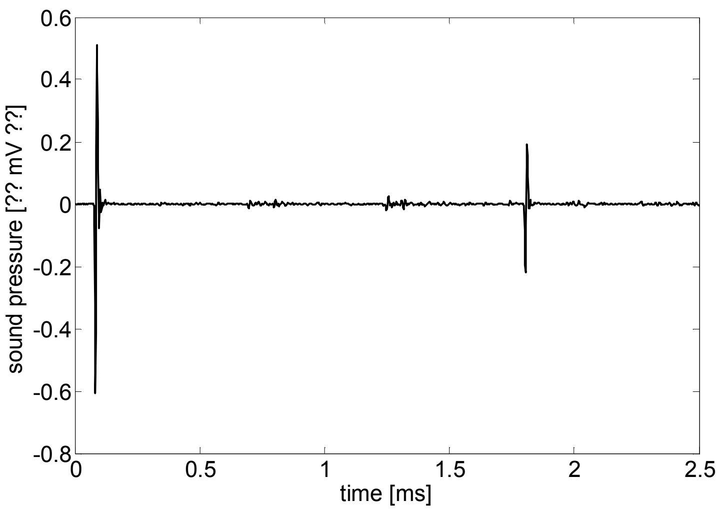

Figure 3.16 : Direct sound plus reflection at 1.8 ms from MDF

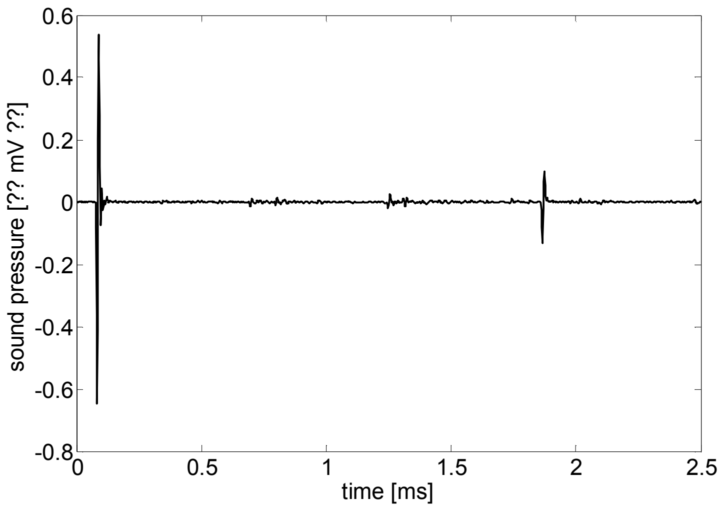

Figure 3.17 : Direct plus reflection at 1.8 ms from 10 mm foam layer on MDF

The difference between magnitudes of first and the second peak for each figure is because of absorption of the material and the air itself. In addition, figure tells the time delay for both direct and the reflected sound, which helps to define distance of reflection path. In the figure, there are also some little movements between the direct sound and the reflected sound peaks due to some little reflections trough the equipments of measurements and they have to be neglected.

Figure 3.18 and 3.19 show the sound spectrums of direct and the reflected sound for MDF and Foam plastic on MDF.

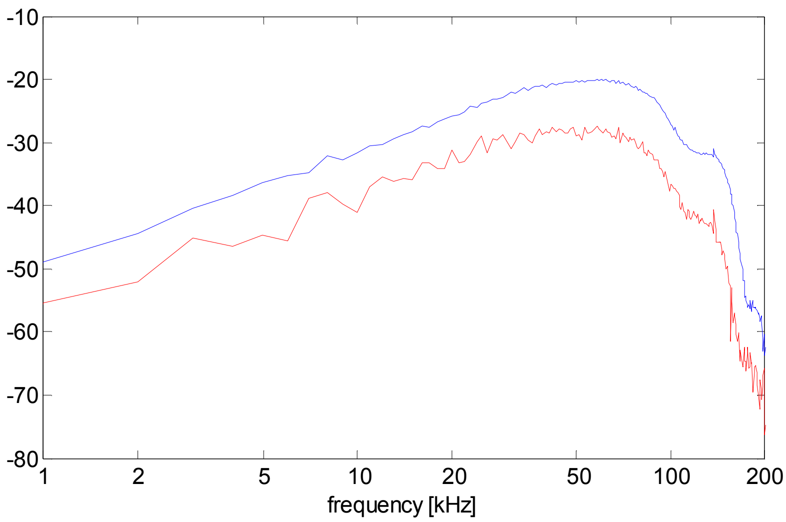

Figure 3.18 : Spectrum of direct sound (blue) plus its reflection on MDF (red)

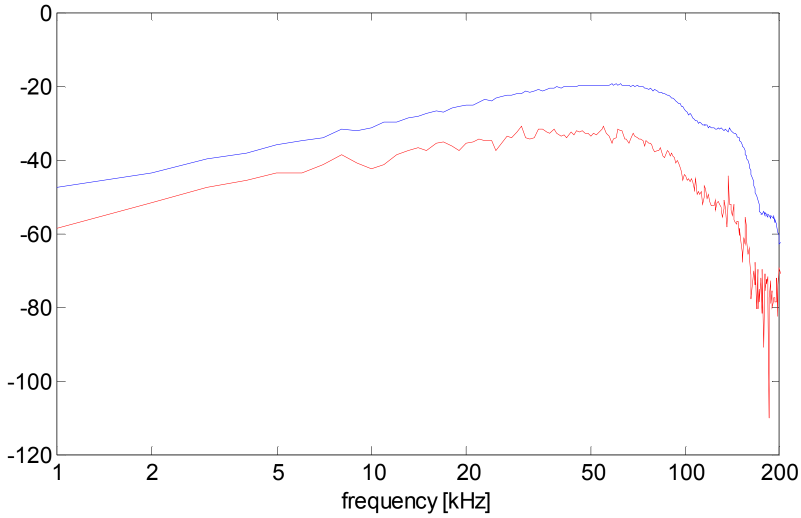

Figure 3.19 : Spectrum of direct sound (blue) plus its reflection on a layer of foam on MDF (red)

The area between blue and red curves, in figures 3.18 and 3.19, shows the energy lost due to the absorption of the material and absorption of air. That is why these results have to be shifted to find exact absorption values of the materials.

The reflected pulse is corrected for the distance and for air absorption; the result is given in the energy-plots of figure 3.20 and 3.21.

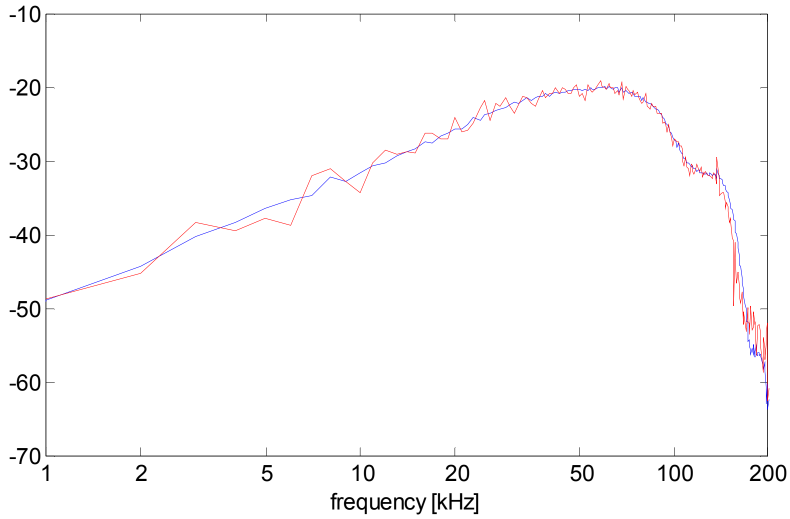

Figure 3.20 : Energy spectrum of direct plus reflection at 1.8 ms from MDF.

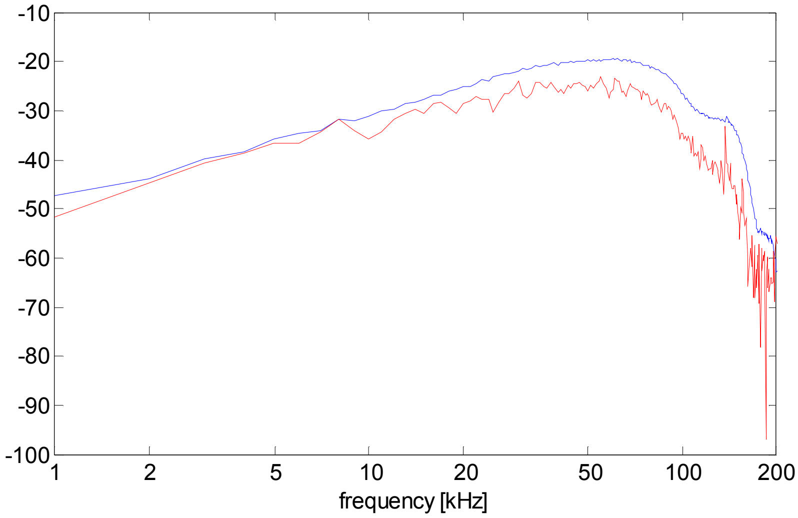

Figure 3.21 : Direct plus reflection at 1.8 ms from 10 mm foam layer on MDF

Even though every material has more or less some absorption values, figures above show that some reflected sound levels are higher than the direct sound (red above the blue). Even if it is theoretically impossible, this means that for some frequencies absorption coefficient is less than zero. This is an obvious error due to some possible reasons, such as imperfections in these measurements, imperfections in the calculations of air absorption, but most important is the extra energy from reflections at microphone stand etc. They can be observed as small reflections in figure 3.16, for instance around 2 ms.

Figure 3.22 and 3.23 gives the difference between the two spectra and hence the energy reflection coefficient.

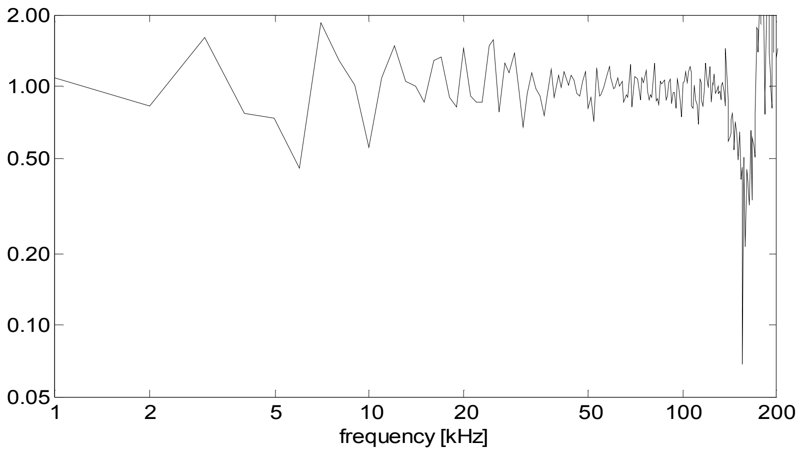

Figure 3.22 : Energy reflection coefficients in linear frequencies for MDF.

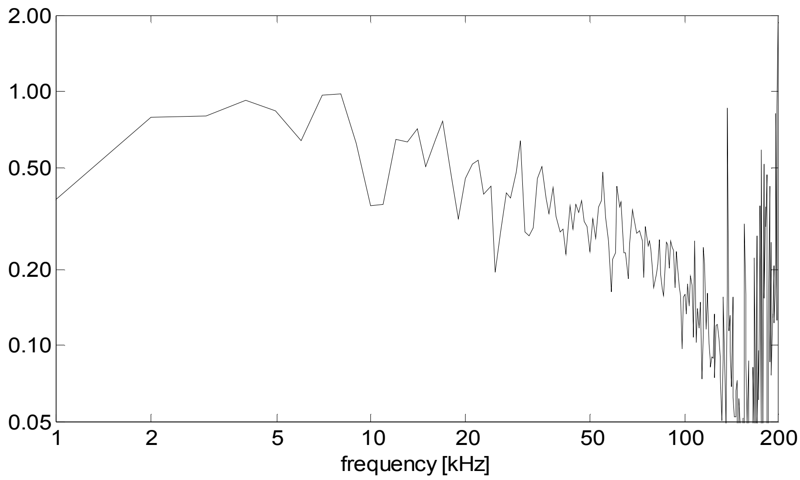

Figure 3.23 : Energy reflection coefficients in linear frequencies for Foam Plastic on MDF.

Figure 3.22 and 3.23 absolutely computes that MDF is more reflective than foam plastic MDF, and hence foam plastic on MDF is more absorptive than MDF itself.

After the air absorption corrections of the reflection coefficients of the material, next step would be to set octave bands. The software of the measurements applies it trough linear frequencies. As it can be read from the figures, measured frequencies increase linearly, 1, 2, 5, 10, 20, 50, 100, 200 Hz, which are not the octave bands.

Figure 3.24 gives the same picture as figure 3.25, but lines at equal intervals are summed in 1/3rd octave bands

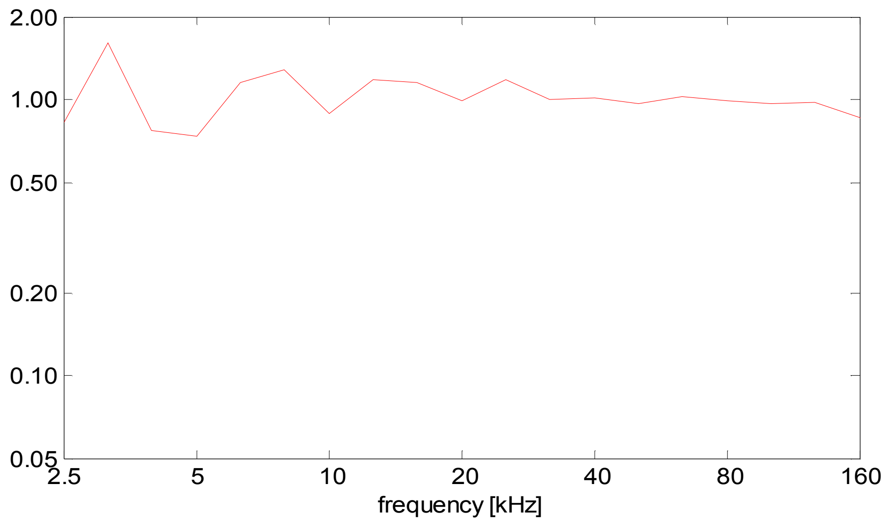

Figure 3.24 : Energy reflection coefficients for MDF in 1.3rd octave bands

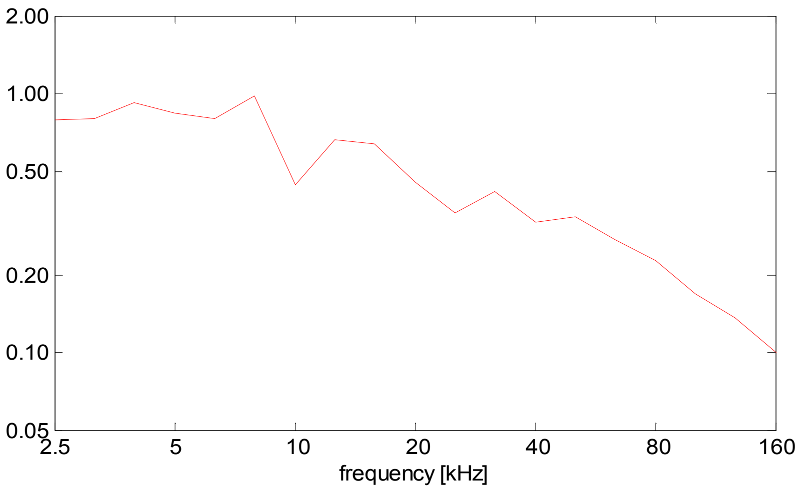

Figure 3.25 : Energy reflection coefficients for foam plastic on MDF in 1.3rd octave bands

After the measurements of the reflection levels from all ceiling types, results are monitored as fallows.

Table 3.1: Sound pressure level data read from the reflected surface of the sample

Frequency	Data Read SPL		
KHz	Foam Plastic	MDF	Wool
2,51	-1,03	1,83	-1,3
3,16	-0,96	0,4	-1,64
3,98	-0,36	-0,47	-2,18
5,01	-0,75	-1,77	-2,77
6,31	-0,97	0,06	-4,21
8	-0,08	1,72	-1,68
10	-3,52	-0,36	-5,1
12,5	-1,78	0,23	-5,91
16	-1,96	0,38	-8,69
19,95	-3,42	-0,55	-6,95
25	-4,62	0,24	-7,42
31,5	-3,82	-0,48	-10,18
40	-4,95	-0,53	-10,74
50	-4,78	-0,62	-11,26
63	-5,62	-0,51	-10,5
80	-6,47	-0,64	-12,21
100	-7,74	-0,68	-13,05
125	-8,68	-0,9	-9,05
160	-10	-0,72	-10,3

To calculate the reflection coefficients of the ceiling types Equation 3.1 is used:

$a= 10^{SPL}/10$ **(3.1)**

SPL: Sound pressure level

a: Reflection coefficient

Calculated results of the reflection coefficients given in the Table 3.2.

Table 3.2: Reflection coefficients of the ceiling materials

Frequency	Reflection Coefficient		
KHz	Foam Plastic	MDF	Wool
2,51	0,79	1,52	0,74
3,16	0,8	1,1	0,69
3,98	0,92	0,9	0,61
5,01	0,84	0,67	0,53
6,31	0,8	1,01	0,38
8	0,98	1,49	0,68
10	0,44	0,92	0,31
12,5	0,66	1,05	0,26
16	0,64	1,09	0,14
19,95	0,45	0,88	0,2
25	0,35	1,06	0,18
31,5	0,41	0,9	0,1
40	0,32	0,89	0,08
50	0,33	0,87	0,07
63	0,27	0,89	0,09
80	0,23	0,86	0,06
100	0,17	0,86	0,05
125	0,14	0,81	0,12
160	0,1	0,85	0,09

To calculate the absorption coefficients of the ceiling materials:

$\alpha = 1- a$ **(3.2)**

α: Absorption coefficient

a: Reflection coefficient

Calculated results of the absorption coefficients are given in the Table 3.3

Table 3.3: Absorption coefficients of the ceiling materials

Frequency	Absorption Coefficient		
KHz	Foam Plastic	MDF	Wool
2,51	0,21	-0,52	0,26
3,16	0,2	-0,1	0,31
3,98	0,08	0,1	0,39
5,01	0,16	0,33	0,47
6,31	0,2	-0,01	0,62
8	0,02	-0,49	0,32
10	0,56	0,08	0,69
12,5	0,34	-0,05	0,74
16	0,36	-0,09	0,86
19,95	0,55	0,12	0,8
25	0,65	-0,06	0,82
31,5	0,59	0,1	0,9
40	0,68	0,11	0,92
50	0,67	0,13	0,93
63	0,73	0,11	0,91
80	0,77	0,14	0,94
100	0,83	0,14	0,95
125	0,86	0,19	0,88
160	0,9	0,15	0,91

Some of the absorption coefficient values are less than zero, which seems theoreticly impossible, but in the fielt measurements sound waves hit to some other reflective surfaces like microphone stands or surface underneath the sample. This unwanted reflections coused some wrong measurements in some frequencies.

Figure 3.26 shows the reflection coefficient comparison of each ceiling types.

