Future Dwellings nearby Highways

K. Schraauwers
Technical University of Delft; Master in Architecture, Urbanism and Building Technology

Abstract

Key words:
Sound power levels, sound pollution, vibrancy problems, highway, technical solutions, noise barriers, sound attenuation, human harm, health problems

With the growing population, cities tend to grow as well. As they grow, city parts and neighborhoods will be build closer and closer to the already existing infrastructures. This means that dwellings will be build nearby highways that were not designed to protect their surroundings from its sound power levels. This paper will discuss what kind of technical solutions can be integrated into a building to be able to create livable residential areas nearby or next to a highway in the future.

To be able to design a building that will attenuate the sound power levels of a highway there has first been done research to the sources of sound and its effects on its surroundings. Second was to analyze the state of the art of sound attenuation nowadays. Third step was to integrate these ways of sound attenuation into a building next to a highway. Finally these solutions were, in their turn transformed, into a design for a building at the A5.

Research(Den Boer&Schroten,2007; Health council of the Netherlands,2001; Rosenhall et al.,1990) has shown that exposure to sound pollution, coming from traffic, can cause severe health problems to human beings. To avoid human harm by the sound pollution one has to design a "soundproof" building skin that reduces the sound power levels produced by a highway to sound levels that will not harm humans. This mitigation of sound can be solves in several ways. These solutions can be subdivided into three categories 1)at the source 2) between the source and the receiver 3) at the level of the building itself.

For a building design at the A5, at several meters from a highway, it is best to solve the sound mitigation problem at the level of the building itself. This can be done using the theory and sound attenuation principles of noise barriers within a façade, without using the traditional noise barriers one uses nowadays. The sound will be captured or directed upwards by the shape of the building to protect the surrounding areas. This will lead to a combination of shapes, well-designed airtight building skins and solving the sound mitigation problem behind the façade by placing sound insensitive zones at the façade side facing the road.

A building aligning the A5, which will protect the residential areas around it, will have the full functional length of at least 1km and well-designed endings to prevent sound propagation incident on the surrounding areas. A building of this size will have exceptions in the building shape and facades for the purpose of urban planning. There will be some portals in the plinth of the building to connect the areas on both sides of the building and there also will be openings in the building top levels to create look-outs for the residents as well as for the motorist. On these spots in the building the noise barrier principle cannot be integrated in the façade design, therefore there will have to be an additional traditional noise barrier integrated to the building.

1. Background information

The world's population is growing, as do the cities that hold the inhabitants. As they grow, city parts and neighborhoods will be build closer and closer to the already existing infrastructures. This means that residential areas will be build nearby highways that were not designed to protect their surroundings from its radiating sound power levels. The World Health Organization did research on the impact of these sound power levels coming from infrastructure. In 2000, more than 44% of the EU25 population were regularly exposed to over 55dB(A) of road traffic noise(fig.1.1). This is about 210 million people(Den Boer&Schroten,2007;WHO,1997; Stewart, et al., 2011). Nearly 20% of the population was exposed to sound levels exceeding 65dB(A) during daytime, and 30% of the population was exposed to sound levels exceeding 55dB(A) during night time(Beckenbauer, 2013).

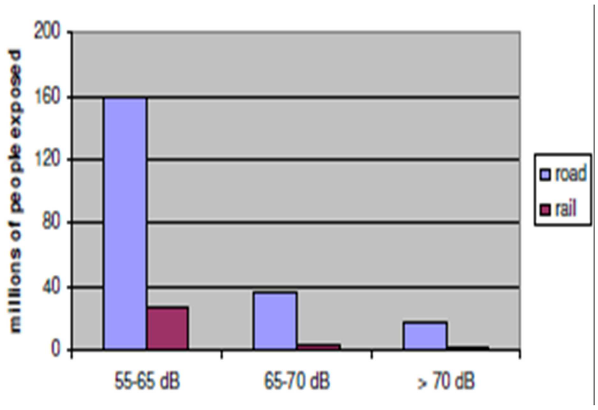

Fig.1.1 Number of people exposed to road and rail traffic noise in 25EU countries in 2000 (Den Boer&Schroten, 2007)