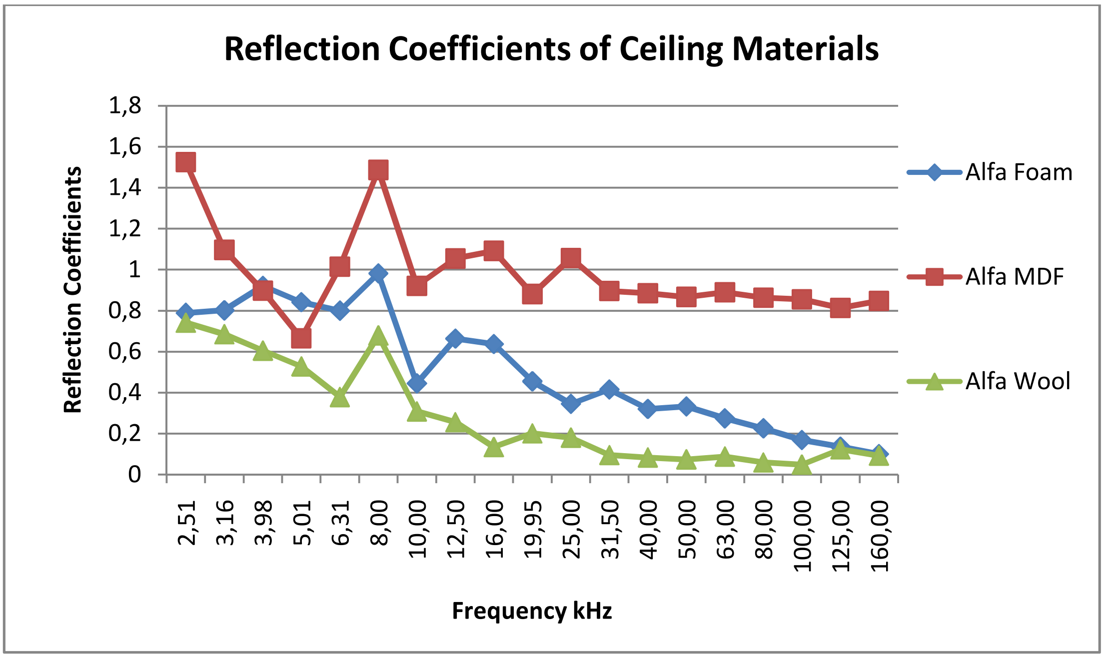

Figure 3.26 : Reflection coefficients of the ceiling materials are given.

Figure 3.26 show MDF is the most reflective and Wool is the least reflective ceiling types.

These values subtracted from 1 to calculate absorption coefficients of the ceiling types. Figure 3.27 shows absorption coefficients of the ceiling types which are used for Insertion Loss measurements.

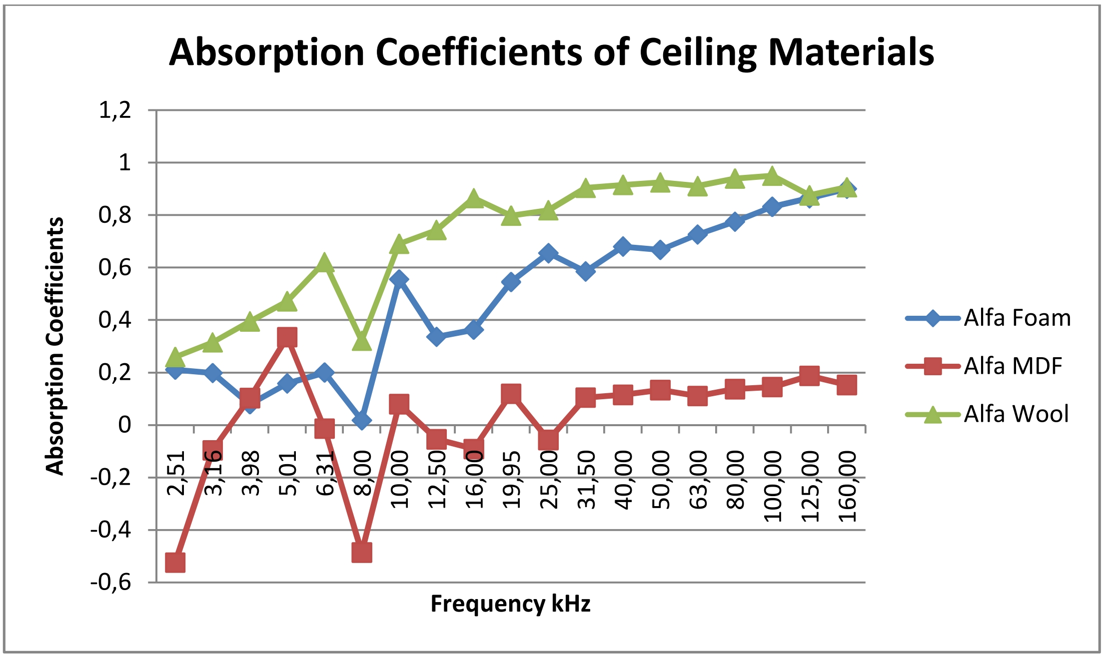

Figure 3.27 : Absorption coefficients of the ceiling materials are given.

After the measurements of the absorption coefficients of different ceiling types, Noise Reduction Coefficients are calculated.

$NRC_{MDF} = 0.02$

$NRC_{FOAM} = 0.36$

$NRC_{WOOL} = 0.55$

3.1.4 Calculations according to the results of the measurements

After measurement the amount of sound transmitted other side of the barrier, insertion loss values are also calculated. Figure 3.28 shows insertion loss values of 150 cm height barrier with different absorptive ceilings. The difference between measured values of direct sound without ceiling with any ceiling types and particular height of barrier for each frequency.

$$IL_{FREQUENCY}=SPL_1-SPL_2 \quad \textbf{(3.2)}$$

SPL_1 = Measured SPL for Ceiling Type with particular barrier height

SPL_2= Measured SPL for direct sound. (no barrier and no ceiling)

For example, with 210 cm height barrier and MDF ceiling, measured SPL for 200 Hz is 28.61dB and measured direct sound without barrier and without ceiling for 200 Hz is 28.08 dB. Therefore, the insertion loss value for MDF ceiling with 210 cm height barrier for 200 Hz is,

$IL_{200} = 28.08 – 28.61= -0.53$ dB;

So this result means, installation of a less absorptive ceiling does not work at 200 Hz, even a high partition (210 cm) is installed. Also increases the sound pressure level 0.53 dB.

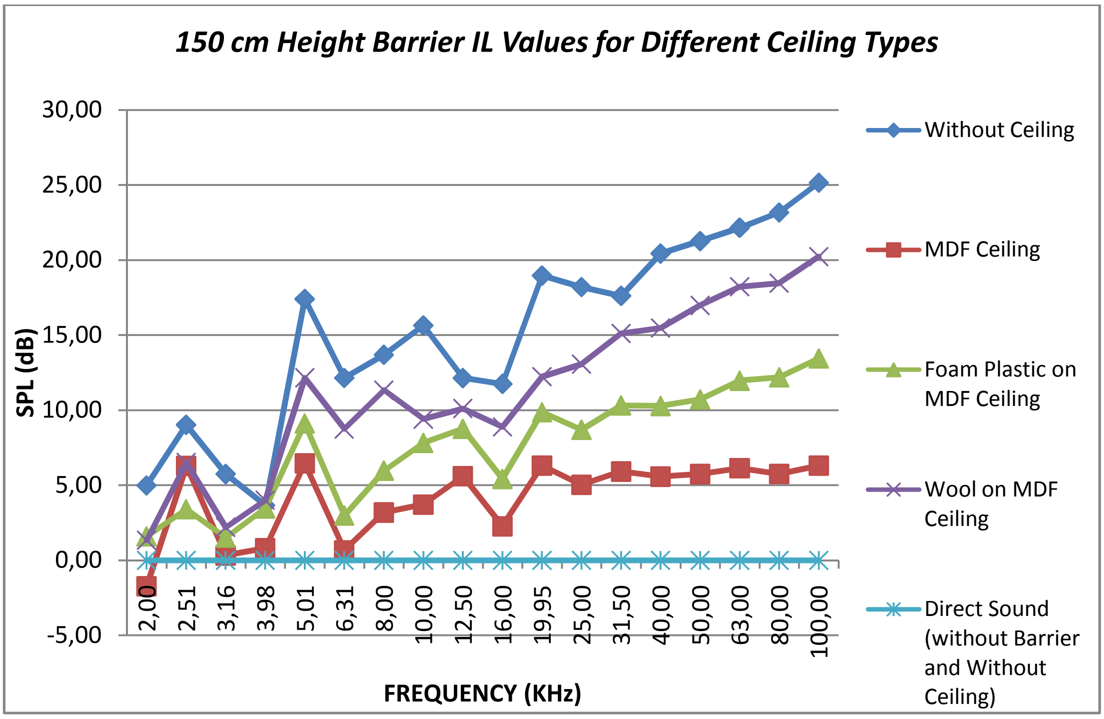

Figure 3.28 : 150 cm height barrier Insertion Loss values for different ceiling types.

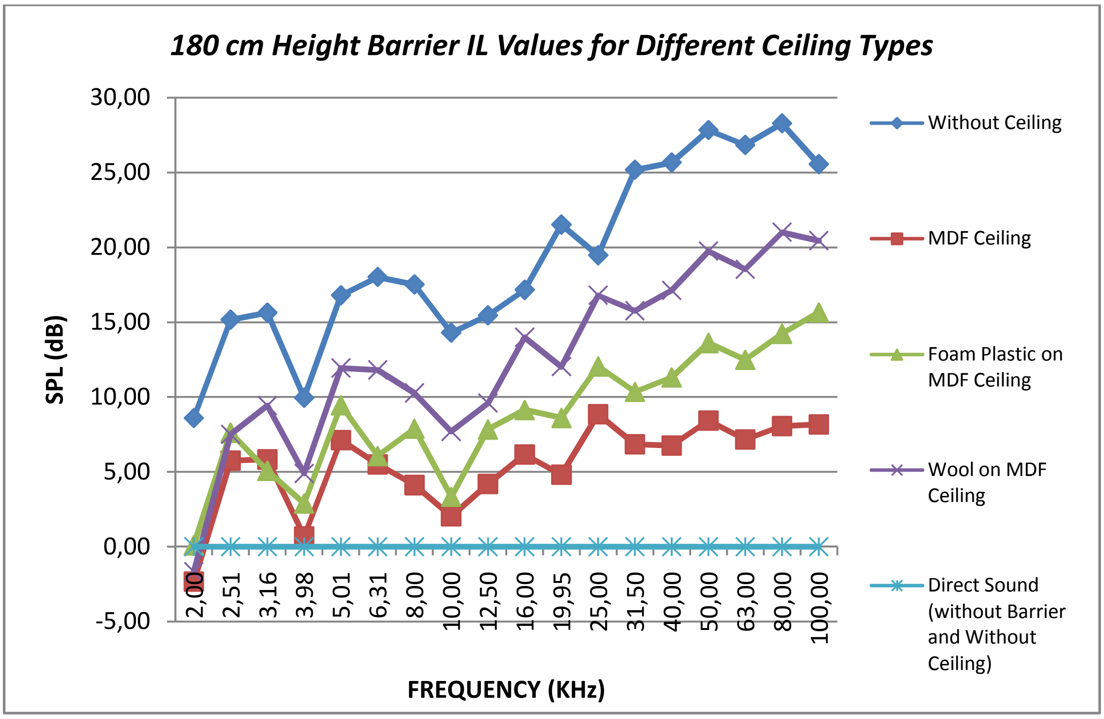

Figure 3.29 : 180 cm height barrier Insertion Loss values for different ceiling types.

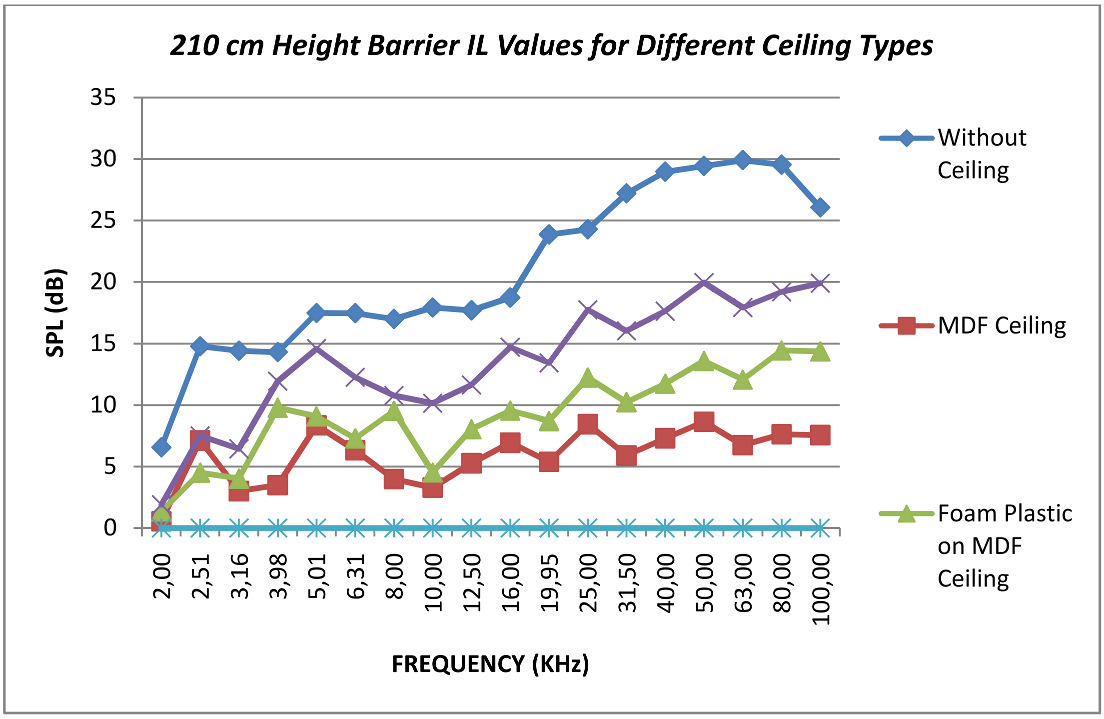

Figure 3.30 : 210 cm height barrier Insertion Loss values for different ceiling types.

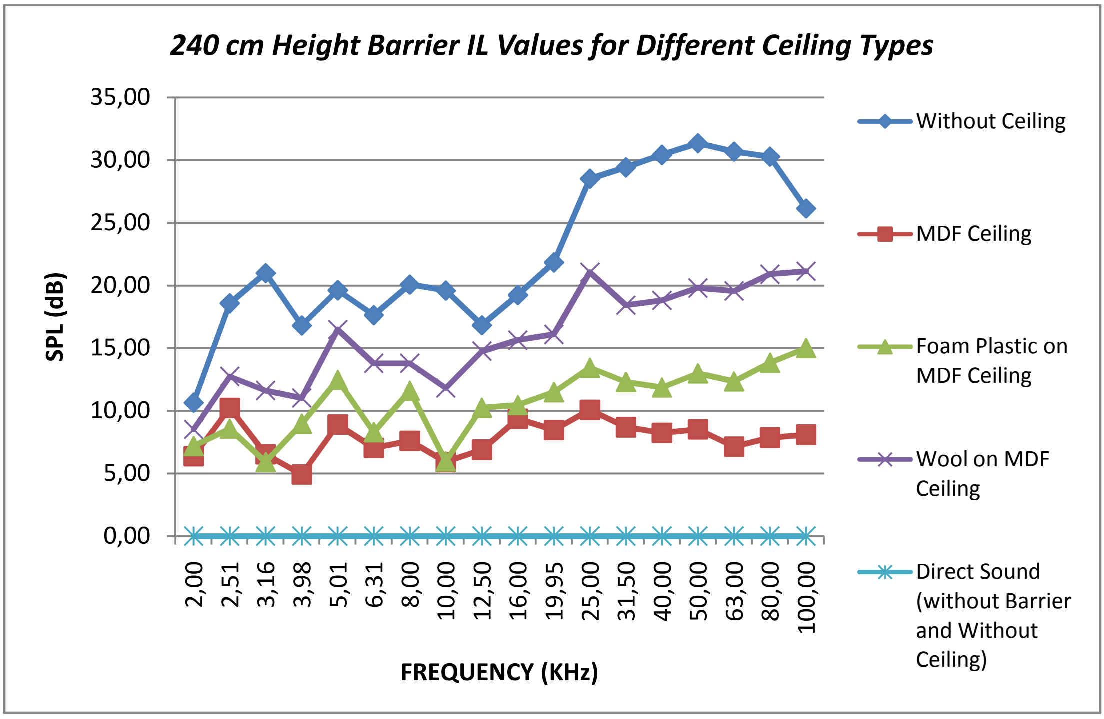

Figure 3.31 : 240 cm height barrier Insertion Loss values for different ceiling types.

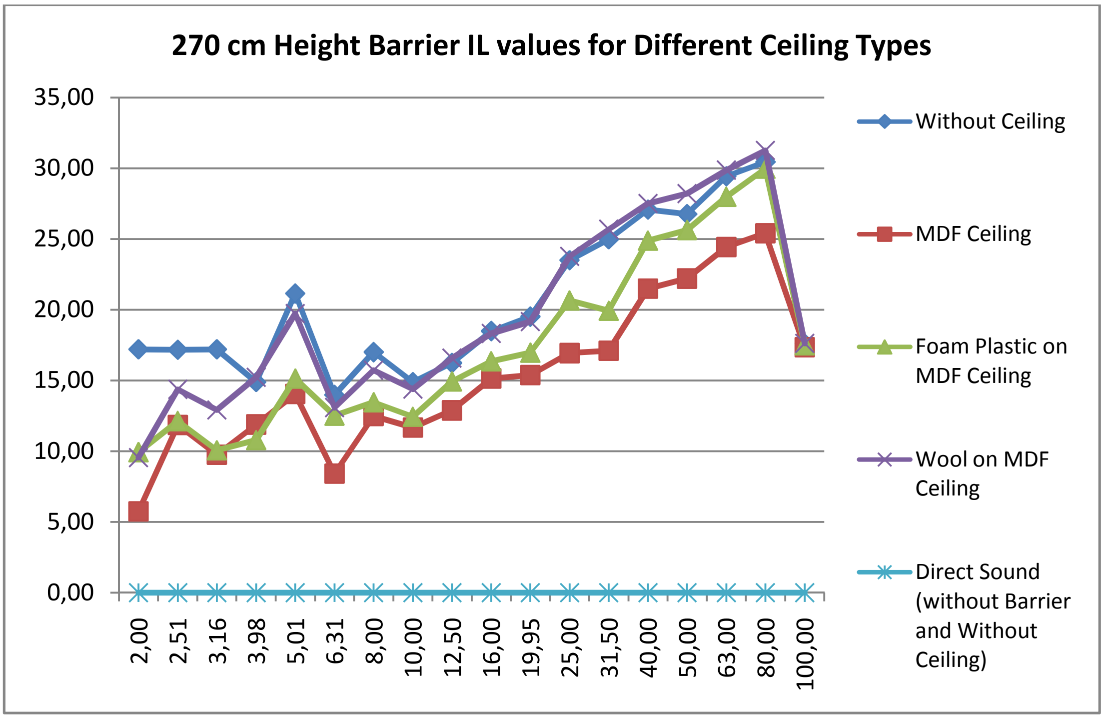

Figure 3.32 : 270 cm height barrier Insertion Loss values for different ceiling types.

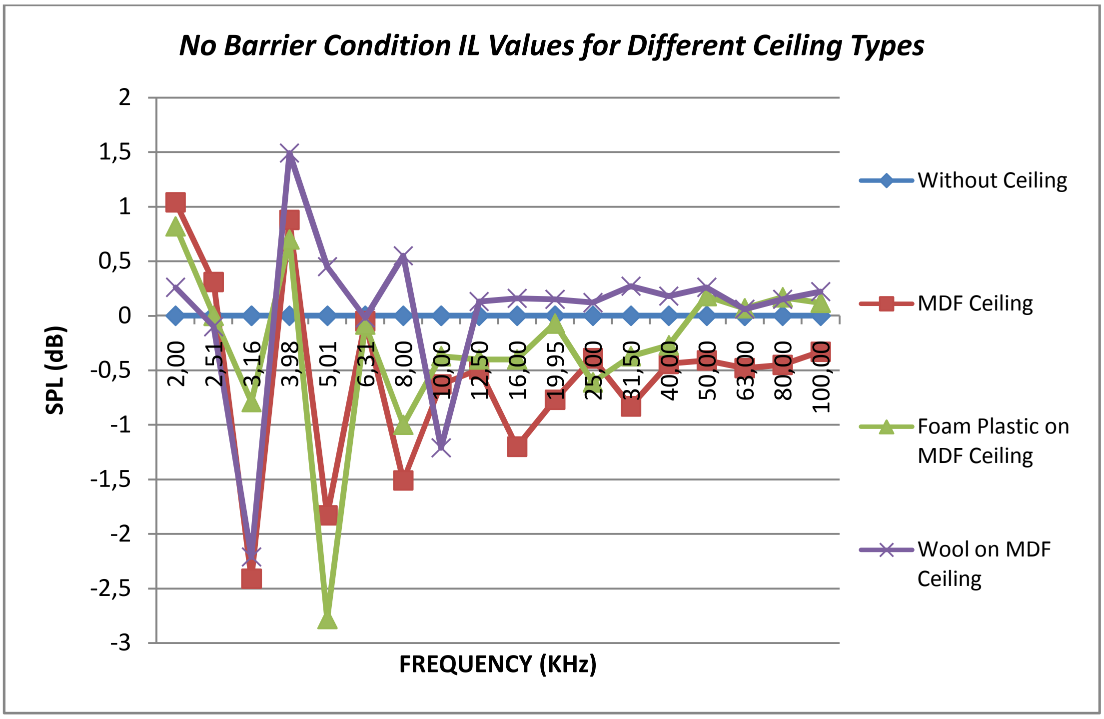

Figure 3.33 : No barrier condition Insertion Loss values for different ceiling types.

The insertion loss capacity of a barrier is very much related with the ceiling absorption. In the figures 3.28, 3.29, 3.30, 3.31, 3.32 and 3.33 the highest capacity of the barrier is achieved with no ceiling, because there is no ceiling reflection to the other side of the barrier so it represents a 100% absorptive ceiling. Moreover, worst capacity is achieved with MDF ceiling and it is the most reflective ceiling. Therefore, we can clearly say that we are not able to fix the acoustics of an open plan environment only with installing some barriers, but also with an absorptive ceiling. Of course, all possible reflection paths should be absorptive such as rear and sidewalls, barriers and floor. However, ceilings are the most effective reflection path in an open plan environments.

As the insertion loss values increase, signal to noise level decreases. Decrease of the signal to the noise level also decreases the AI values.

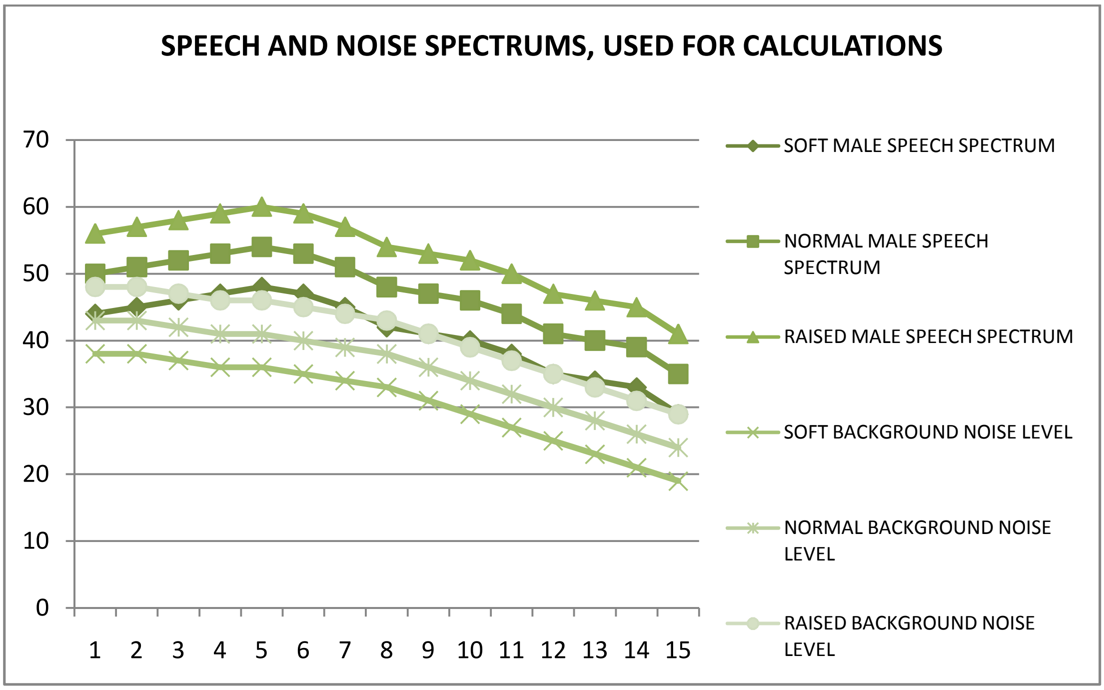

Figure 3.34 : Signal and noise levels, used for AI calculations.

There are some further studies about distracting level of background noise levels on office workers. For example, Bradley claims that noise levels more than 45 dBA is distracting ones [20]. So for AI calculations, several background noise levels are used to detect how great the increasing or decreasing effect of 5 dB is degrease or increase on AI. Moreover, signal levels are varied. The normal male speech spectrum is added and subtracted 6 dB to see the effect of signal to noise differences on AI.

Table 3.4: Speech spectrums used for calculations of articulation index calculations.

FREQUENCY (Hz)	200	250	316	398	501	631	800	1k	1,25k	1,6k	2k	2,5k	3,15k	4k	5k
Soft Male Speech Spectrum	44	45	46	47	48	47	45	42	41	40	38	35	34	33	29
Normal Male Speech Spectrum	50	51	52	53	54	53	51	48	47	46	44	41	40	39	35
Raised Male Speech Spectrum	56	57	58	59	60	59	57	54	53	52	50	47	46	45	41

Table 3.5: Background noise spectrums used for calculations of articulation index values.

FREQUENCY (Hz)	200	250	316	398	501	631	800	1k	1,25k	1,6k	2k	2,5k	3,15k	4k	5k
Soft Background Noise Level	38	38	37	36	36	35	34	33	31	29	27	25	23	21	19
Normal Background Noise Level	43	43	42	41	41	40	39	38	36	34	32	30	28	26	24
Raised Background Noise Level	48	48	47	46	46	45	44	43	41	39	37	35	33	31	29

For scale model AI calculations, insertion loss values are used to find the sound propagated to the other side of the sound barrier. And following formula is used:

$$AI = \sum_{200}^{5000}[(\text{Signal} - \text{Noise}) + 12] \times \text{Weighting Factor} \quad \textbf{(3.3)}$$

So the for the AI calculations valid sound and noise levels should be used, in order to predict open plan conditions. To find proper signal to noise ratio for every frequency;

$$S - N = NMSS - BNL - IL \quad \textbf{(3.4)}$$

S-N= Signal to Noise Ratio

NMSS= Normal Male Speech Spectrum

BNL= Background Noise Level

IL= Insertion loss due to the barrier and absorption of ceiling

So articulation index will calculated with;

$$AI = \sum_{200}^{5000}[(\text{Signal} - \text{Noise} - \text{IL}) + 12] \times \text{Weighting Factor} \quad \textbf{(3.5)}$$

Table 3.6: Normal male speech spectrum according to ANSI S. 3, 5 1997

FREQUENCY (Hz)	200	250	316	398	501	631	800	1k	1,25k	1,6k	2k	2,5k	3,15k	4k	5k
Normal Speech Spectrum	50	51	52	53	54	53	51	48	47	46	44	41	40	39	35

Table 3.6 Normal male speech spectrum calculated as 54 dBA.

For different kind of speech, spectrums are also calculated. Soft, normal and raised spectrums are also calculated to see their effect on AI.

For the background noise level it seems like, it is, supposed to be as high as possible, but the limit for background noise level is the limit of distraction. Some measurements are figured out to examine the upper limit of possible, not distracting background noise level spectrum. According to the measurements ideal background noise level in an open plan office can be 43-dBA. Which corresponds, NC (Noise criteria) 38. For 43-dBA spectrum all noise levels are specified for each octave bands are given Table 3.7 [28].

Table 3.7: Normal background noise level spectrum for octave bands [28]

FREQUENCY (Hz)	200	250	316	398	501	631	800	1k	1,25k	1,6k	2k	2,5k	3,15k	4k	5k
Normal Background Noise Level Spectrum	43	43	42	41	41	40	39	38	36	34	32	30	28	26	24

For AI method speech intelligibility is proportional to the long-term RMS speech signal plus 12 dB, minus the noise in each band [19].

Weighting factor differs according to the importance of the frequency for human ear. Weighting factors for each octave bands are given in the Table 3.8.

Table 3.8: Weighting factors for each octave bands, used for articulation index calculations.

FREQUENCY (Hz)	200	250	316	398	501	631	800	1k	1,25k	1,6k	2k	2,5k	3,15k	4k	5k
Weighting factors	0.0004	0.001	0.001	0.0014	0.0014	0.002	0.002	0.0024	0.003	0.0037	0.0037	0.0034	0.0034	0.0024	0.002

Calculation results for all AI values are in the table 9. These values are calculated within estimated signal and noise levels, with 150 cm height barrier and MDF ceiling. Normal signal and normal noise level result is bolded.

Table 3.9: Calculation table for articulation index for 150 cm height with MDF ceiling

Hz	SIGNAL SPEECH SPECTRUM	SIGNAL IL	NOISE (dB)	Weighting Factor	(S-N+1) X WF	(S-N+6) X WF	(S-N+7) X WF	(S-N+11) X WF	**(S-N+12) X WF**	(S-N+13) X WF	(S-N+17) X WF	(S-N+18) X WF	(S-N+23) X WF
200	50	-1,72	43	4,00E-04	0,0039	0,0059	0,0063	0,0079	**0,0083**	0,0087	0,0103	0,0107	0,0127
250	51	6,3	43	0,001	0,0027	0,0077	0,0087	0,0127	**0,0137**	0,0147	0,0187	0,0197	0,0247
316	52	0,32	42	0,001	0,0107	0,0157	0,0167	0,0207	**0,0217**	0,0227	0,0267	0,0277	0,0327
398	53	0,81	41	0,001	0,0171	0,0241	0,0255	0,0311	**0,0325**	0,0339	0,0395	0,0409	0,0479
501	54	6,46	41	0,001	0,0106	0,0176	0,019	0,0246	**0,026**	0,0274	0,033	0,0344	0,0414
631	53	0,67	40	0,002	0,0267	0,0367	0,0387	0,0467	**0,0487**	0,0507	0,0587	0,0607	0,0707
800	51	3,19	39	0,002	0,0196	0,0296	0,0316	0,0396	**0,0416**	0,0436	0,0516	0,0536	0,0636
1k	48	3,72	38	0,002	0,0175	0,0295	0,0319	0,0415	**0,0439**	0,0463	0,0559	0,0583	0,0703
1,25k	47	5,61	36	0,003	0,0192	0,0342	0,0372	0,0492	**0,0522**	0,0552	0,0672	0,0702	0,0852
1,6k	46	2,27	34	0,004	0,0397	0,0582	0,0619	0,0767	**0,0804**	0,0841	0,0989	0,1026	0,1211
2k	44	6,32	32	0,004	0,0254	0,0444	0,0482	0,0634	**0,0672**	0,071	0,0862	0,09	0,109
2,5k	41	5,03	30	0,003	0,0237	0,0407	0,0441	0,0577	**0,0611**	0,0645	0,0781	0,0815	0,0985
3,15k	40	5,92	28	0,003	0,0241	0,0411	0,0445	0,0581	**0,0615**	0,0649	0,0785	0,0819	0,0989
4k	39	5,58	26	0,002	0,0202	0,0322	0,0346	0,0442	**0,0466**	0,049	0,0586	0,061	0,073
5k	35	5,75	24	0,002	0,0125	0,0225	0,0245	0,0325	**0,0345**	0,0365	0,0445	0,0465	0,0565
	ARTICULATION INDEX =				0,273	0,439	0,473	0,606	**0,639**	0,673	0,806	0,839	1

Table 3.9 shows calculation method of AI male speech spectrum in every frequency minus insertion loss results the signal received by receiver. Background noise level is subtracted from signal level to find signal to noise level. 12 dB RMS peak level added to signal to noise level to count peaks of speech. After this summation, weighting factor is multiplied by signal to noise ratio plus 12 dB.

3.1.5 Evaluations of AI calculation results

Figures 3.36, 3.37 and 3.38 show the AI differences with different height barriers and different ceiling types in terms of different signal to noise ratios. AI calculations also involve full height barrier results. Even partial height measurements are performed within 30 cm (represents 3m) barrier, for full height barrier measurements, ceiling height assumed to be 270 cm. Therefore, for the figures 3.35, 3.36 and 3.37, 270 cm height barrier means full height barrier.

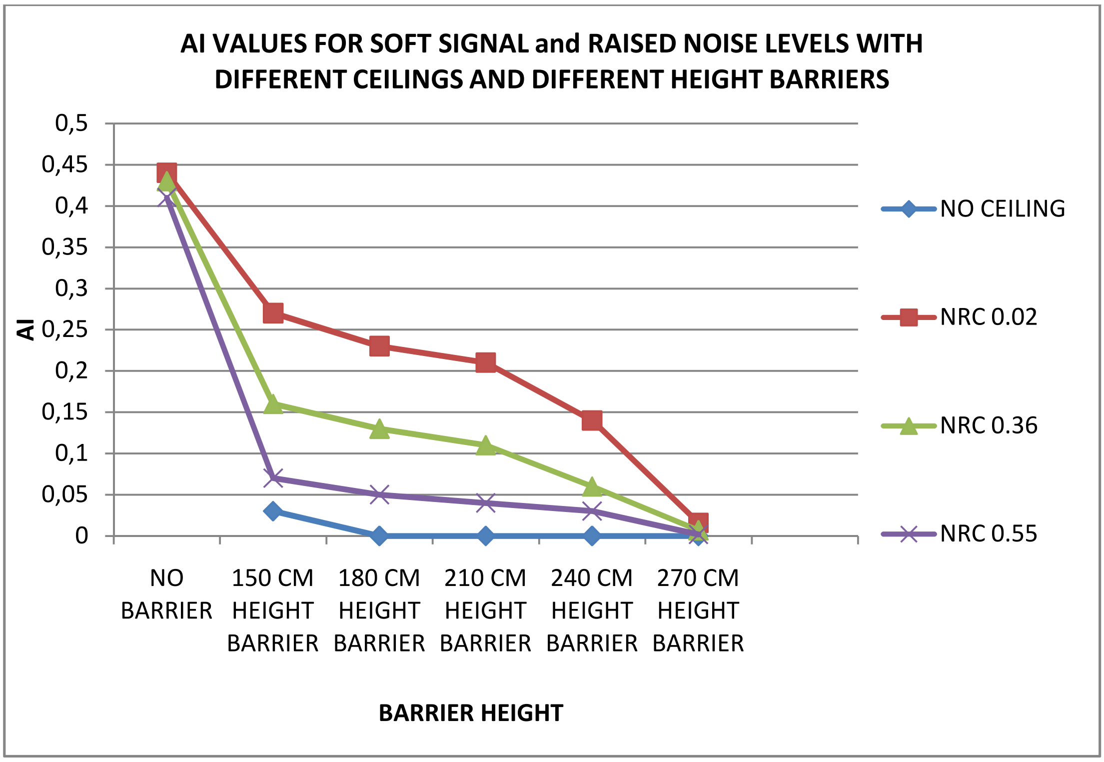

Figure 3.35 : Articulation index values for soft signal and raised noise levels with different ceilings and different height barriers.

Figure 3.35 shows AI values with different type ceilings. As mentioned above design goal was to achieve less than 0.15 AI to have an acoustically private open plan office. Therefore, with a soft signal and raised noise, which means soft speaking in a noisy environment, even a reflective ceiling can sustain 0.15 AI but at least 240 cm height barrier must be installed. As the ceiling gets more absorptive, height of the barrier can be lower.

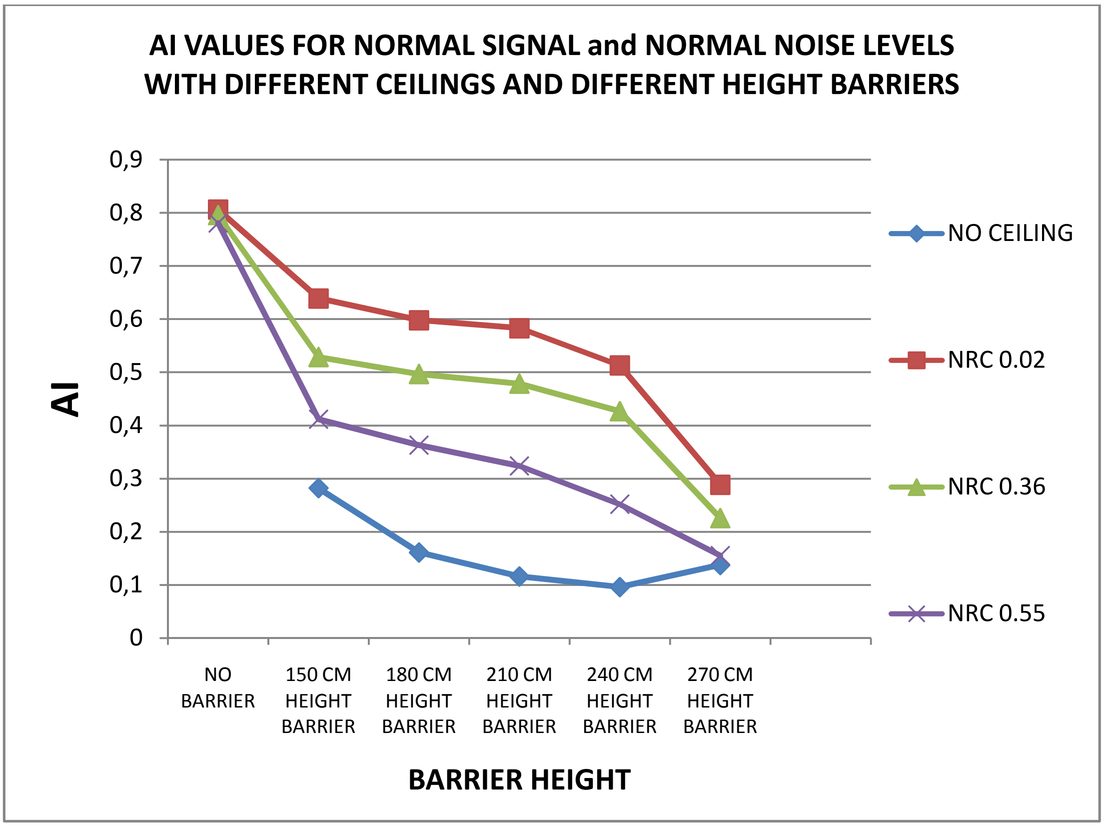

Figure 3.36 : Articulation Index values for normal signal and normal noise levels with different ceilings and different height barriers.

Figure 3.36 shows AI values achieved with normal speech and normal noise. Goal of 0.15 AI could not be achieved. This means under these conditions, (normal male speech spectrum and 48 dBA background noise levels) acoustically private office conditions could not sustained. So more absorptive ceilings should be installed or higher barriers should be located to this open plan office conditions.

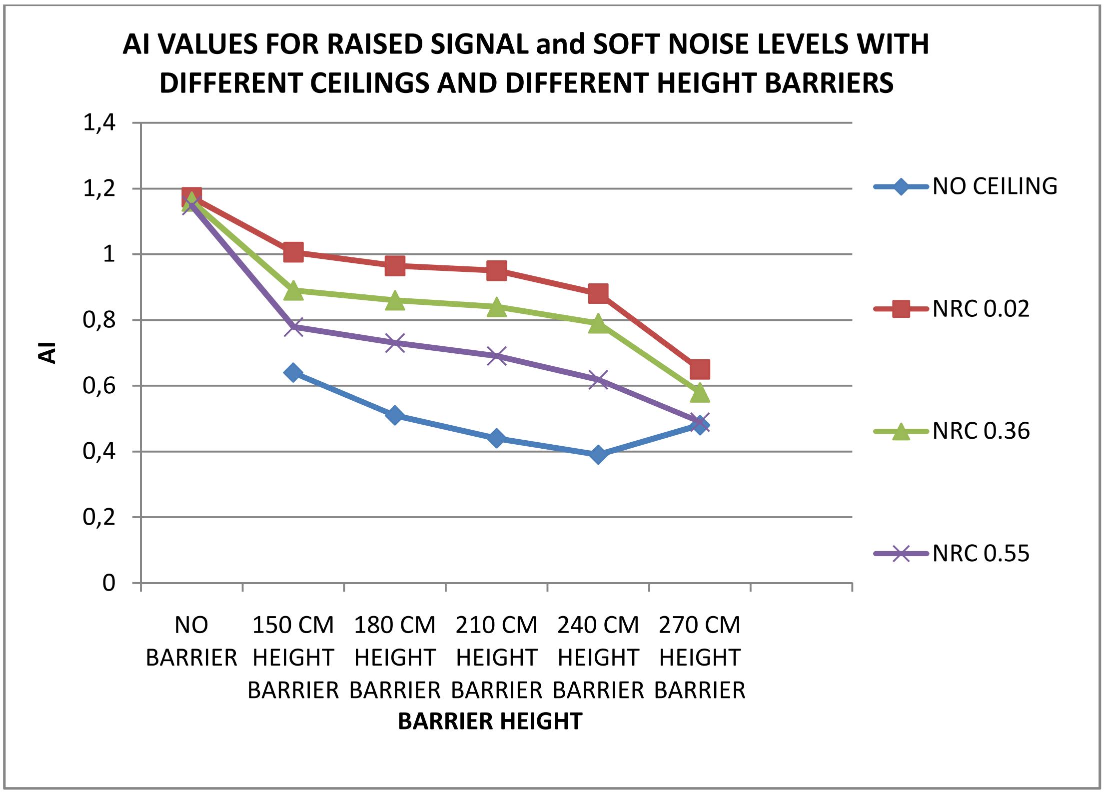

Figure 3.37 : Articulation Index values for raised signal and soft noise levels with different ceiling types and different height barriers.