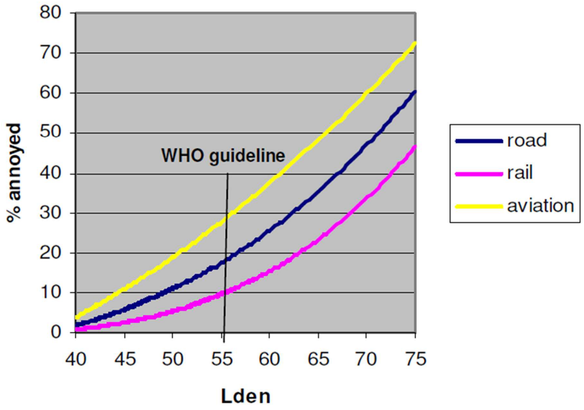

Fig. 1.2 Percentage of people annoyed as a function of noise exposure of dwellings(dB(A)) (Miederma&Oudshoorn,2001)

Research(Den Boer&Schroten,2007; Health council of the Netherlands,2001; Rosenhall et al.,1990) has shown that sound pollution of certain levels can cause severe health problems to human beings. Noise can have effects on the humans in different ways. The most known one is annoyance, but there are some other effects that more clearly damage the human body. For example, noise can lead to disturbance of sleep and daily activities, annoyance and stress. Stress can trigger the production of certain hormones like cortisol, noradrenalin and adrenaline, which can lead to a variety of intermediate effects, including increasing blood pressure. If a human body is exposed to these hormones over a longer period of time, these effects will increase the risk of cardiovascular disease and psychiatric disorders(Den Boer&Schroten,2007; Health council of the Netherlands,2001). Cumulative exposure to noise levels above 70dB(A), common along major roads, may lead to irreversible loss of hearing as well(Rosenhall et al.,1990). In fig. 1.2 is shown what percentage of inhabitants will be annoyed by certain sound power levels.

The health effects that traffic noise bring along has social costs. In the EU22[1] is estimated to be 40 billion per year, which corresponds to a loss of 0.4% of the total GDP(Den Boer&Schroten,2007; Beckenbauer,2013). The Dutch Noise Innovation Program calculated that for every decibel reduced at-source would save E100 million in national expenditure on noise barriers and sound insulation(Dutch Ministry of Transport, 2002).

It is clear that city planners, architects and designers have to take great care in sound attenuation measurements at areas where cities expanding, getting closer to main infrastructural arteries.

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[1] EU27 except Cyprus, Estonia, Latvia, Lithuania and Malta

2. New design task Amsterdam

This year the building of one of the biggest viaduct, the A5 through Amsterdam with a length of 3.3km, has been finished. This main traffic artery will be substituting the Haarlemmerweg. The part of the viaduct running above the Basisweg, called the Westrandweg (Fig.2.1), now runs through a car boulevard.

Fig.2.1 Bird view on the Westrandweg (Rijkswaterstaat1,2013)

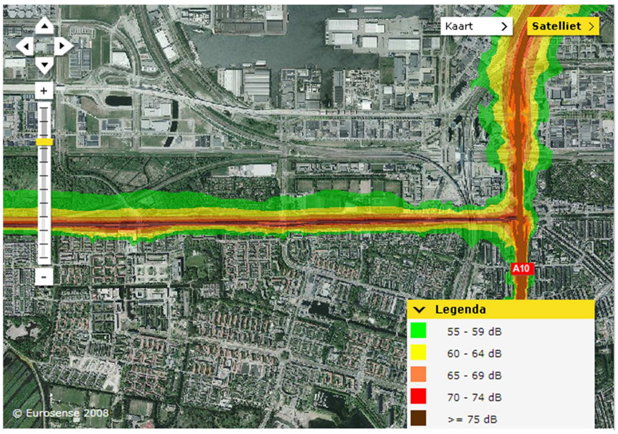


Fig.2.2 Sound power levels along roads (Rijkswaterstaat,2012)

Nonetheless, this area will be transformed to a working and residential area by 2040. The area will obtain 14.400 dwellings and 71.000 jobs. Building a neighborhood this close to a highway without noise barriers will cause problems like sound and air pollution for the inhabitants of these areas. However, in this case one can assume that by 2040 the energy sources of transportation have changed from fuel to hydrogen and electricity. This means that a highway will only cause vibrancy problems and sound pollution.