Figure 3.37 shows the AI results under the condition of raised signal and soft noise. Assume that someone is shouting in a silent open plan office. Even with the most absorptive ceiling and the highest barrier, AI is around 0, 6.

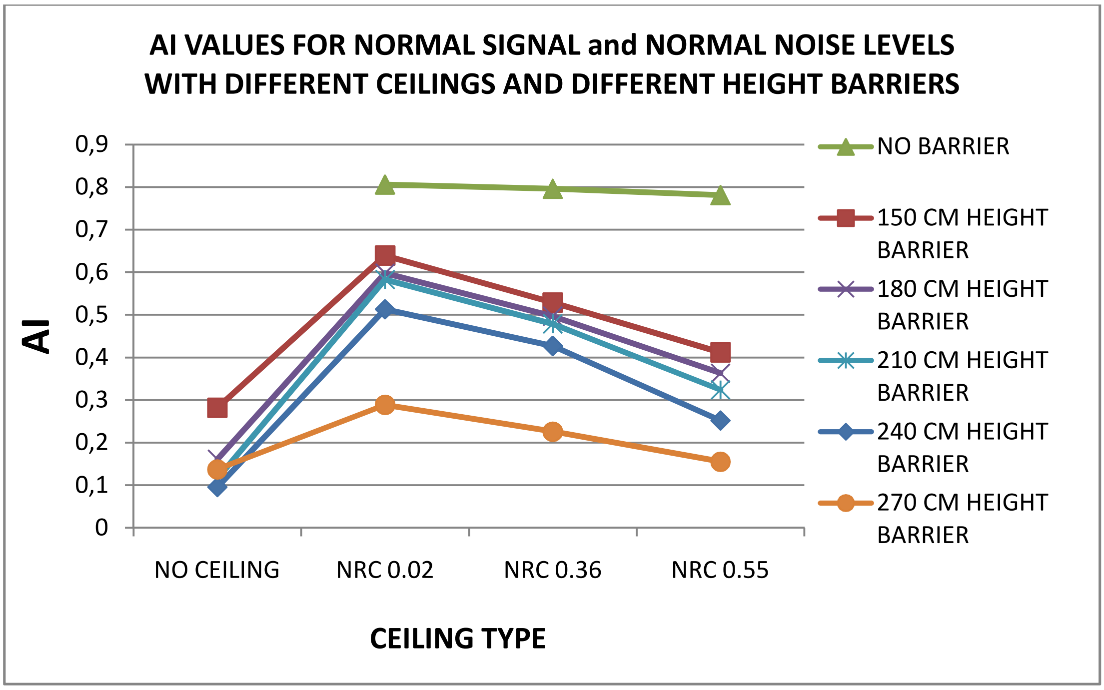

Figure 3.38 : AI depended on ceiling absorption

As the absorption coefficient of ceiling increase, AI decreases for every barrier height.

Figure 3.39, 3.40 show AI depended on signal to noise ratio.

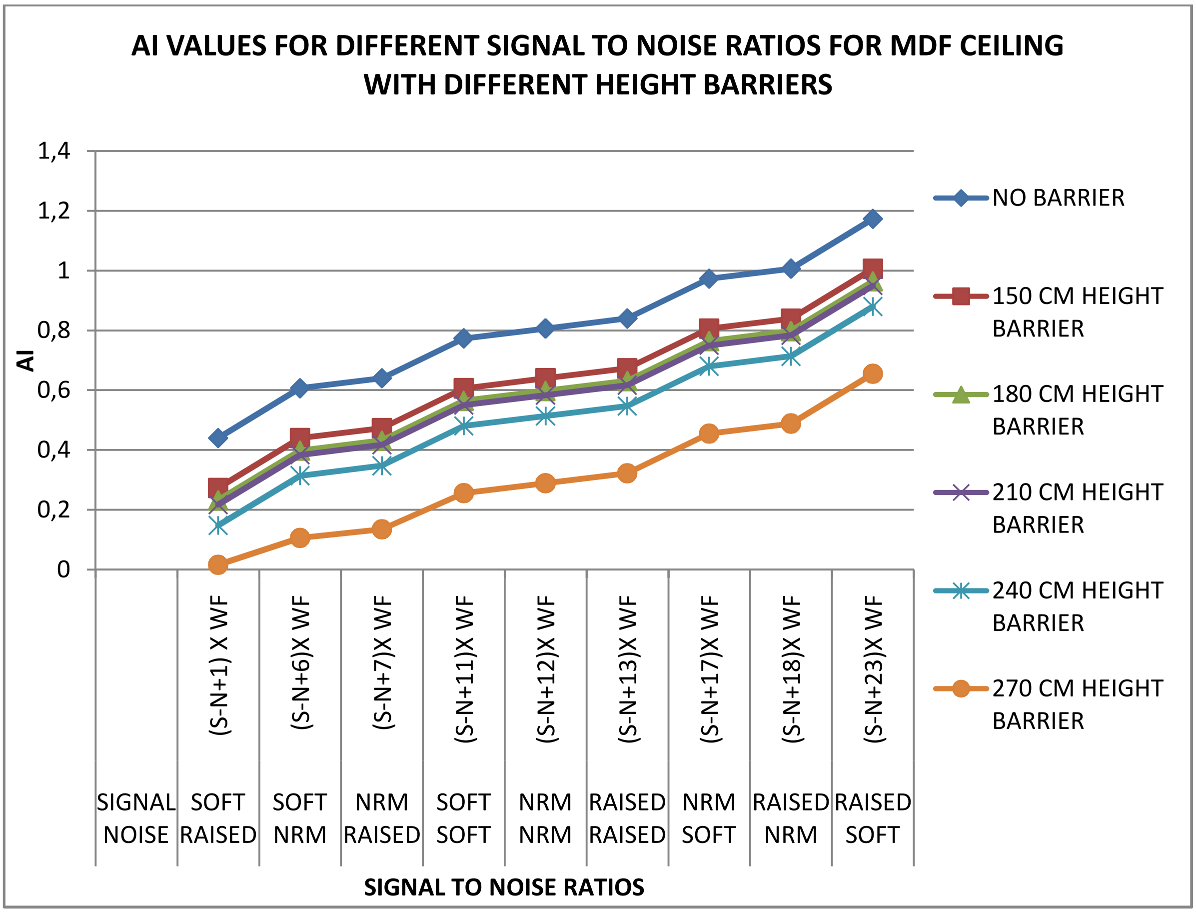

Figure 3.39 : Articulation Index values for different signal to noise ratios for MDF ceiling with different height barriers.

As AI is very dependent on signal to noise ratios, this graph shows AI changes of every height barrier with MDF ceiling. Figure shows that under these conditions, 1 dB change of Signal to noise level, changes AI around 0,04. In addition, 5 dB changes the AI around 0, 15. Design goal of 0, 15 AI can only be achieved with soft speech and raised background noise level and with 240 cm height barrier. With 240 cm height barrier and MDF ceiling, AI change according to the signal to noise levels is around 0, 75 (difference between soft signal, raised noise and raised signal, soft noise). As the slopes of the barrier heights are parallel in the graph, signal to noise level has the same effect on every height barrier.

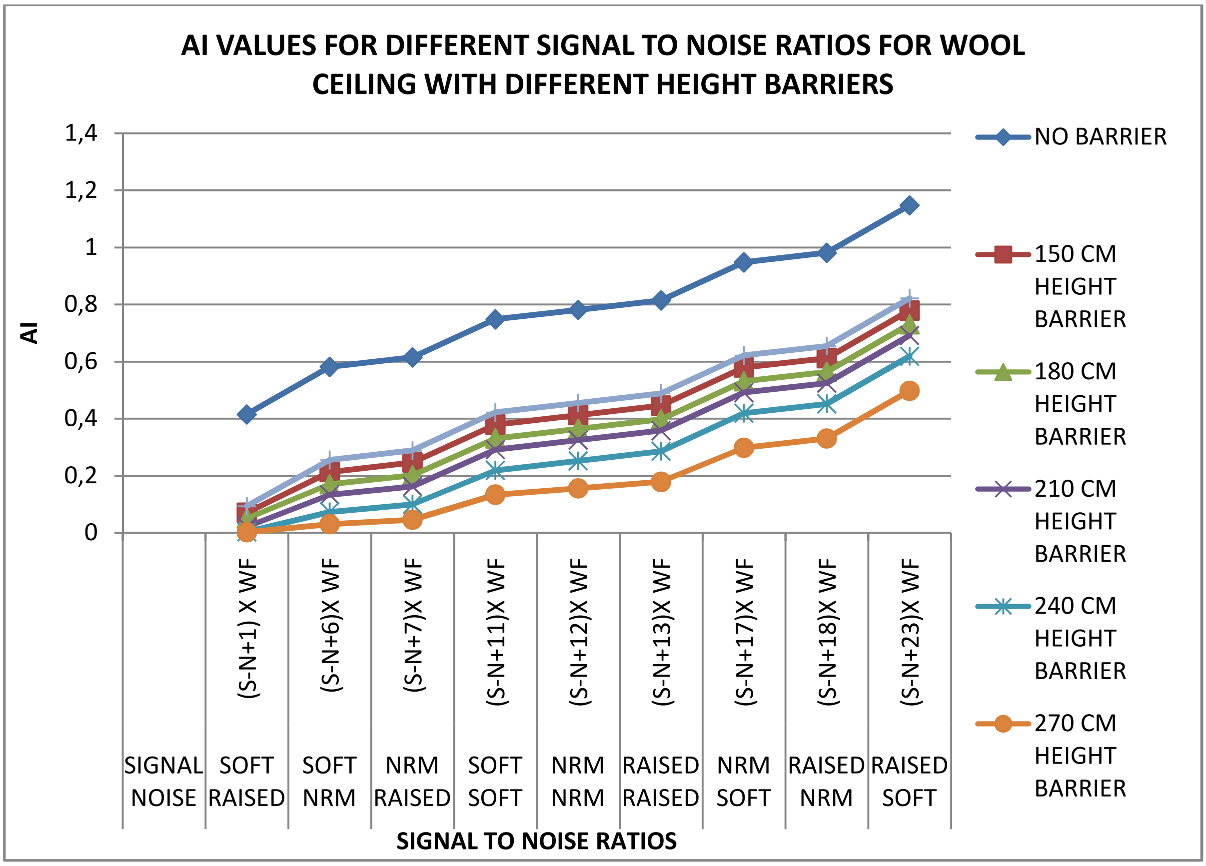

Figure 3.40 : Articulation Index values for different signal to noise ratios for wool ceiling with different height barriers

Figure 3.40 shows AI changes of every height barrier with wool on MDF ceiling. Design goal of 0, 15 AI can be achieved with soft speech and raised background noise level and with all heights of barriers. However, as the absorption coefficient of ceilings are increased, design goal of 0, 15 AI is achieved with increased signal to noise levels. With 240 cm height barrier and wool on MDF ceiling, AI change according to the signal to noise levels is around 0, 61 (difference between soft signal, raised noise and raised signal, soft noise).

If the design goal shifted to 0, 20 AI, then results shown in Table 3.10.

Table 3.10: Articulation Index values and corresponding Barrier Height and ceiling absorption levels with signal to noise levels.

- 0,8<AI
- 0,6<AI<0,8
- 0,4<AI<0,6
- 0,2<AI<0,4
- 0.1<AI<0,2
- 0,05<AI<0,1
- AI<0,05

	SIGNAL	Soft	Soft	Normal	Soft	Normal	Raised	Normal	Raised	Raised
	NOISE	Raised	Normal	Raised	Soft	Normal	Raised	Soft	Normal	Soft
		(S-N+1)	(S-N+6)	(S-N+7)	(S-N+11)	(S-N+12)	(S-N+13)	(S-N+17)	(S-N+18)	(S-N+23)
o cm Barrier	NRC 0,02									
	NRC 0,36									
	NRC 0,55									
	NRC 1									
150 cm Barrier	NRC 0,02									
	NRC 0,36									
	NRC 0,55									
	NRC 1									
180 cm Barrier	NRC 0,02									
	NRC 0,36									
	NRC 0,55									
	NRC 1									
210 cm Barrier	NRC 0,02									
	NRC 0,36									
	NRC 0,55									
	NRC 1									
240 cm Barrier	NRC 0,02									
	NRC 0,36									
	NRC 0,55									
	NRC 1									
270 cm Barrier	NRC 0,02									
	NRC 0,36									
	NRC 0,55									
	NRC 1									

4. CONCLUSION AND RECOMMENDATIONS

To achieve privacy in an open plan office (AI<0.20) the most important parameter is signal to noise level. Although it is hard to change background noise level in open plan offices, changing speech level would work better. If an employee would lower his or her voice in a noisy environment even with 150 cm height barrier with any kind of ceiling 0.30 AI is achieved. But this study showed that barrier height must be at least 180 cm hight even under a very absorptive ceiling. Under that condition with special care of the employee, he or she can achieve privacy. Second important parameter is ceiling absorption. The ceiling must be as absorptive as possible to avoid unwanted office noise and reflections.

These measurements are performed with semi finite barrier between two workers. Ceiling height is assumed 300 cm height. Side reflections trough windows, doors and other workstations are not represented during this work. Interaction of two workers are searched.

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APPENDICES

APPENDIX A: Data read from the barrier measurements

APPENDIX A

Table A.1 –A.6 shows the data read from the scale model measurements. Background noise level, and results of SPL read for all ceiling types in octave bands are measured.

Table A.1: Data read from the sound pressure level for 150 cm height barrier measurements

FREQUENCY	*150 cm Height Barrier SPL Results*					
	Without Ceiling	MDF Ceiling	Foam Plastic on MDF Ceiling	Wool on MDF Ceiling	Direct Sound (without Barrier and Without Ceiling)	Background Noise Level
2,0	-42,54	-35,84	-39,15	-38,90	-37,56	-77,92
2,5	-39,61	-36,89	-33,99	-37,10	-30,59	-75,45
3,2	-34,29	-28,87	-30,06	-30,75	-28,55	-73,30
4,0	-34,01	-31,16	-33,81	-34,35	-30,35	-70,90
5,0	-38,29	-27,34	-29,99	-33,04	-20,88	-67,43
6,3	-32,88	-21,40	-23,71	-29,48	-20,73	-63,07
8,0	-27,69	-17,19	-19,97	-25,33	-14,00	-59,12
10,0	-26,94	-15,01	-19,11	-20,70	-11,29	-56,15
12,5	-26,22	-19,69	-22,83	-24,19	-14,08	-51,69
16,0	-28,90	-19,42	-22,57	-26,03	-17,15	-60,43
20,0	-34,37	-21,72	-25,26	-27,63	-15,40	-63,63
25,0	-35,43	-22,25	-25,91	-30,28	-17,22	-64,50
31,5	-38,96	-27,26	-31,65	-36,45	-21,34	-67,13
40,0	-45,19	-30,33	-35,03	-40,22	-24,75	-68,82
50,0	-47,51	-31,99	-36,95	-43,22	-26,24	-69,96
63,0	-51,26	-35,25	-41,06	-47,33	-29,10	-71,45
80,0	-56,53	-39,11	-45,54	-51,81	-33,35	-72,92
100,0	-62,75	-43,90	-51,03	-57,82	-37,59	-74,41

Table A.2: Read from the sound pressure level for 180 cm height barrier measurements

FREQUENCY	*180 cm Height Barrier SPL Results*					
	Without Ceiling	MDF Ceiling	Foam Plastic on MDF Ceiling	Wool on MDF Ceiling	Direct Sound (without Barrier and Without Ceiling)	Background Noise Level
2,0	-36,67	-25,76	-28,18	-26,41	-28,08	-68,01
2,5	-41,47	-32,07	-33,93	-33,81	-26,31	-70,31
3,2	-44,75	-34,95	-34,20	-38,54	-29,12	-72,76
4,0	-45,91	-36,66	-38,86	-40,86	-35,97	-75,38
5,0	-49,45	-39,78	-42,11	-44,59	-32,66	-76,75
6,3	-54,19	-41,68	-42,25	-47,98	-36,18	-78,19
8,0	-53,79	-40,40	-44,17	-46,54	-36,28	-79,95
10,0	-52,10	-39,85	-41,15	-45,51	-37,81	-81,50
12,5	-55,57	-44,31	-47,96	-49,71	-40,12	-76,56
16,0	-58,10	-47,11	-50,09	-54,93	-40,95	-83,30
20,0	-59,54	-42,84	-46,64	-50,05	-38,03	-84,77
25,0	-58,18	-47,57	-50,77	-55,51	-38,72	-83,07
31,5	-67,56	-49,23	-52,74	-58,15	-42,39	-80,53
40,0	-72,13	-53,23	-57,78	-63,59	-46,47	-86,17
50,0	-75,32	-55,92	-61,11	-67,24	-47,50	-83,10
63,0	-77,47	-57,80	-63,13	-69,17	-50,64	-83,55
80,0	-82,79	-62,58	-68,75	-75,52	-54,52	-85,64
100,0	-84,52	-67,14	-74,62	-79,41	-58,97	-85,52

Table A.3: Read from the sound pressure level for 210 cm height barrier measurements

FREQUENCY	210 cm Height Barrier SPL Results					
	Without Ceiling	MDF Ceiling	Foam Plastic on MDF Ceiling	Wool on MDF Ceiling	Direct Sound (without Barrier and Without Ceiling)	Background Noise Level
2,0	-34,64	-28,61	-29,42	-29,98	-28,08	-68,01
2,5	-41,08	-33,41	-30,81	-33,79	-26,31	-70,31
3,2	-43,53	-32,11	-33,13	-35,55	-29,12	-72,76
4,0	-50,27	-39,44	-45,75	-47,9	-35,97	-75,38
5,0	-50,14	-41	-41,74	-47,23	-32,66	-76,75
6,3	-53,65	-42,48	-43,46	-48,42	-36,18	-78,19
8,0	-53,27	-40,24	-45,8	-47,04	-36,28	-79,95
10,0	-55,73	-41,08	-42,32	-47,95	-37,81	-81,5
12,5	-57,81	-45,37	-48,15	-51,75	-40,12	-76,56
16,0	-59,68	-47,87	-50,5	-55,64	-40,95	-83,3
20,0	-61,89	-43,4	-46,73	-51,45	-38,03	-84,77
25,0	-63	-47,15	-50,95	-56,46	-38,72	-83,07
31,5	-69,59	-48,27	-52,62	-58,41	-42,39	-80,53
40,0	-75,43	-53,75	-58,21	-64,09	-46,47	-86,17
50,0	-76,93	-56,12	-61,09	-67,44	-47,5	-83,1
63,0	-80,54	-57,37	-62,71	-68,55	-50,64	-83,55
80,0	-84,05	-62,13	-68,96	-73,71	-54,52	-85,64
100,0	-85,03	-66,51	-73,33	-78,86	-58,97	-85,52

Table A.4: Read from the sound pressure level for 240 cm height barrier measurements