To predict what kind of sound power levels this residential area will be exposed to(without the use of noise barriers) one could compare it to the SPL produced by the Haarlemmerweg. As shown in fig.2.2 this could mean that the A5 probably will produce over 75dB(A) on top of the road and directly next to the highway this will be 70-74dB(A).

The design task coming from this sound pollution problem is to design a type of noise barrier integrated building next to or around the A5 that will protect the areas behind it.

3. Regulations

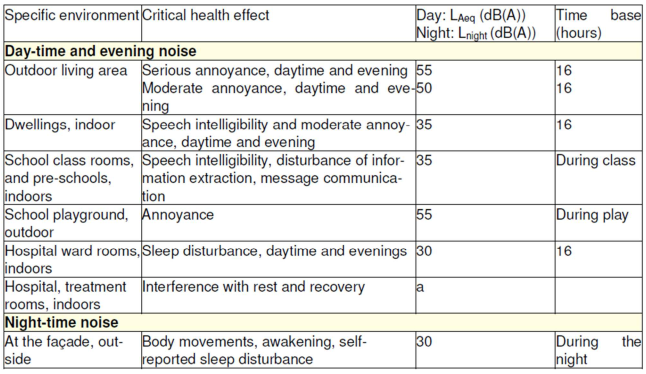
Because neighborhoods have to be protected from these kind of sound power levels national and international governments made policies to protect the inhabitants. These regulations were made for motorized vehicles as well as for the built environment.

3.1 Motorized vehicles

For motorized vehicles there are several kinds of regulations that a vehicle has to measure up to before it gets produced for the market. To obtain the needed certificates and approvals in Europe, the car has to be tested according to the regulations and tests of the European directives(EG directives and ECE regulations) and the national guidelines. In the Netherlands the RDW issues these certificates and approvals(RDW,2013). These certifications will be granted if a car measures up to the maximum values given in appendix1. As shown in appendix 1 the maximum value of the heaviest vehicle is set at 79dB(A).

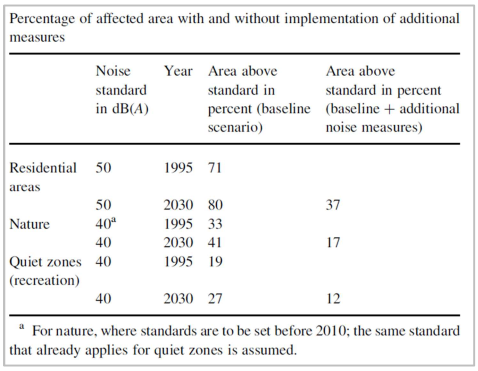
3.2 Building regulations

Then there are the regulations and guidelines of international and national levels for acceptable sound power levels within the built environment. For the Netherlands they are set as given in fig.3.1.



Specific environment	Critical health effect	Day: L_{Aeq} (dB(A)) Night: L_{night} (dB(A))	Time base (hours)
Day-time and evening noise			
Outdoor living area	Serious annoyance, daytime and evening Moderate annoyance, daytime and evening	55 50	16 16
Dwellings, indoor	Speech intelligibility and moderate annoyance, daytime and evening	35	16
School class rooms, and pre-schools, indoors	Speech intelligibility, disturbance of information extraction, message communication	35	During class
School playground, outdoor	Annoyance	55	During play
Hospital ward rooms, indoors	Sleep disturbance, daytime and evenings	30	16
Hospital, treatment rooms, indoors	Interference with rest and recovery	a	
Night-time noise			
At the façade, outside	Body movements, awakening, self-reported sleep disturbance	30	During the night

Fig.3.1 Allowed sound power levels in the Netherlands (Den Boer&Schroten, 2007)



Percentage of affected area with and without implementation of additional measures

	Noise standard in dB(*A*)	Year	Area above standard in percent (baseline scenario)	Area above standard in percent (baseline + additional noise measures)
Residential areas	50	1995	71	
	50	2030	80	37
Nature	40[a]	1995	33	
	40	2030	41	17
Quiet zones (recreation)	40	1995	19	
	40	2030	27	12

[a] For nature, where standards are to be set before 2010; the same standard that already applies for quiet zones is assumed.

Fig.3.2 Percentage of affected area with and without implementation of additional measures (Nijland,Van Kempen. Et al., 2002)

As can be seen in fig.1.1 in 2000, more than 44% of the EU25 population were regularly exposed to over 55dB(A) of road traffic noise. This means that 44% of the population is not protected according to the regulations set by the government. Since the urban areas are increasing and residential areas are becoming situated more and more nearby highways. In fig. 3.2 one can see the noise standards and the percentage of areas that gets affected by the traffic noise which exceeds the standards for the year 1995 and the prediction for the year 2030. By 2030 one assumes that 80% of the urban areas will be exceeding sound levels of 50dB(A). These numbers are not very promising for the future of urban areas. There are regulations that have to be lived up to by designers of cars as well as urban planners. As an urban planner or architect it is important to know what causes the sound pollution coming from traffic and how this propagates with or without additional protection.

4. Sources of sound regarding highways

To be able to design solutions that will reduce sound power levels coming from highways, one has to know what the sources of the sound are. According to T. Beckenbauer (2013) there are several sources of sound regarding traffic and its vehicles. There is the motor power that produces sound emissions, the airborne sound in the ducts, the spinning or breaking wheels, the friction between the wheels and the road, the gear noise and the incidental airflow of the body and of the parts attached to the vehicle. These subject can be combined in the three principal components: Propulsion noise, tire-road noise and airflow noise.
The airflow noise of passenger cars can be disregarded, according to T. Beckenbauer(2013), because it does not dominate the total noise level below 130km/h. For commercial cars this is below 100km/h. The main cause of the sound emission of vehicles is the tire-road noise.

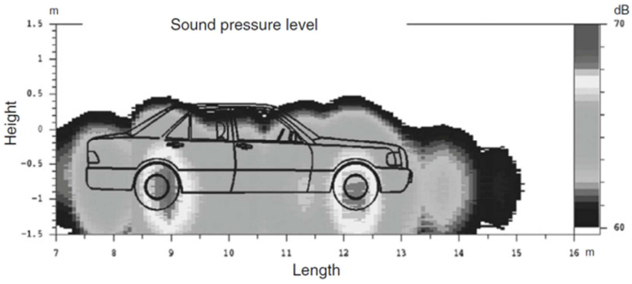


Fig.4.1 Spatial distribution of the sound pressure level caused by a rolling vehicle in the frequency band between 280 and 4.500Hz (Beckenbauer,2013).

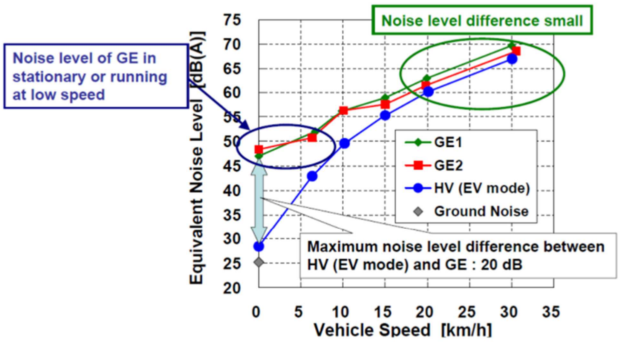


Fig.4.2 Results of sound measurements at different speeds for two kinds of fuel cars (GE1 and GE2) and a hybrid car (HV) driving on electricity. The environmental sounds(ground noise) is constant at 25 dB(A) (Jasic,2009).