FREQUENCY	240 cm Height Barrier SPL Results					
	Without Ceiling	MDF Ceiling	Foam Plastic on MDF Ceiling	Wool on MDF Ceiling	Direct Sound (without Barrier and Without Ceiling)	Background Noise Level
2,0	-38,73	-34,45	-35,26	-36,59	-28,08	-68,01
2,5	-44,88	-36,53	-34,88	-39,04	-26,31	-70,31
3,2	-50,10	-35,65	-35,03	-40,73	-29,12	-72,76
4,0	-52,77	-40,89	-44,93	-46,98	-35,97	-75,38
5,0	-52,27	-41,55	-45,13	-49,13	-32,66	-76,75
6,3	-53,81	-43,22	-44,47	-49,96	-36,18	-78,19
8,0	-56,34	-43,88	-47,88	-50,06	-36,28	-79,95
10,0	-57,39	-43,72	-43,76	-49,61	-37,81	-81,50
12,5	-56,94	-47,01	-50,36	-54,87	-40,12	-76,56
16,0	-60,18	-50,30	-51,40	-56,57	-40,95	-83,30
20,0	-59,86	-46,49	-49,51	-54,11	-38,03	-84,77
25,0	-67,22	-48,79	-52,15	-59,76	-38,72	-83,07
31,5	-71,80	-51,07	-54,69	-60,80	-42,39	-80,53
40,0	-76,87	-54,71	-58,33	-65,27	-46,47	-86,17
50,0	-78,83	-56,01	-60,48	-67,28	-47,50	-83,10
63,0	-81,31	-57,77	-62,98	-70,19	-50,64	-83,55
80,0	-84,78	-62,38	-68,35	-75,40	-54,52	-85,64
100,0	-85,10	-67,06	-73,97	-80,09	-58,97	-85,52

Table A.5: Read from the sound pressure level for 270 cm height barrier measurements

FREQUENCY	*270 cm Height Barrier SPL Results*					
	Without Ceiling	MDF Ceiling	Foam Plastic on MDF Ceiling	Wool on MDF Ceiling	Direct Sound (without Barrier and Without Ceiling)	Background Noise Level
2,0	-61,82	-50,37	-54,56	-54,18	-44,62	-86,19
2,5	-58,69	-53,38	-53,66	-55,90	-41,52	-84,24
3,2	-58,02	-50,58	-50,89	-53,75	-40,82	-82,71
4,0	-52,18	-49,19	-48,09	-52,53	-37,30	-79,68
5,0	-51,20	-44,12	-45,20	-49,78	-30,06	-77,32
6,3	-44,01	-38,45	-42,55	-43,12	-30,03	-73,47
8,0	-41,27	-36,77	-37,74	-40,00	-24,27	-68,42
10,0	-36,00	-32,79	-33,56	-35,52	-21,12	-66,73
12,5	-39,80	-36,46	-38,51	-40,15	-23,57	-61,68
16,0	-44,34	-41,00	-42,21	-44,17	-25,85	-70,82
20,0	-45,94	-41,82	-43,40	-45,59	-26,43	-73,52
25,0	-52,15	-45,59	-49,31	-52,42	-28,65	-74,42
31,5	-57,56	-49,70	-52,52	-58,27	-32,59	-76,80
40,0	-63,18	-57,61	-61,00	-63,61	-36,11	-78,43
50,0	-64,77	-60,22	-63,65	-66,21	-38,01	-78,09
63,0	-70,55	-65,56	-69,11	-70,98	-41,12	-77,12
80,0	-76,15	-71,12	-75,68	-76,96	-45,71	-82,13
100,0	-67,92	-67,69	-67,83	-67,95	-50,33	-68,25

Table A.6 :Read from the sound pressure level for No barrier measurements

FREQUENCY	*No Barrier*					
	Without Ceiling	MDF Ceiling	Foam Plastic on MDF Ceiling	Wool on MDF Ceiling	Direct Sound (without Barrier and Without Ceiling)	Background Noise Level
2,0	-41,37	-42,41	-42,19	-41,63	-28,08	-68,01
2,5	-32,39	-32,7	-32,39	-32,29	-26,31	-70,31
3,2	-28,16	-25,75	-27,37	-25,95	-29,12	-72,76
4,0	-28,2	-29,08	-28,9	-29,69	-35,97	-75,38
5,0	-27,43	-25,6	-24,65	-27,88	-32,66	-76,75
6,3	-18,85	-18,8	-18,77	-18,83	-36,18	-78,19
8,0	-17,42	-15,91	-16,42	-17,97	-36,28	-79,95
10,0	-11,97	-11,34	-11,6	-10,76	-37,81	-81,5
12,5	-14,47	-13,98	-14,07	-14,6	-40,12	-76,56
16,0	-17,96	-16,76	-17,56	-18,12	-40,95	-83,3
20,0	-16,36	-15,59	-16,29	-16,51	-38,03	-84,77
25,0	-18,93	-18,54	-18,32	-19,05	-38,72	-83,07
31,5	-21,78	-20,95	-21,41	-22,05	-42,39	-80,53
40,0	-26,49	-26,05	-26,22	-26,67	-46,47	-86,17
50,0	-28,07	-27,66	-28,25	-28,33	-47,50	-83,1
63,0	-30,52	-30,04	-30,59	-30,58	-50,64	-83,55
80,0	-34,67	-34,22	-34,84	-34,82	-54,52	-85,64
100,0	-39,23	-38,9	-39,35	-39,45	-58,97	-85,52

To find the Insertion Loss value of a certain barrier height with a certain ceiling absorption, SPL value of that situation must subtracted from direct sound value. That value would show the performance of that barrier with that ceiling absorption. IL means the SPL decreases via barrier and ceiling.

Table A.7 – A.13 Shows Insertion Loss values calculated trough the data read from scale model measurements.

Table A.7: Insertion loss values for 150 cm height barrier with different ceiling types

FREQUENCY	150 cm Height Barrier Insertion Loss calculations					
	Without Ceiling	NRC 0,02	NRC 0,36	NRC 0,55	Direct Sound (without Barrier and Without Ceiling)	Background Noise Level
2,00	4,98	-1,72	1,59	1,34	0,00	40,36
2,51	9,02	6,30	3,40	6,51	0,00	44,86
3,16	5,74	0,32	1,51	2,20	0,00	44,75
3,98	3,66	0,81	3,46	4,00	0,00	40,55
5,01	17,41	6,46	9,11	12,16	0,00	46,55
6,31	12,15	0,67	2,98	8,75	0,00	42,34
8,00	13,69	3,19	5,97	11,33	0,00	45,12
10,00	15,65	3,72	7,82	9,41	0,00	44,86
12,50	12,14	5,61	8,75	10,11	0,00	37,61
16,00	11,75	2,27	5,42	8,88	0,00	43,28
19,95	18,97	6,32	9,86	12,23	0,00	48,23
25,00	18,21	5,03	8,69	13,06	0,00	47,28
31,50	17,62	5,92	10,31	15,11	0,00	45,79
40,00	20,44	5,58	10,28	15,47	0,00	44,07
50,00	21,27	5,75	10,71	16,98	0,00	43,72
63,00	22,16	6,15	11,96	18,23	0,00	42,35
80,00	23,18	5,76	12,19	18,46	0,00	39,57
100,00	25,16	6,31	13,44	20,23	0,00	36,82

Table A.8: Insertion loss values for 180 cm height barrier with different ceiling types

FREQUENCY	180 cm Height Barrier Insertion Loss calculations					
	Without Ceiling	NRC 0,02	NRC 0,36	NRC 0,55	Direct Sound (without Barrier and Without Ceiling)	Background Noise Level
2,00	8,59	-2,32	0,10	-1,67	0,00	39,93
2,51	15,16	5,76	7,62	7,50	0,00	44,00
3,16	15,63	5,83	5,08	9,42	0,00	43,64
3,98	9,94	0,69	2,89	4,89	0,00	39,41
5,01	16,79	7,12	9,45	11,93	0,00	44,09
6,31	18,01	5,50	6,07	11,80	0,00	42,01
8,00	17,51	4,12	7,89	10,26	0,00	43,67
10,00	14,29	2,04	3,34	7,70	0,00	43,69
12,50	15,45	4,19	7,84	9,59	0,00	36,44
16,00	17,15	6,16	9,14	13,98	0,00	42,35
19,95	21,51	4,81	8,61	12,02	0,00	46,74
25,00	19,46	8,85	12,05	16,79	0,00	44,35
31,50	25,17	6,84	10,35	15,76	0,00	38,14
40,00	25,66	6,76	11,31	17,12	0,00	39,70
50,00	27,82	8,42	13,61	19,74	0,00	35,60
63,00	26,83	7,16	12,49	18,53	0,00	32,91
80,00	28,27	8,06	14,23	21,00	0,00	31,12
100,00	25,55	8,17	15,65	20,44	0,00	26,55

Table A.9: Insertion loss values for 210 cm height barrier with different ceiling types

FREQUENCY	*210 cm Height Barrier Insertion Loss calculations*					
	Without Ceiling	NRC 0,02	NRC 0,36	NRC 0,55	Direct Sound (without Barrier and Without Ceiling)	Background Noise Level
2,00	6,56	0,53	1,34	1,9	0	39,93
2,51	14,77	7,1	4,5	7,48	0	44
3,16	14,41	2,99	4,01	6,43	0	43,64
3,98	14,3	3,47	9,78	11,93	0	39,41
5,01	17,48	8,34	9,08	14,57	0	44,09
6,31	17,47	6,3	7,28	12,24	0	42,01
8,00	16,99	3,96	9,52	10,76	0	43,67
10,00	17,92	3,27	4,51	10,14	0	43,69
12,50	17,69	5,25	8,03	11,63	0	36,44
16,00	18,73	6,92	9,55	14,69	0	42,35
19,95	23,86	5,37	8,7	13,42	0	46,74
25,00	24,28	8,43	12,23	17,74	0	44,35
31,50	27,2	5,88	10,23	16,02	0	38,14
40,00	28,96	7,28	11,74	17,62	0	39,7
50,00	29,43	8,62	13,59	19,94	0	35,6
63,00	29,9	6,73	12,07	17,91	0	32,91
80,00	29,53	7,61	14,44	19,19	0	31,12
100,00	26,06	7,54	14,36	19,89	0	26,55

Table A.10: Insertion loss values for 240 cm height barrier with different ceiling types

FREQUENCY	*240 cm Height Barrier Insertion Loss calculations*					
	Without Ceiling	NRC 0,02	NRC 0,36	NRC 0,55	Direct Sound (without Barrier and Without Ceiling)	Background Noise Level
2,00	10,65	6,37	7,18	8,51	0,00	39,93
2,51	18,57	10,22	8,57	12,73	0,00	44,00
3,16	20,98	6,53	5,91	11,61	0,00	43,64
3,98	16,80	4,92	8,96	11,01	0,00	39,41
5,01	19,61	8,89	12,47	16,47	0,00	44,09
6,31	17,63	7,04	8,29	13,78	0,00	42,01
8,00	20,06	7,60	11,60	13,78	0,00	43,67
10,00	19,58	5,91	5,95	11,80	0,00	43,69
12,50	16,82	6,89	10,24	14,75	0,00	36,44
16,00	19,23	9,35	10,45	15,62	0,00	42,35
19,95	21,83	8,46	11,48	16,08	0,00	46,74
25,00	28,50	10,07	13,43	21,04	0,00	44,35
31,50	29,41	8,68	12,30	18,41	0,00	38,14
40,00	30,40	8,24	11,86	18,80	0,00	39,70
50,00	31,33	8,51	12,98	19,78	0,00	35,60
63,00	30,67	7,13	12,34	19,55	0,00	32,91
80,00	30,26	7,86	13,83	20,88	0,00	31,12
100,00	26,13	8,09	15,00	21,12	0,00	26,55

Table A.11: Insertion loss values for 270 cm height barrier with different ceiling types

FREQUENCY	*270 cm Height Barrier Insertion Loss calculations*					
	Without Ceiling	NRC 0,02	NRC 0,36	NRC 0,55	Direct Sound (without Barrier and Without Ceiling)	Background Noise Level
2,00	17,20	5,75	9,94	9,56	0,00	41,57
2,51	17,17	11,86	12,14	14,38	0,00	42,72
3,16	17,20	9,76	10,07	12,93	0,00	41,89
3,98	14,88	11,89	10,79	15,23	0,00	42,38
5,01	21,14	14,06	15,14	19,72	0,00	47,26
6,31	13,98	8,42	12,52	13,09	0,00	43,44
8,00	17,00	12,50	13,47	15,73	0,00	44,15
10,00	14,88	11,67	12,44	14,40	0,00	45,61
12,50	16,23	12,89	14,94	16,58	0,00	38,11
16,00	18,49	15,15	16,36	18,32	0,00	44,97
19,95	19,51	15,39	16,97	19,16	0,00	47,09
25,00	23,50	16,94	20,66	23,77	0,00	45,77
31,50	24,97	17,11	19,93	25,68	0,00	44,21
40,00	27,07	21,50	24,89	27,50	0,00	42,32
50,00	26,76	22,21	25,64	28,20	0,00	40,08
63,00	29,43	24,44	27,99	29,86	0,00	36,00
80,00	30,44	25,41	29,97	31,25	0,00	36,42
100,00	17,59	17,36	17,50	17,62	0,00	17,92

Table A.12: Insertion loss values for No barrier situation with different ceiling types

FREQUENCY	*No Barrier Insertion Loss calculations*					
	Without Ceiling	NRC 0,02	NRC 0,36	NRC 0,55	Direct Sound (without Barrier and Without Ceiling)	Background Noise Level
2,00	0,00	1,04	0,82	0,26	0,00	-13,29
2,51	0,00	0,31	0	-0,1	0,00	-6,08
3,16	0,00	-2,41	-0,79	-2,21	0,00	0,96
3,98	0,00	0,88	0,7	1,49	0,00	7,77
5,01	0,00	-1,83	-2,78	0,45	0,00	5,23
6,31	0,00	-0,05	-0,08	-0,02	0,00	17,33
8,00	0,00	-1,51	-1	0,55	0,00	18,86
10,00	0,00	-0,63	-0,37	-1,21	0,00	25,84
12,50	0,00	-0,49	-0,4	0,13	0,00	25,65
16,00	0,00	-1,2	-0,4	0,16	0,00	22,99
19,95	0,00	-0,77	-0,07	0,15	0,00	21,67
25,00	0,00	-0,39	-0,61	0,12	0,00	19,79
31,50	0,00	-0,83	-0,37	0,27	0,00	20,61
40,00	0,00	-0,44	-0,27	0,18	0,00	19,98
50,00	0,00	-0,41	0,18	0,26	0,00	19,43
63,00	0,00	-0,48	0,07	0,06	0,00	20,12
80,00	0,00	-0,45	0,17	0,15	0,00	19,85
100,00	0,00	-0,33	0,12	0,22	0,00	19,74

After insertion loss values for six different heights of barriers with four different ceiling types are calculated. To calculate Articulation index values of all calculated insertion loss values of barrier height and ceiling absorption combinations. To calculate articulation index;

$$AI = \sum_{200}^{5000}[(\mathrm{S} - \mathrm{N} - \mathrm{IL}) + 12] \times \mathrm{W\ F}$$

where,

S= selected speech spectrum of source (for this study soft, normal or raised spectrums given above)

N= Selected background noise level (for this study soft, normal or raised spectrums given above)

IL= Insertion Loss values according to the performance measurements of barrier and ceiling types.

Table A.13: Articulation index calculation for 150 cm height barrier with different absorptive ceilings for different signal to noise levels.

150 CM HEIGHT BARRIER	FREQUENCY	SIGNAL: SPEECH SPECTRUM	SIGNAL: INSERTION LOSS	NOISE: BACKGROUND NOISE LEVEL	WEIGHTING FACTOR	(S-N+1)X WF	(S-N+7)X WF	(S-N+13)X WF	(S-N+6)X WF	(S-N+12)X WF	(S-N+18)X WF	(S-N+11)X WF	(S-N+17)X WF	(S-N+23)X WF
NO CEILING	2,00	50	4,98	43	0,0004	0,00121	0,00361	0,00601	0,00321	0,00561	0,00801	0,00521	0,00761	0,01001
NO CEILING	2,51	51	9,02	43	0,001	-0,00002	0,00598	0,01198	0,00498	0,01098	0,01698	0,00998	0,01598	0,02198
NO CEILING	3,16	52	5,74	42	0,001	0,00526	0,01126	0,01726	0,01026	0,01626	0,02226	0,01526	0,02126	0,02726
NO CEILING	3,98	53	3,66	41	0,0014	0,01308	0,02148	0,02988	0,02008	0,02848	0,03688	0,02708	0,03548	0,04388
NO CEILING	5,01	54	17,41	41	0,0014	-0,00477	0,00363	0,01203	0,00223	0,01063	0,01903	0,00923	0,01763	0,02603
NO CEILING	6,31	53	12,15	40	0,002	0,00370	0,01570	0,02770	0,01370	0,02570	0,03770	0,02370	0,03570	0,04770
NO CEILING	8,00	51	13,69	39	0,002	-0,00138	0,01062	0,02262	0,00862	0,02062	0,03262	0,01862	0,03062	0,04262
NO CEILING	10,00	48	15,65	38	0,0024	-0,01116	0,00324	0,01764	0,00084	0,01524	0,02964	0,01284	0,02724	0,04164
NO CEILING	12,50	47	12,14	36	0,003	-0,00042	0,01758	0,03558	0,01458	0,03258	0,05058	0,02958	0,04758	0,06558
NO CEILING	16,00	46	11,75	34	0,0037	0,00463	0,02683	0,04903	0,02313	0,04533	0,06753	0,04163	0,06383	0,08603
NO CEILING	19,95	44	18,97	32	0,0038	-0,02269	0,00011	0,02291	-0,00369	0,01911	0,04191	0,01531	0,03811	0,06091
NO CEILING	25,00	41	18,21	30	0,0034	-0,02111	-0,00071	0,01969	-0,00411	0,01629	0,03669	0,01289	0,03329	0,05369
NO CEILING	31,50	40	17,62	28	0,0034	-0,01571	0,00469	0,02509	0,00129	0,02169	0,04209	0,01829	0,03869	0,05909
NO CEILING	40,00	39	20,44	26	0,0024	-0,01546	-0,00106	0,01334	-0,00346	0,01094	0,02534	0,00854	0,02294	0,03734
NO CEILING	50,00	35	21,27	24	0,002	-0,01854	-0,00654	0,00546	-0,00854	0,00346	0,01546	0,00146	0,01346	0,02546
NO CEILING	ARTICULATION INDEX VALUES FOR 150 CM HEIGHT BARRIER WITH NO CEILING					0,027869	0,124721	0,316211	0,102907	0,282911	0,482711	0,249611	0,449411	0,649211
MDF CEILING	2,00	50	-1,72	43	0,0004	0,003888	0,006288	0,008688	0,005888	0,008288	0,010688	0,007888	0,010288	0,012688
MDF CEILING	2,51	51	6,30	43	0,001	0,0027	0,0087	0,0147	0,0077	0,0137	0,0197	0,0127	0,0187	0,0247
MDF CEILING	3,16	52	0,32	42	0,001	0,01068	0,01668	0,02268	0,01568	0,02168	0,02768	0,02068	0,02668	0,03268
MDF CEILING	3,98	53	0,81	41	0,0014	0,017066	0,025466	0,033866	0,024066	0,032466	0,040866	0,031066	0,039466	0,047866
MDF CEILING	5,01	54	6,46	41	0,0014	0,010556	0,018956	0,027356	0,017556	0,025956	0,034356	0,024556	0,032956	0,041356
MDF CEILING	6,31	53	0,67	40	0,002	0,02666	0,03866	0,05066	0,03666	0,04866	0,06066	0,04666	0,05866	0,07066
MDF CEILING	8,00	51	3,19	39	0,002	0,01962	0,03162	0,04362	0,02962	0,04162	0,05362	0,03962	0,05162	0,06362
MDF CEILING	10,00	48	3,72	38	0,0024	0,017472	0,031872	0,046272	0,029472	0,043872	0,058272	0,041472	0,055872	0,070272
MDF CEILING	12,50	47	5,61	36	0,003	0,01917	0,03717	0,05517	0,03417	0,05217	0,07017	0,04917	0,06717	0,08517
MDF CEILING	16,00	46	2,27	34	0,0037	0,039701	0,061901	0,084101	0,058201	0,080401	0,102601	0,076701	0,098901	0,121101
MDF CEILING	19,95	44	6,32	32	0,0038	0,025384	0,048184	0,070984	0,044384	0,067184	0,089984	0,063384	0,086184	0,108984
MDF CEILING	25,00	41	5,03	30	0,0034	0,023698	0,044098	0,064498	0,040698	0,061098	0,081498	0,057698	0,078098	0,098498
MDF CEILING	31,50	40	5,92	28	0,0034	0,024072	0,044472	0,064872	0,041072	0,061472	0,081872	0,058072	0,078472	0,098872
MDF CEILING	40,00	39	5,58	26	0,0024	0,020208	0,034608	0,049008	0,032208	0,046608	0,061008	0,044208	0,058608	0,073008
MDF CEILING	50,00	35	5,75	24	0,002	0,0125	0,0245	0,0365	0,0225	0,0345	0,0465	0,0325	0,0445	0,0565
MDF CEILING	ARTICULATION INDEX VALUES FOR 150 CM HEIGHT BARRIER WITH MDF CEILING					0,273375	0,473175	0,672975	0,439875	0,639675	0,839475	0,606375	0,806175	1,005975
FOAM PLASTIC ON MDF CEILING	2,00	50	1,59	43	0,0004	0,002564	0,004964	0,007364	0,004564	0,006964	0,009364	0,006564	0,008964	0,011364
FOAM PLASTIC ON MDF CEILING	2,51	51	3,4	43	0,001	0,0056	0,0116	0,0176	0,0106	0,0166	0,0226	0,0156	0,0216	0,0276
FOAM PLASTIC ON MDF CEILING	3,16	52	1,51	42	0,001	0,00949	0,01549	0,02149	0,01449	0,02049	0,02649	0,01949	0,02549	0,03149
FOAM PLASTIC ON MDF CEILING	3,98	53	3,46	41	0,0014	0,013356	0,021756	0,030156	0,020356	0,028756	0,037156	0,027356	0,035756	0,044156
FOAM PLASTIC ON MDF CEILING	5,01	54	9,11	41	0,0014	0,006846	0,015246	0,023646	0,013846	0,022246	0,030646	0,020846	0,029246	0,037646
FOAM PLASTIC ON MDF CEILING	6,31	53	2,98	40	0,002	0,02204	0,03404	0,04604	0,03204	0,04404	0,05604	0,04204	0,05404	0,06604
FOAM PLASTIC ON MDF CEILING	8,00	51	5,97	39	0,002	0,01406	0,02606	0,03806	0,02406	0,03606	0,04806	0,03406	0,04606	0,05806
FOAM PLASTIC ON MDF CEILING	10,00	48	7,82	38	0,0024	0,007632	0,022032	0,036432	0,019632	0,034032	0,048432	0,031632	0,046032	0,060432
FOAM PLASTIC ON MDF CEILING	12,50	47	8,75	36	0,003	0,00975	0,02775	0,04575	0,02475	0,04275	0,06075	0,03975	0,05775	0,07575
FOAM PLASTIC ON MDF CEILING	16,00	46	5,42	34	0,0037	0,028046	0,050246	0,072446	0,046546	0,068746	0,090946	0,065046	0,087246	0,109446
FOAM PLASTIC ON MDF CEILING	19,95	44	9,86	32	0,0038	0,011932	0,034732	0,057532	0,030932	0,053732	0,076532	0,049932	0,072732	0,095532
FOAM PLASTIC ON MDF CEILING	25,00	41	8,69	30	0,0034	0,011254	0,031654	0,052054	0,028254	0,048654	0,069054	0,045254	0,065654	0,086054
FOAM PLASTIC ON MDF CEILING	31,50	40	10,31	28	0,0034	0,009146	0,029546	0,049946	0,026146	0,046546	0,066946	0,043146	0,063546	0,083946
FOAM PLASTIC ON MDF CEILING	40,00	39	10,28	26	0,0024	0,008928	0,023328	0,037728	0,020928	0,035328	0,049728	0,032928	0,047328	0,061728
FOAM PLASTIC ON MDF CEILING	50,00	35	10,71	24	0,002	0,00258	0,01458	0,02658	0,01258	0,02458	0,03658	0,02258	0,03458	0,04658
FOAM PLASTIC ON MDF CEILING	ARTICULATION INDEX VALUES FOR 150 CM HEIGHT BARRIER WITH FOAM PLASTIC ON MDF CEILING					0,163224	0,363024	0,562824	0,329724	0,529524	0,729324	0,496224	0,696024	0,895824
WOOL ON MDF CEILING	2,00	50	1,34	43	0,0004	0,002664	0,005064	0,007464	0,004664	0,007064	0,009464	0,006664	0,009064	0,011464
WOOL ON MDF CEILING	2,51	51	6,51	43	0,001	0,00249	0,00849	0,01449	0,00749	0,01349	0,01949	0,01249	0,01849	0,02449
WOOL ON MDF CEILING	3,16	52	2,2	42	0,001	0,0088	0,0148	0,0208	0,0138	0,0198	0,0258	0,0188	0,0248	0,0308
WOOL ON MDF CEILING	3,98	53	4	41	0,0014	0,0126	0,021	0,0294	0,0196	0,028	0,0364	0,0266	0,035	0,0434
WOOL ON MDF CEILING	5,01	54	12,16	41	0,0014	0,002576	0,010976	0,019376	0,009576	0,017976	0,026376	0,016576	0,024976	0,033376
WOOL ON MDF CEILING	6,31	53	8,75	40	0,002	0,0105	0,0225	0,0345	0,0205	0,0325	0,0445	0,0305	0,0425	0,0545
WOOL ON MDF CEILING	8,00	51	11,33	39	0,002	0,00334	0,01534	0,02734	0,01334	0,02534	0,03734	0,02334	0,03534	0,04734
WOOL ON MDF CEILING	10,00	48	9,41	38	0,0024	0,003816	0,018216	0,032616	0,015816	0,030216	0,044616	0,027816	0,042216	0,056616
WOOL ON MDF CEILING	12,50	47	10,11	36	0,003	0,00567	0,02367	0,04167	0,02067	0,03867	0,05667	0,03567	0,05367	0,07167
WOOL ON MDF CEILING	16,00	46	8,88	34	0,0037	0,015244	0,037444	0,059644	0,033744	0,055944	0,078144	0,052244	0,074444	0,096644
WOOL ON MDF CEILING	19,95	44	12,23	32	0,0038	0,002926	0,025726	0,048526	0,021926	0,044726	0,067526	0,040926	0,063726	0,086526
WOOL ON MDF CEILING	25,00	41	13,06	30	0,0034	-0,0036	0,016796	0,037196	0,013396	0,033796	0,054196	0,030396	0,050796	0,071196
WOOL ON MDF CEILING	31,50	40	15,11	28	0,0034	-0,00717	0,013226	0,033626	0,009826	0,030226	0,050626	0,026826	0,047226	0,067626
WOOL ON MDF CEILING	40,00	39	15,47	26	0,0024	-0,00353	0,010872	0,025272	0,008472	0,022872	0,037272	0,020472	0,034872	0,049272
WOOL ON MDF CEILING	50,00	35	16,98	24	0,002	-0,00996	0,00204	0,01404	4E-05	0,01204	0,02404	0,01004	0,02204	0,03404
WOOL ON MDF CEILING	ARTICULATION INDEX VALUES FOR 150 CM HEIGHT BARRIER WITH WOOL ON MDF CEILING					0,070626	0,24616	0,44596	0,21286	0,41266	0,61246	0,37936	0,57916	0,77896

Table A.14: Articulation index calculation for 180 cm height barrier with different absorptive ceilings for different signal to noise levels.

		FREQUENCY	SIGNAL MALE SPEECH SPECTRUM	SIGNAL INSERTION LOSS	NOISE BACKGROUND NOISE LEVEL	WEIGHTING FACTOR	(S-N+1) X WF	(S-N+7)X WF	(S-N+13)X WF	(S-N+6)X WF	(S-N+12)X WF	(S-N+18)X WF	(S-N+11)X WF	(S-N+17)X WF	(S-N+23)X WF
180 CM HEIGHT BARRIER	NO CEILING	2,00	50	8,59	43	0,0004	-0,00024	0,002164	0,004564	0,001764	0,004164	0,006564	0,003764	0,006164	0,008564
		2,51	51	15,16	43	0,001	-0,00616	-0,00016	0,00584	-0,00116	0,00484	0,01084	0,00384	0,00984	0,01584
		3,16	52	15,63	42	0,001	-0,00463	0,00137	0,00737	0,00037	0,00637	0,01237	0,00537	0,01137	0,01737
		3,98	53	9,94	41	0,0014	0,004284	0,012684	0,021084	0,011284	0,019684	0,028084	0,018284	0,026684	0,035084
		5,01	54	16,79	41	0,0014	-0,00391	0,004494	0,012894	0,003094	0,011494	0,019894	0,010094	0,018494	0,026894
		6,31	53	18,01	40	0,002	-0,00802	0,00398	0,01598	0,00198	0,01398	0,02598	0,01198	0,02398	0,03598
		8,00	51	17,51	39	0,002	-0,00902	0,00298	0,01498	0,00098	0,01298	0,02498	0,01098	0,02298	0,03498
		10,00	48	14,29	38	0,0024	-0,0079	0,006504	0,020904	0,004104	0,018504	0,032904	0,016104	0,030504	0,044904
		12,50	47	15,45	36	0,003	-0,01035	0,00765	0,02565	0,00465	0,02265	0,04065	0,01965	0,03765	0,05565
		16,00	46	17,15	34	0,0037	-0,01536	0,006845	0,029045	0,003145	0,025345	0,047545	0,021645	0,043845	0,066045
		19,95	44	21,51	32	0,0038	-0,03234	-0,009538	0,013262	-0,01334	0,009462	0,032262	0,005662	0,028462	0,051262
		25,00	41	19,46	30	0,0034	-0,02536	-0,004964	0,015436	-0,00836	0,012036	0,032436	0,008636	0,029036	0,049436
		31,50	40	25,17	28	0,0034	-0,04138	-0,020978	-0,00058	-0,02438	-0,00398	0,016422	-0,00738	0,013022	0,033422
		40,00	39	25,66	26	0,0024	-0,02798	-0,013584	0,000816	-0,01598	-0,00158	0,012816	-0,00398	0,010416	0,024816
		50,00	35	27,82	24	0,002	-0,03164	-0,01964	-0,00764	-0,02164	-0,00964	0,00236	-0,01164	0,00036	0,01236
		TION INDEX VALUES FOR 180 CM HEIGHT BARRIER WITH N					**0,004284**	**0,048671**	**0,187825**	**0,031371**	**0,161509**	**0,346107**	**0,136009**	**0,312807**	**0,512607**
	MDF CEILING	2,00	50	-2,32	43	0,0004	0,004128	0,006528	0,008928	0,006128	0,008528	0,010928	0,008128	0,010528	0,012928
		2,51	51	5,76	43	0,001	0,00324	0,00924	0,01524	0,00824	0,01424	0,02024	0,01324	0,01924	0,02524
		3,16	52	5,83	42	0,001	0,00517	0,01117	0,01717	0,01017	0,01617	0,02217	0,01517	0,02117	0,02717
		3,98	53	0,69	41	0,0014	0,017234	0,025634	0,034034	0,024234	0,032634	0,041034	0,031234	0,039634	0,048034
		5,01	54	7,12	41	0,0014	0,009632	0,018032	0,026432	0,016632	0,025032	0,033432	0,023632	0,032032	0,040432
		6,31	53	5,5	40	0,002	0,017	0,029	0,041	0,027	0,039	0,051	0,037	0,049	0,061
		8,00	51	4,12	39	0,002	0,01776	0,02976	0,04176	0,02776	0,03976	0,05176	0,03776	0,04976	0,06176
		10,00	48	2,04	38	0,0024	0,021504	0,035904	0,050304	0,033504	0,047904	0,062304	0,045504	0,059904	0,074304
		12,50	47	4,19	36	0,003	0,02343	0,04143	0,05943	0,03843	0,05643	0,07443	0,05343	0,07143	0,08943
		16,00	46	6,16	34	0,0037	0,025308	0,047508	0,069708	0,043808	0,066008	0,088208	0,062308	0,084508	0,106708
		19,95	44	4,81	32	0,0038	0,031122	0,053922	0,076722	0,050122	0,072922	0,095722	0,069122	0,091922	0,114722
		25,00	41	8,85	30	0,0034	0,01071	0,03111	0,05151	0,02771	0,04811	0,06851	0,04471	0,06511	0,08551
		31,50	40	6,84	28	0,0034	0,020944	0,041344	0,061744	0,037944	0,058344	0,078744	0,054944	0,075344	0,095744
		40,00	39	6,76	26	0,0024	0,017376	0,031776	0,046176	0,029376	0,043776	0,058176	0,041376	0,055776	0,070176
		50,00	35	8,42	24	0,002	0,00716	0,01916	0,03116	0,01716	0,02916	0,04116	0,02716	0,03916	0,05116
		ION INDEX VALUES FOR 180 CM HEIGHT BARRIER WITH M					**0,231718**	**0,431518**	**0,631318**	**0,398218**	**0,598018**	**0,797818**	**0,564718**	**0,764518**	**0,964318**
	FOAM PLASTIC ON MDF CEILING	2,00	50	0,1	43	0,0004	0,00316	0,00556	0,00796	0,00516	0,00756	0,00996	0,00716	0,00956	0,01196
		2,51	51	7,62	43	0,001	0,00138	0,00738	0,01338	0,00638	0,01238	0,01838	0,01138	0,01738	0,02338
		3,16	52	5,08	42	0,001	0,00592	0,01192	0,01792	0,01092	0,01692	0,02292	0,01592	0,02192	0,02792
		3,98	53	2,89	41	0,0014	0,014154	0,022554	0,030954	0,021154	0,029554	0,037954	0,028154	0,036554	0,044954
		5,01	54	9,45	41	0,0014	0,00637	0,01477	0,02317	0,01337	0,02177	0,03017	0,02037	0,02877	0,03717
		6,31	53	6,07	40	0,002	0,01586	0,02786	0,03986	0,02586	0,03786	0,04986	0,03586	0,04786	0,05986
		8,00	51	7,89	39	0,002	0,01022	0,02222	0,03422	0,02022	0,03222	0,04422	0,03022	0,04222	0,05422
		10,00	48	3,34	38	0,0024	0,018384	0,032784	0,047184	0,030384	0,044784	0,059184	0,042384	0,056784	0,071184
		12,50	47	7,84	36	0,003	0,01248	0,03048	0,04848	0,02748	0,04548	0,06348	0,04248	0,06048	0,07848
		16,00	46	9,14	34	0,0037	0,014282	0,036482	0,058682	0,032782	0,054982	0,077182	0,051282	0,073482	0,095682
		19,95	44	8,61	32	0,0038	0,016682	0,039482	0,062282	0,035682	0,058482	0,081282	0,054682	0,077482	0,100282
		25,00	41	12,05	30	0,0034	-0,00017	0,02023	0,04063	0,01683	0,03723	0,05763	0,03383	0,05423	0,07463
		31,50	40	10,35	28	0,0034	0,00901	0,02941	0,04981	0,02601	0,04641	0,06681	0,04301	0,06341	0,08381
		40,00	39	11,31	26	0,0024	0,006456	0,020856	0,035256	0,018456	0,032856	0,047256	0,030456	0,044856	0,059256
		50,00	35	13,61	24	0,002	-0,00322	0,00878	0,02078	0,00678	0,01878	0,03078	0,01678	0,02878	0,04078
		X VALUES FOR 180 CM HEIGHT BARRIER WITH FOAM PLAS					**0,134358**	**0,330768**	**0,530568**	**0,297468**	**0,497268**	**0,697068**	**0,463968**	**0,663768**	**0,863568**
	WOOL ON MDF CEILING	2,00	50	-1,67	43	0,0004	0,003868	0,006268	0,008668	0,005868	0,008268	0,010668	0,007868	0,010268	0,012668
		2,51	51	7,5	43	0,001	0,0015	0,0075	0,0135	0,0065	0,0125	0,0185	0,0115	0,0175	0,0235
		3,16	52	9,42	42	0,001	0,00158	0,00758	0,01358	0,00658	0,01258	0,01858	0,01158	0,01758	0,02358
		3,98	53	4,89	41	0,0014	0,011354	0,019754	0,028154	0,018354	0,026754	0,035154	0,025354	0,033754	0,042154
		5,01	54	11,93	41	0,0014	0,002898	0,011298	0,019698	0,009898	0,018298	0,026698	0,016898	0,025298	0,033698
		6,31	53	11,8	40	0,002	0,0044	0,0164	0,0284	0,0144	0,0264	0,0384	0,0244	0,0364	0,0484
		8,00	51	10,26	39	0,002	0,00548	0,01748	0,02948	0,01548	0,02748	0,03948	0,02548	0,03748	0,04948
		10,00	48	7,7	38	0,0024	0,00792	0,02232	0,03672	0,01992	0,03432	0,04872	0,03192	0,04632	0,06072
		12,50	47	9,59	36	0,003	0,00723	0,02523	0,04323	0,02223	0,04023	0,05823	0,03723	0,05523	0,07323
		16,00	46	13,98	34	0,0037	-0,00363	0,018574	0,040774	0,014874	0,037074	0,059274	0,033374	0,055574	0,077774
		19,95	44	12,02	32	0,0038	0,003724	0,026524	0,049324	0,022724	0,045524	0,068324	0,041724	0,064524	0,087324
		25,00	41	16,79	30	0,0034	-0,01629	0,004114	0,024514	0,000714	0,021114	0,041514	0,017714	0,038114	0,058514
		31,50	40	15,76	28	0,0034	-0,00938	0,011016	0,031416	0,007616	0,028016	0,048416	0,024616	0,045016	0,065416
		40,00	39	17,12	26	0,0024	-0,00749	0,006912	0,021312	0,004512	0,018912	0,033312	0,016512	0,030912	0,045312
		50,00	35	19,74	24	0,002	-0,01548	-0,00348	0,00852	-0,00548	0,00652	0,01852	0,00452	0,01652	0,02852
		NDEX VALUES FOR 180 CM HEIGHT BARRIER WITH WOOL					**0,049954**	**0,20097**	**0,39729**	**0,16967**	**0,36399**	**0,56379**	**0,33069**	**0,53049**	**0,73029**

Table A.15: Articulation index calculation for 210 cm height barrier with different absorptive ceilings for different signal to noise levels.

		FREQUENCY	SIGNAL: MALE SPEECH SPECTRUM	SIGNAL: INSERTION LOSS	NOISE: BACKGROUND NOISE LEVEL	WEIGHTING FACTOR	(S-N+1) X WF	(S-N+7)X WF	(S-N+13)X WF	(S-N+6)X WF	(S-N+12)X WF	(S-N+18)X WF	(S-N+11)X WF	(S-N+17)X WF	(S-N+23)X WF
210 CM HEIGHT BARRIER	NO CEILING	2,00	50	6,56	43	0,0004	0,000576	0,002976	0,005376	0,002576	0,004976	0,007376	0,004576	0,006976	0,009376
		2,51	51	14,77	43	0,001	-0,00577	0,00023	0,00623	-0,00077	0,00523	0,01123	0,00423	0,01023	0,01623
		3,16	52	14,41	42	0,001	-0,00341	0,00259	0,00859	0,00159	0,00759	0,01359	0,00659	0,01259	0,01859
		3,98	53	14,3	41	0,0014	-0,00182	0,00658	0,01498	0,00518	0,01358	0,02198	0,01218	0,02058	0,02898
		5,01	54	17,48	41	0,0014	-0,00487	0,003528	0,011928	0,002128	0,010528	0,018928	0,009128	0,017528	0,025928
		6,31	53	17,47	40	0,002	-0,00694	0,00506	0,01706	0,00306	0,01506	0,02706	0,01306	0,02506	0,03706
		8,00	51	16,99	39	0,002	-0,00798	0,00402	0,01602	0,00202	0,01402	0,02602	0,01202	0,02402	0,03602
		10,00	48	17,92	38	0,0024	-0,01661	-0,002208	0,012192	-0,00461	0,009792	0,024192	0,007392	0,021792	0,036192
		12,50	47	17,69	36	0,003	-0,01707	0,00093	0,01893	-0,00207	0,01593	0,03393	0,01293	0,03093	0,04893
		16,00	46	18,73	34	0,0037	-0,0212	0,000999	0,023199	-0,0027	0,019499	0,041699	0,015799	0,037999	0,060199
		19,95	44	23,86	32	0,0038	-0,04127	-0,018468	0,004332	-0,02227	0,000532	0,023332	-0,00327	0,019532	0,042332
		25,00	41	24,28	30	0,0034	-0,04175	-0,021352	-0,00095	-0,02475	-0,00435	0,016048	-0,00775	0,012648	0,033048
		31,50	40	27,2	28	0,0034	-0,04828	-0,02788	-0,00748	-0,03128	-0,01088	0,00952	-0,01428	0,00612	0,02652
		40,00	39	28,96	26	0,0024	-0,0359	-0,021504	-0,0071	-0,0239	-0,0095	0,004896	-0,0119	0,002496	0,016896
		50,00	35	29,43	24	0,002	-0,03486	-0,02286	-0,01086	-0,02486	-0,01286	-0,00086	-0,01486	-0,00286	0,00914
		TION INDEX VALUES FOR 210 CM HEIGHT BARRIER WITH N					0,000576	0,026913	0,138837	0,016554	0,116737	0,279801	0,097905	0,248501	0,445441
	MDF CEILING	2,00	50	0,53	43	0,0004	0,002988	0,005388	0,007788	0,004988	0,007388	0,009788	0,006988	0,009388	0,011788
		2,51	51	7,1	43	0,001	0,0019	0,0079	0,0139	0,0069	0,0129	0,0189	0,0119	0,0179	0,0239
		3,16	52	2,99	42	0,001	0,00801	0,01401	0,02001	0,01301	0,01901	0,02501	0,01801	0,02401	0,03001
		3,98	53	3,47	41	0,0014	0,013342	0,021742	0,030142	0,020342	0,028742	0,037142	0,027342	0,035742	0,044142
		5,01	54	8,34	41	0,0014	0,007924	0,016324	0,024724	0,014924	0,023324	0,031724	0,021924	0,030324	0,038724
		6,31	53	6,3	40	0,002	0,0154	0,0274	0,0394	0,0254	0,0374	0,0494	0,0354	0,0474	0,0594
		8,00	51	3,96	39	0,002	0,01808	0,03008	0,04208	0,02808	0,04008	0,05208	0,03808	0,05008	0,06208
		10,00	48	3,27	38	0,0024	0,018552	0,032952	0,047352	0,030552	0,044952	0,059352	0,042552	0,056952	0,071352
		12,50	47	5,25	36	0,003	0,02025	0,03825	0,05625	0,03525	0,05325	0,07125	0,05025	0,06825	0,08625
		16,00	46	6,92	34	0,0037	0,022496	0,044696	0,066896	0,040996	0,063196	0,085396	0,059496	0,081696	0,103896
		19,95	44	5,37	32	0,0038	0,028994	0,051794	0,074594	0,047994	0,070794	0,093594	0,066994	0,089794	0,112594
		25,00	41	8,43	30	0,0034	0,012138	0,032538	0,052938	0,029138	0,049538	0,069938	0,046138	0,066538	0,086938
		31,50	40	5,88	28	0,0034	0,024208	0,044608	0,065008	0,041208	0,061608	0,082008	0,058208	0,078608	0,099008
		40,00	39	7,28	26	0,0024	0,016128	0,030528	0,044928	0,028128	0,042528	0,056928	0,040128	0,054528	0,068928
		50,00	35	8,62	24	0,002	0,00676	0,01876	0,03076	0,01676	0,02876	0,04076	0,02676	0,03876	0,05076
		ION INDEX VALUES FOR 210 CM HEIGHT BARRIER WITH M					0,21717	0,41697	0,61677	0,38367	0,58347	0,78327	0,55017	0,74997	0,94977
	FOAM PLASTIC ON MDF CEILING	2,00	50	1,34	43	0,0004	0,002664	0,005064	0,007464	0,004664	0,007064	0,009464	0,006664	0,009064	0,011464
		2,51	51	4,5	43	0,001	0,0045	0,0105	0,0165	0,0095	0,0155	0,0215	0,0145	0,0205	0,0265
		3,16	52	4,01	42	0,001	0,00699	0,01299	0,01899	0,01199	0,01799	0,02399	0,01699	0,02299	0,02899
		3,98	53	9,78	41	0,0014	0,004508	0,012908	0,021308	0,011508	0,019908	0,028308	0,018508	0,026908	0,035308
		5,01	54	9,08	41	0,0014	0,006888	0,015288	0,023688	0,013888	0,022288	0,030688	0,020888	0,029288	0,037688
		6,31	53	7,28	40	0,002	0,01344	0,02544	0,03744	0,02344	0,03544	0,04744	0,03344	0,04544	0,05744
		8,00	51	9,52	39	0,002	0,00696	0,01896	0,03096	0,01696	0,02896	0,04096	0,02696	0,03896	0,05096
		10,00	48	4,51	38	0,0024	0,015576	0,029976	0,044376	0,027576	0,041976	0,056376	0,039576	0,053976	0,068376
		12,50	47	8,03	36	0,003	0,01191	0,02991	0,04791	0,02691	0,04491	0,06291	0,04191	0,05991	0,07791
		16,00	46	9,55	34	0,0037	0,012765	0,034965	0,057165	0,031265	0,053465	0,075665	0,049765	0,071965	0,094165
		19,95	44	8,7	32	0,0038	0,01634	0,03914	0,06194	0,03534	0,05814	0,08094	0,05434	0,07714	0,09994
		25,00	41	12,23	30	0,0034	-0,00078	0,019618	0,040018	0,016218	0,036618	0,057018	0,033218	0,053618	0,074018
		31,50	40	10,23	28	0,0034	0,009418	0,029818	0,050218	0,026418	0,046818	0,067218	0,043418	0,063818	0,084218
		40,00	39	11,74	26	0,0024	0,005424	0,019824	0,034224	0,017424	0,031824	0,046224	0,029424	0,043824	0,058224
		50,00	35	13,59	24	0,002	-0,00318	0,00882	0,02082	0,00682	0,01882	0,03082	0,01682	0,02882	0,04082
		X VALUES FOR 210 CM HEIGHT BARRIER WITH FOAM PLAS					0,117383	0,313221	0,513021	0,279921	0,479721	0,679521	0,446421	0,646221	0,846021
	WOOL ON MDF CEILING	2,00	50	1,9	43	0,0004	0,00244	0,00484	0,00724	0,00444	0,00684	0,00924	0,00644	0,00884	0,01124
		2,51	51	7,48	43	0,001	0,00152	0,00752	0,01352	0,00652	0,01252	0,01852	0,01152	0,01752	0,02352
		3,16	52	6,43	42	0,001	0,00457	0,01057	0,01657	0,00957	0,01557	0,02157	0,01457	0,02057	0,02657
		3,98	53	11,93	41	0,0014	0,001498	0,009898	0,018298	0,008498	0,016898	0,025298	0,015498	0,023898	0,032298
		5,01	54	14,57	41	0,0014	-0,0008	0,007602	0,016002	0,006202	0,014602	0,023002	0,013202	0,021602	0,030002
		6,31	53	12,24	40	0,002	0,00352	0,01552	0,02752	0,01352	0,02552	0,03752	0,02352	0,03552	0,04752
		8,00	51	10,76	39	0,002	0,00448	0,01648	0,02848	0,01448	0,02648	0,03848	0,02448	0,03648	0,04848
		10,00	48	10,14	38	0,0024	0,002064	0,016464	0,030864	0,014064	0,028464	0,042864	0,026064	0,040464	0,054864
		12,50	47	11,63	36	0,003	0,00111	0,01911	0,03711	0,01611	0,03411	0,05211	0,03111	0,04911	0,06711
		16,00	46	14,69	34	0,0037	-0,00625	0,015947	0,038147	0,012247	0,034447	0,056647	0,030747	0,052947	0,075147
		19,95	44	13,42	32	0,0038	-0,0016	0,021204	0,044004	0,017404	0,040204	0,063004	0,036404	0,059204	0,082004
		25,00	41	17,74	30	0,0034	-0,01952	0,000884	0,021284	-0,00252	0,017884	0,038284	0,014484	0,034884	0,055284
		31,50	40	16,02	28	0,0034	-0,01027	0,010132	0,030532	0,006732	0,027132	0,047532	0,023732	0,044132	0,064532
		40,00	39	17,62	26	0,0024	-0,00869	0,005712	0,020112	0,003312	0,017712	0,032112	0,015312	0,029712	0,044112
		50,00	35	19,94	24	0,002	-0,01588	-0,00388	0,00812	-0,00588	0,00612	0,01812	0,00412	0,01612	0,02812
		NDEX VALUES FOR 210 CM HEIGHT BARRIER WITH WOOL (					0,021202	0,161883	0,357803	0,133099	0,324503	0,524303	0,291203	0,491003	0,690803

Table A.16: Articulation index calculation for 240 cm height barrier with different absorptive ceilings for different signal to noise levels.

		FREQUENCY	SIGNAL: MALE SPEECH SPECTRUM	SIGNAL: INSERTION LOSS	NOISE: BACKGROUND NOISE LEVEL	WEIGHTING FACTOR	(S-N+1) X WF	(S-N+7)X WF	(S-N+13)X WF	(S-N+6)X WF	(S-N+12)X WF	(S-N+18)X WF	(S-N+11)X WF	(S-N+17)X WF	(S-N+23)X WF
240 CM HEIGHT BARRIER	NO CEILING	2,00	50	10,65	43	0,0004	-0,00106	0,00134	0,00374	0,00094	0,00334	0,00574	0,00294	0,00534	0,00774
		2,51	51	18,57	43	0,001	-0,00957	-0,00357	0,00243	-0,00457	0,00143	0,00743	0,00043	0,00643	0,01243
		3,16	52	20,98	42	0,001	-0,00998	-0,00398	0,00202	-0,00498	0,00102	0,00702	2E-05	0,00602	0,01202
		3,98	53	16,8	41	0,0014	-0,00532	0,00308	0,01148	0,00168	0,01008	0,01848	0,00868	0,01708	0,02548
		5,01	54	19,61	41	0,0014	-0,00785	0,000546	0,008946	-0,00085	0,007546	0,015946	0,006146	0,014546	0,022946
		6,31	53	17,63	40	0,002	-0,00726	0,00474	0,01674	0,00274	0,01474	0,02674	0,01274	0,02474	0,03674
		8,00	51	20,06	39	0,002	-0,01412	-0,00212	0,00988	-0,00412	0,00788	0,01988	0,00588	0,01788	0,02988
		10,00	48	19,58	38	0,0024	-0,02059	-0,006192	0,008208	-0,00859	0,005808	0,020208	0,003408	0,017808	0,032208
		12,50	47	16,82	36	0,003	-0,01446	0,00354	0,02154	0,00054	0,01854	0,03654	0,01554	0,03354	0,05154
		16,00	46	19,23	34	0,0037	-0,02305	-0,000851	0,021349	-0,00455	0,017649	0,039849	0,013949	0,036149	0,058349
		19,95	44	21,83	32	0,0038	-0,03355	-0,010754	0,012046	-0,01455	0,008246	0,031046	0,004446	0,027246	0,050046
		25,00	41	28,5	30	0,0034	-0,0561	-0,0357	-0,0153	-0,0391	-0,0187	0,0017	-0,0221	-0,0017	0,0187
		31,50	40	29,41	28	0,0034	-0,05579	-0,035394	-0,01499	-0,03879	-0,01839	0,002006	-0,02179	-0,00139	0,019006
		40,00	39	30,4	26	0,0024	-0,03936	-0,02496	-0,01056	-0,02736	-0,01296	0,00144	-0,01536	-0,00096	0,01344
		50,00	35	31,33	24	0,002	-0,03866	-0,02666	-0,01466	-0,02866	-0,01666	-0,00466	-0,01866	-0,00666	0,00534
		TION INDEX VALUES FOR 240 CM HEIGHT BARRIER WITH N					**0**	**0,013246**	**0,118379**	**0,0059**	**0,096279**	**0,234025**	**0,074179**	**0,206779**	**0,395865**
	MDF CEILING	2,00	50	6,37	43	0,0004	0,000652	0,003052	0,005452	0,002652	0,005052	0,007452	0,004652	0,007052	0,009452
		2,51	51	10,22	43	0,001	-0,00122	0,00478	0,01078	0,00378	0,00978	0,01578	0,00878	0,01478	0,02078
		3,16	52	6,53	42	0,001	0,00447	0,01047	0,01647	0,00947	0,01547	0,02147	0,01447	0,02047	0,02647
		3,98	53	4,92	41	0,0014	0,011312	0,019712	0,028112	0,018312	0,026712	0,035112	0,025312	0,033712	0,042112
		5,01	54	8,89	41	0,0014	0,007154	0,015554	0,023954	0,014154	0,022554	0,030954	0,021154	0,029554	0,037954
		6,31	53	7,04	40	0,002	0,01392	0,02592	0,03792	0,02392	0,03592	0,04792	0,03392	0,04592	0,05792
		8,00	51	7,6	39	0,002	0,0108	0,0228	0,0348	0,0208	0,0328	0,0448	0,0308	0,0428	0,0548
		10,00	48	5,91	38	0,0024	0,012216	0,026616	0,041016	0,024216	0,038616	0,053016	0,036216	0,050616	0,065016
		12,50	47	6,89	36	0,003	0,01533	0,03333	0,05133	0,03033	0,04833	0,06633	0,04533	0,06333	0,08133
		16,00	46	9,35	34	0,0037	0,013505	0,035705	0,057905	0,032005	0,054205	0,076405	0,050505	0,072705	0,094905
		19,95	44	8,46	32	0,0038	0,017252	0,040052	0,062852	0,036252	0,059052	0,081852	0,055252	0,078052	0,100852
		25,00	41	10,07	30	0,0034	0,006562	0,026962	0,047362	0,023562	0,043962	0,064362	0,040562	0,060962	0,081362
		31,50	40	8,68	28	0,0034	0,014688	0,035088	0,055488	0,031688	0,052088	0,072488	0,048688	0,069088	0,089488
		40,00	39	8,24	26	0,0024	0,013824	0,028224	0,042624	0,025824	0,040224	0,054624	0,037824	0,052224	0,066624
		50,00	35	8,51	24	0,002	0,00698	0,01898	0,03098	0,01698	0,02898	0,04098	0,02698	0,03898	0,05098
		TION INDEX VALUES FOR 240 CM HEIGHT BARRIER WITH M					**0,147445**	**0,347245**	**0,547045**	**0,313945**	**0,513745**	**0,713545**	**0,480445**	**0,680245**	**0,880045**
	FOAM PLASTIC ON MDF CEILING	2,00	50	7,18	43	0,0004	0,000328	0,002728	0,005128	0,002328	0,004728	0,007128	0,004328	0,006728	0,009128
		2,51	51	8,57	43	0,001	0,00043	0,00643	0,01243	0,00543	0,01143	0,01743	0,01043	0,01643	0,02243
		3,16	52	5,91	42	0,001	0,00509	0,01109	0,01709	0,01009	0,01609	0,02209	0,01509	0,02109	0,02709
		3,98	53	8,96	41	0,0014	0,005656	0,014056	0,022456	0,012656	0,021056	0,029456	0,019656	0,028056	0,036456
		5,01	54	12,47	41	0,0014	0,002142	0,010542	0,018942	0,009142	0,017542	0,025942	0,016142	0,024542	0,032942
		6,31	53	8,29	40	0,002	0,01142	0,02342	0,03542	0,02142	0,03342	0,04542	0,03142	0,04342	0,05542
		8,00	51	11,6	39	0,002	0,0028	0,0148	0,0268	0,0128	0,0248	0,0368	0,0228	0,0348	0,0468
		10,00	48	5,95	38	0,0024	0,01212	0,02652	0,04092	0,02412	0,03852	0,05292	0,03612	0,05052	0,06492
		12,50	47	10,24	36	0,003	0,00528	0,02328	0,04128	0,02028	0,03828	0,05628	0,03528	0,05328	0,07128
		16,00	46	10,45	34	0,0037	0,009435	0,031635	0,053835	0,027935	0,050135	0,072335	0,046435	0,068635	0,090835
		19,95	44	11,48	32	0,0038	0,005776	0,028576	0,051376	0,024776	0,047576	0,070376	0,043776	0,066576	0,089376
		25,00	41	13,43	30	0,0034	-0,00486	0,015538	0,035938	0,012138	0,032538	0,052938	0,029138	0,049538	0,069938
		31,50	40	12,3	28	0,0034	0,00238	0,02278	0,04318	0,01938	0,03978	0,06018	0,03638	0,05678	0,07718
		40,00	39	11,86	26	0,0024	0,005136	0,019536	0,033936	0,017136	0,031536	0,045936	0,029136	0,043536	0,057936
		50,00	35	12,98	24	0,002	-0,00196	0,01004	0,02204	0,00804	0,02004	0,03204	0,01804	0,03004	0,04204
		X VALUES FOR 240 CM HEIGHT BARRIER WITH FOAM PLAS					**0,067993**	**0,260971**	**0,460771**	**0,227671**	**0,427471**	**0,627271**	**0,394171**	**0,593971**	**0,793771**
	WOOL ON MDF CEILING	2,00	50	8,51	43	0,0004	-0,0002	0,002196	0,004596	0,001796	0,004196	0,006596	0,003796	0,006196	0,008596
		2,51	51	12,73	43	0,001	-0,00373	0,00227	0,00827	0,00127	0,00727	0,01327	0,00627	0,01227	0,01827
		3,16	52	11,61	42	0,001	-0,00061	0,00539	0,01139	0,00439	0,01039	0,01639	0,00939	0,01539	0,02139
		3,98	53	11,01	41	0,0014	0,002786	0,011186	0,019586	0,009786	0,018186	0,026586	0,016786	0,025186	0,033586
		5,01	54	16,47	41	0,0014	-0,00346	0,004942	0,013342	0,003542	0,011942	0,020342	0,010542	0,018942	0,027342
		6,31	53	13,78	40	0,002	0,00044	0,01244	0,02444	0,01044	0,02244	0,03444	0,02044	0,03244	0,04444
		8,00	51	13,78	39	0,002	-0,00156	0,01044	0,02244	0,00844	0,02044	0,03244	0,01844	0,03044	0,04244
		10,00	48	11,8	38	0,0024	-0,00192	0,01248	0,02688	0,01008	0,02448	0,03888	0,02208	0,03648	0,05088
		12,50	47	14,75	36	0,003	-0,00825	0,00975	0,02775	0,00675	0,02475	0,04275	0,02175	0,03975	0,05775
		16,00	46	15,62	34	0,0037	-0,00969	0,012506	0,034706	0,008806	0,031006	0,053206	0,027306	0,049506	0,071706
		19,95	44	16,08	32	0,0038	-0,0117	0,011096	0,033896	0,007296	0,030096	0,052896	0,026296	0,049096	0,071896
		25,00	41	21,04	30	0,0034	-0,03074	-0,010336	0,010064	-0,01374	0,006664	0,027064	0,003264	0,023664	0,044064
		31,50	40	18,41	28	0,0034	-0,01839	0,002006	0,022406	-0,00139	0,019006	0,039406	0,015606	0,036006	0,056406
		40,00	39	18,8	26	0,0024	-0,01152	0,00288	0,01728	0,00048	0,01488	0,02928	0,01248	0,02688	0,04128
		50,00	35	19,78	24	0,002	-0,01556	-0,00356	0,00844	-0,00556	0,00644	0,01844	0,00444	0,01644	0,02844
		NDEX VALUES FOR 240 CM HEIGHT BARRIER WITH WOOL (					**0,003226**	**0,099582**	**0,285486**	**0,073076**	**0,252186**	**0,451986**	**0,218886**	**0,418686**	**0,618486**

Table A.17: Articulation index calculation for 270 cm height barrier with different absorptive ceilings for different signal to noise levels.

		FREQUENCY	SIGNAL: MALE SPEECH SPECTRUM	SIGNAL: INSERTION LOSS	NOISE: BACKGROUND NOISE LEVEL	WEIGHTING FACTOR	(S-N+1) X WF	(S-N+7)X WF	(S-N+13)X WF	(S-N+6)X WF	(S-N+12)X WF	(S-N+18)X WF	(S-N+11)X WF	(S-N+17)X WF	(S-N+23)X WF
270 CM HEIGHT BARRIER	NO CEILING	2,00	50	17,2	43	0,0004	-0,00368	-0,00128	0,00112	-0,00168	0,00072	0,00312	0,00032	0,00272	0,00512
		2,51	51	17,17	43	0,001	-0,00817	-0,00217	0,00383	-0,00317	0,00283	0,00883	0,00183	0,00783	0,01383
		3,16	52	17,2	42	0,001	-0,0062	-0,0002	0,0058	-0,0012	0,0048	0,0108	0,0038	0,0098	0,0158
		3,98	53	14,88	41	0,0014	-0,00263	0,005768	0,014168	0,004368	0,012768	0,021168	0,011368	0,019768	0,028168
		5,01	54	21,14	41	0,0014	-0,01	-0,001596	0,006804	-0,003	0,005404	0,013804	0,004004	0,012404	0,020804
		6,31	53	13,98	40	0,002	4E-05	0,01204	0,02404	0,01004	0,02204	0,03404	0,02004	0,03204	0,04404
		8,00	51	17,00	39	0,002	-0,008	0,004	0,016	0,002	0,014	0,026	0,012	0,024	0,036
		10,00	48	14,88	38	0,0024	-0,00931	0,005088	0,019488	0,002688	0,017088	0,031488	0,014688	0,029088	0,043488
		12,50	47	16,23	36	0,003	-0,01269	0,00531	0,02331	0,00231	0,02031	0,03831	0,01731	0,03531	0,05331
		16,00	46	18,49	34	0,0037	-0,02031	0,001887	0,024087	-0,00181	0,020387	0,042587	0,016687	0,038887	0,061087
		19,95	44	19,51	32	0,0038	-0,02474	-0,001938	0,020862	-0,00574	0,017062	0,039862	0,013262	0,036062	0,058862
		25,00	41	23,50	30	0,0034	-0,0391	-0,0187	0,0017	-0,0221	-0,0017	0,0187	-0,0051	0,0153	0,0357
		31,50	40	24,97	28	0,0034	-0,0407	-0,020298	0,000102	-0,0237	-0,0033	0,017102	-0,0067	0,013702	0,034102
		40,00	39	27,07	26	0,0024	-0,03137	-0,016968	-0,00257	-0,01937	-0,00497	0,009432	-0,00737	0,007032	0,021432
		50,00	35	26,76	24	0,002	-0,02952	-0,01752	-0,00552	-0,01952	-0,00752	0,00448	-0,00952	0,00248	0,01448
		ICULATION INDEX VALUES FOR NO BARRIER WITH NO CEI					**0**	**0,034093**	**0,161311**	**0,021406**	**0,137409**	**0,319723**	**0,115309**	**0,286423**	**0,486223**
	MDF CEILING	2,00	50	5,75	43	0,0004	0,0009	0,0033	0,0057	0,0029	0,0053	0,0077	0,0049	0,0073	0,0097
		2,51	51	11,86	43	0,001	-0,00286	0,00314	0,00914	0,00214	0,00814	0,01414	0,00714	0,01314	0,01914
		3,16	52	9,76	42	0,001	0,00124	0,00724	0,01324	0,00624	0,01224	0,01824	0,01124	0,01724	0,02324
		3,98	53	11,89	41	0,0014	0,001554	0,009954	0,018354	0,008554	0,016954	0,025354	0,015554	0,023954	0,032354
		5,01	54	14,06	41	0,0014	-8,4E-05	0,008316	0,016716	0,006916	0,015316	0,023716	0,013916	0,022316	0,030716
		6,31	53	8,42	40	0,002	0,01116	0,02316	0,03516	0,02116	0,03316	0,04516	0,03116	0,04316	0,05516
		8,00	51	12,5	39	0,002	0,001	0,013	0,025	0,011	0,023	0,035	0,021	0,033	0,045
		10,00	48	11,67	38	0,0024	-0,00161	0,012792	0,027192	0,010392	0,024792	0,039192	0,022392	0,036792	0,051192
		12,50	47	12,89	36	0,003	-0,00267	0,01533	0,03333	0,01233	0,03033	0,04833	0,02733	0,04533	0,06333
		16,00	46	15,15	34	0,0037	-0,00796	0,014245	0,036445	0,010545	0,032745	0,054945	0,029045	0,051245	0,073445
		19,95	44	15,39	32	0,0038	-0,00908	0,013718	0,036518	0,009918	0,032718	0,055518	0,028918	0,051718	0,074518
		25,00	41	16,94	30	0,0034	-0,0168	0,003604	0,024004	0,000204	0,020604	0,041004	0,017204	0,037604	0,058004
		31,50	40	17,11	28	0,0034	-0,01397	0,006426	0,026826	0,003026	0,023426	0,043826	0,020026	0,040426	0,060826
		40,00	39	21,5	26	0,0024	-0,018	-0,0036	0,0108	-0,006	0,0084	0,0228	0,006	0,0204	0,0348
		50,00	35	22,21	24	0,002	-0,02042	-0,00842	0,00358	-0,01042	0,00158	0,01358	-0,00042	0,01158	0,02358
		CULATION INDEX VALUES FOR NO BARRIER WITH MDF CE					**0,015854**	**0,134225**	**0,322005**	**0,105325**	**0,288705**	**0,488505**	**0,255825**	**0,455205**	**0,655005**
	FOAM PLASTIC ON MDF CEILING	2,00	50	9,94	43	0,0004	-0,00078	0,001624	0,004024	0,001224	0,003624	0,006024	0,003224	0,005624	0,008024
		2,51	51	12,14	43	0,001	-0,00314	0,00286	0,00886	0,00186	0,00786	0,01386	0,00686	0,01286	0,01886
		3,16	52	10,07	42	0,001	0,00093	0,00693	0,01293	0,00593	0,01193	0,01793	0,01093	0,01693	0,02293
		3,98	53	10,79	41	0,0014	0,003094	0,011494	0,019894	0,010094	0,018494	0,026894	0,017094	0,025494	0,033894
		5,01	54	15,14	41	0,0014	-0,0016	0,006804	0,015204	0,005404	0,013804	0,022204	0,012404	0,020804	0,029204
		6,31	53	12,52	40	0,002	0,00296	0,01496	0,02696	0,01296	0,02496	0,03696	0,02296	0,03496	0,04696
		8,00	51	13,47	39	0,002	-0,00094	0,01106	0,02306	0,00906	0,02106	0,03306	0,01906	0,03106	0,04306
		10,00	48	12,44	38	0,0024	-0,00346	0,010944	0,025344	0,008544	0,022944	0,037344	0,020544	0,034944	0,049344
		12,50	47	14,94	36	0,003	-0,00882	0,00918	0,02718	0,00618	0,02418	0,04218	0,02118	0,03918	0,05718
		16,00	46	16,36	34	0,0037	-0,01243	0,009768	0,031968	0,006068	0,028268	0,050468	0,024568	0,046768	0,068968
		19,95	44	16,97	32	0,0038	-0,01509	0,007714	0,030514	0,003914	0,026714	0,049514	0,022914	0,045714	0,068514
		25,00	41	20,66	30	0,0034	-0,02944	-0,009044	0,011356	-0,01244	0,007956	0,028356	0,004556	0,024956	0,045356
		31,50	40	19,93	28	0,0034	-0,02356	-0,003162	0,017238	-0,00656	0,013838	0,034238	0,010438	0,030838	0,051238
		40,00	39	24,89	26	0,0024	-0,02614	-0,011736	0,002664	-0,01414	0,000264	0,014664	-0,00214	0,012264	0,026664
		50,00	35	25,64	24	0,002	-0,02728	-0,01528	-0,00328	-0,01728	-0,00528	0,00672	-0,00728	0,00472	0,01672
		N INDEX VALUES FOR NO BARRIER WITH FOAM PLASTIC O					**0,006984**	**0,093338**	**0,257196**	**0,071238**	**0,225896**	**0,420416**	**0,196732**	**0,387116**	**0,586916**
	WOOL ON MDF CEILING	2,00	50	9,56	43	0,0004	-0,00062	0,001776	0,004176	0,001376	0,003776	0,006176	0,003376	0,005776	0,008176
		2,51	51	14,38	43	0,001	-0,00538	0,00062	0,00662	-0,00038	0,00562	0,01162	0,00462	0,01062	0,01662
		3,16	52	12,93	42	0,001	-0,00193	0,00407	0,01007	0,00307	0,00907	0,01507	0,00807	0,01407	0,02007
		3,98	53	15,23	41	0,0014	-0,00312	0,005278	0,013678	0,003878	0,012278	0,020678	0,010878	0,019278	0,027678
		5,01	54	19,72	41	0,0014	-0,00801	0,000392	0,008792	-0,00101	0,007392	0,015792	0,005992	0,014392	0,022792
		6,31	53	13,09	40	0,002	0,00182	0,01382	0,02582	0,01182	0,02382	0,03582	0,02182	0,03382	0,04582
		8,00	51	15,73	39	0,002	-0,00546	0,00654	0,01854	0,00454	0,01654	0,02854	0,01454	0,02654	0,03854
		10,00	48	14,4	38	0,0024	-0,00816	0,00624	0,02064	0,00384	0,01824	0,03264	0,01584	0,03024	0,04464
		12,50	47	16,58	36	0,003	-0,01374	0,00426	0,02226	0,00126	0,01926	0,03726	0,01626	0,03426	0,05226
		16,00	46	18,32	34	0,0037	-0,01968	0,002516	0,024716	-0,00118	0,021016	0,043216	0,017316	0,039516	0,061716
		19,95	44	19,16	32	0,0038	-0,02341	-0,000608	0,022192	-0,00441	0,018392	0,041192	0,014592	0,037392	0,060192
		25,00	41	23,77	30	0,0034	-0,04002	-0,019618	0,000782	-0,02302	-0,00262	0,017782	-0,00602	0,014382	0,034782
		31,50	40	25,68	28	0,0034	-0,04311	-0,022712	-0,00231	-0,02611	-0,00571	0,014688	-0,00911	0,011288	0,031688
		40,00	39	27,5	26	0,0024	-0,0324	-0,018	-0,0036	-0,0204	-0,006	0,0084	-0,0084	0,006	0,0204
		50,00	35	28,2	24	0,002	-0,0324	-0,0204	-0,0084	-0,0224	-0,0104	0,0016	-0,0124	-0,0004	0,0116
		TION INDEX VALUES FOR NO BARRIER WITH WOOL ON M					**0,00182**	**0,045512**	**0,178286**	**0,029784**	**0,155404**	**0,330474**	**0,133304**	**0,297574**	**0,496974**

Table A.18: Articulation index calculation for no barrier situation with different absorptive ceilings for different signal to noise levels.

		FREQUENCY	SIGNAL: MALE SPEECH SPECTRUM	SIGNAL: INSERTION LOSS	NOISE: BACKGROUND NOISE LEVEL	WEIGHTING FACTOR	(S-N+1) X WF	(S-N+7)X WF	(S-N+13)X WF	(S-N+6)X WF	(S-N+12)X WF	(S-N+18)X WF	(S-N+11)X WF	(S-N+17)X WF	(S-N+23)X WF
NO BARRIER	NO CEILING	2,00	50	0	43	0	0	0	0	0	0	0	0	0	0
		2,51	51	0	43	0	0	0	0	0	0	0	0	0	0
		3,16	52	0	42	0	0	0	0	0	0	0	0	0	0
		3,98	53	0	41	0	0	0	0	0	0	0	0	0	0
		5,01	54	0	41	0	0	0	0	0	0	0	0	0	0
		6,31	53	0	40	0	0	0	0	0	0	0	0	0	0
		8,00	51	0	39	0	0	0	0	0	0	0	0	0	0
		10,00	48	0	38	0	0	0	0	0	0	0	0	0	0
		12,50	47	0	36	0	0	0	0	0	0	0	0	0	0
		16,00	46	0	34	0	0	0	0	0	0	0	0	0	0
		19,95	44	0	32	0	0	0	0	0	0	0	0	0	0
		25,00	41	0	30	0	0	0	0	0	0	0	0	0	0
		31,50	40	0	28	0	0	0	0	0	0	0	0	0	0
		40,00	39	0	26	0	0	0	0	0	0	0	0	0	0
		50,00	35	0	24	0	0	0	0	0	0	0	0	0	0
		ICULATION INDEX VALUES FOR NO BARRIER WITH NO CEIL					0	0	0	0	0	0	0	0	0
	MDF CEILING	2,00	50	1,04	43	0,0004	0,002784	0,005184	0,007584	0,004784	0,007184	0,009584	0,006784	0,009184	0,011584
		2,51	51	0,31	43	0,001	0,00869	0,01469	0,02069	0,01369	0,01969	0,02569	0,01869	0,02469	0,03069
		3,16	52	-2,41	42	0,001	0,01341	0,01941	0,02541	0,01841	0,02441	0,03041	0,02341	0,02941	0,03541
		3,98	53	0,88	41	0,0014	0,016968	0,025368	0,033768	0,023968	0,032368	0,040768	0,030968	0,039368	0,047768
		5,01	54	-1,83	41	0,0014	0,022162	0,030562	0,038962	0,029162	0,037562	0,045962	0,036162	0,044562	0,052962
		6,31	53	-0,05	40	0,002	0,0281	0,0401	0,0521	0,0381	0,0501	0,0621	0,0481	0,0601	0,0721
		8,00	51	-1,51	39	0,002	0,02902	0,04102	0,05302	0,03902	0,05102	0,06302	0,04902	0,06102	0,07302
		10,00	48	-0,63	38	0,0024	0,027912	0,042312	0,056712	0,039912	0,054312	0,068712	0,051912	0,066312	0,080712
		12,50	47	-0,49	36	0,003	0,03747	0,05547	0,07347	0,05247	0,07047	0,08847	0,06747	0,08547	0,10347
		16,00	46	-1,2	34	0,0037	0,05254	0,07474	0,09694	0,07104	0,09324	0,11544	0,08954	0,11174	0,13394
		19,95	44	-0,77	32	0,0038	0,052326	0,075126	0,097926	0,071326	0,094126	0,116926	0,090326	0,113126	0,135926
		25,00	41	-0,39	30	0,0034	0,042126	0,062526	0,082926	0,059126	0,079526	0,099926	0,076126	0,096526	0,116926
		31,50	40	-0,83	28	0,0034	0,047022	0,067422	0,087822	0,064022	0,084422	0,104822	0,081022	0,101422	0,121822
		40,00	39	-0,44	26	0,0024	0,034656	0,049056	0,063456	0,046656	0,061056	0,075456	0,058656	0,073056	0,087456
		50,00	35	-0,41	24	0,002	0,02482	0,03682	0,04882	0,03482	0,04682	0,05882	0,04482	0,05682	0,06882
		CULATION INDEX VALUES FOR NO BARRIER WITH MDF CE					0,440006	0,639806	0,839606	0,606506	0,806306	1,006106	0,773006	0,972806	1,172606
	FOAM PLASTIC ON MDF CEILING	2,00	50	0,82	43	0,0004	0,002872	0,005272	0,007672	0,004872	0,007272	0,009672	0,006872	0,009272	0,011672
		2,51	51	0	43	0,001	0,009	0,015	0,021	0,014	0,02	0,026	0,019	0,025	0,031
		3,16	52	-0,79	42	0,001	0,01179	0,01779	0,02379	0,01679	0,02279	0,02879	0,02179	0,02779	0,03379
		3,98	53	0,7	41	0,0014	0,01722	0,02562	0,03402	0,02422	0,03262	0,04102	0,03122	0,03962	0,04802
		5,01	54	-2,78	41	0,0014	0,023492	0,031892	0,040292	0,030492	0,038892	0,047292	0,037492	0,045892	0,054292
		6,31	53	-0,08	40	0,002	0,02816	0,04016	0,05216	0,03816	0,05016	0,06216	0,04816	0,06016	0,07216
		8,00	51	-1	39	0,002	0,028	0,04	0,052	0,038	0,05	0,062	0,048	0,06	0,072
		10,00	48	-0,37	38	0,0024	0,027288	0,041688	0,056088	0,039288	0,053688	0,068088	0,051288	0,065688	0,080088
		12,50	47	-0,4	36	0,003	0,0372	0,0552	0,0732	0,0522	0,0702	0,0882	0,0672	0,0852	0,1032
		16,00	46	-0,4	34	0,0037	0,04958	0,07178	0,09398	0,06808	0,09028	0,11248	0,08658	0,10878	0,13098
		19,95	44	-0,07	32	0,0038	0,049666	0,072466	0,095266	0,068666	0,091466	0,114266	0,087666	0,110466	0,133266
		25,00	41	-0,61	30	0,0034	0,042874	0,063274	0,083674	0,059874	0,080274	0,100674	0,076874	0,097274	0,117674
		31,50	40	-0,37	28	0,0034	0,045458	0,065858	0,086258	0,062458	0,082858	0,103258	0,079458	0,099858	0,120258
		40,00	39	-0,27	26	0,0024	0,034248	0,048648	0,063048	0,046248	0,060648	0,075048	0,058248	0,072648	0,087048
		50,00	35	0,18	24	0,002	0,02364	0,03564	0,04764	0,03364	0,04564	0,05764	0,04364	0,05564	0,06764
		I INDEX VALUES FOR NO BARRIER WITH FOAM PLASTIC ON					0,430488	0,630288	0,830088	0,596988	0,796788	0,996588	0,763488	0,963288	1,163088
	WOOL ON MDF CEILING	2,00	50	0,26	43	0,0004	0,003096	0,005496	0,007896	0,005096	0,007496	0,009896	0,007096	0,009496	0,011896
		2,51	51	-0,1	43	0,001	0,0091	0,0151	0,0211	0,0141	0,0201	0,0261	0,0191	0,0251	0,0311
		3,16	52	-2,21	42	0,001	0,01321	0,01921	0,02521	0,01821	0,02421	0,03021	0,02321	0,02921	0,03521
		3,98	53	1,49	41	0,0014	0,016114	0,024514	0,032914	0,023114	0,031514	0,039914	0,030114	0,038514	0,046914
		5,01	54	0,45	41	0,0014	0,01897	0,02737	0,03577	0,02597	0,03437	0,04277	0,03297	0,04137	0,04977
		6,31	53	-0,02	40	0,002	0,02804	0,04004	0,05204	0,03804	0,05004	0,06204	0,04804	0,06004	0,07204
		8,00	51	0,55	39	0,002	0,0249	0,0369	0,0489	0,0349	0,0469	0,0589	0,0449	0,0569	0,0689
		10,00	48	-1,21	38	0,0024	0,029304	0,043704	0,058104	0,041304	0,055704	0,070104	0,053304	0,067704	0,082104
		12,50	47	0,13	36	0,003	0,03561	0,05361	0,07161	0,05061	0,06861	0,08661	0,06561	0,08361	0,10161
		16,00	46	0,16	34	0,0037	0,047508	0,069708	0,091908	0,066008	0,088208	0,110408	0,084508	0,106708	0,128908
		19,95	44	0,15	32	0,0038	0,04883	0,07163	0,09443	0,06783	0,09063	0,11343	0,08683	0,10963	0,13243
		25,00	41	0,12	30	0,0034	0,040392	0,060792	0,081192	0,057392	0,077792	0,098192	0,074392	0,094792	0,115192
		31,50	40	0,27	28	0,0034	0,043282	0,063682	0,084082	0,060282	0,080682	0,101082	0,077282	0,097682	0,118082
		40,00	39	0,18	26	0,0024	0,033168	0,047568	0,061968	0,045168	0,059568	0,073968	0,057168	0,071568	0,085968
		50,00	35	0,26	24	0,002	0,02348	0,03548	0,04748	0,03348	0,04548	0,05748	0,04348	0,05548	0,06748
		TION INDEX VALUES FOR NO BARRIER WITH WOOL ON MI					0,415004	0,614804	0,814604	0,581504	0,781304	0,981104	0,748004	0,947804	1,147604

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