The amount of noise emission does not only depends on the tire-road noise, but also on the kind of vehicle. Vehicles can be divided into four categories:

- Light motor vehicles
- Medium heavy motor vehicles
- Heavy motor vehicles
- Powered two-wheelers>50cc

Appendix 2 shows the total sound power levels(A-weighted) of these four categories separately. From these graphs can be concluded that the tire-road noise is the main source of sound from speeds exceeding 80km/h(Beckenbauer,2013).

Like mentioned before, in this design case at the A5 one can assume that by 2040 the energy sources of transportation have changed from fuel to hydrogen and electricity. Electric and hybrid cars are known to be quieter yet they do produce noise, but according to the Agentschap NL (Wilbers,2012) and the SWOV (Schoon&Huijskens,2011) the difference with fuel cars is that they produce hardly any propulsion noise when driving below 20km/h. Above this speed the tire-road noise is predominating the sound emission of the car. Therefor one could state that an electrical car makes as much noise on a highway as a 'normal' fuel car. This statement has been tested. According to fig.4.2 the noise levels of electric cars is the same as 'normal' fuel cars ones their speed levels exceeds 15-20km/h (Schoon&Huijskens,2011; Jasic,2009). For future projects of the built environment nearby highways this means that, regarding sound power levels, electric and hybrid cars can be considered as to be the same.

5. SPL Attenuation Solutions

Regarding the traffic of the Westrandweg by the year of 2040 one could state that electric and hybrid cars produce the same amount of sound power levels as nowadays, coming from the tire-road friction. To reduce these sound power levels, for the surrounding areas, there are several kinds of solutions. These solutions can be subdivided into three categories(see appendix 3 for the sound attenuation values and profits) :

- at the source
- solutions between the source and the receiver
- solutions at the level of the building itself

5.1 Solutions at the source

To reduce the sound power levels at the source one could take change the design of the profile of the tires or the choice of materials used for the tires, use quiet road surfaces(Kurtze,2013 pg360;Beckenbauer,2013) or lower the speed limits(Appendix2). According to CROW the use of a better tire profile can reduce the sound power levels (produced by the tire) by 0-3dB(CROW,2012). The use of Very Quiet Asphalt can reduce the sound power levels up to 6dB(Crow,2012).

Fig.5.1 Double layered ZOAB or Very Quiet Asphalt(Crow,2012)

Fig.5.2 Quiet tire profile (Crow,2012)

5.2 Solutions between the source and the receiver

There are several ways of mitigating the sound power levels between the source and the receiver. One solution could be to create a blockage along the path of the sound by for example creating a distant between the road and the residents. By doubling the distant to the source one can reduce to sound power levels with 3-6dB(McMullan,2012 pg204) depending on the ground surface material.

Another mitigation of the sound waves could be created by the placement of a screen or noise barrier. A barrier can reduce the sound power levels by 0-15dB. Depending on the shape and material of the top part of the barrier, the top part can reduce 0-3dB extra. The placement of a barrier in the middle of traffic lanes also can reduce 0-3dB extra(Crow,2012).
A noise barrier can be placed best as close to the source or the receiver as possible(Fig.5.3(Kotzen&English,2009; McMullan,2012)).
However, the placement closest to the receiver is seldom practical, because the space in between the road and the barrier can be used for better purposes. So, this is only suitable for isolated properties at some distant from the road.
A second exception is when the road is in a cutting or where the properties are raised from the ground level. Here it is most wisely to place the barrier at the top of the slope of the cutting(Kotzen&English,2009).
The traffic lane that is the furthest from the protected area is the most dominating one(Kotzen&English,2009). One option is to increase the height of the barrier. However, there is a limit to which height a barrier is acceptable for the protected area. Therefore it is important to consider to place an extra barrier in between traffic lanes to decrease the distance of the furthest lane to the receiver. This could be in between two carriageways, this close to the sound source the second barrier is most effective for both carriageways and prevents the main barriers from getting too high(Kotzen&English,2009).

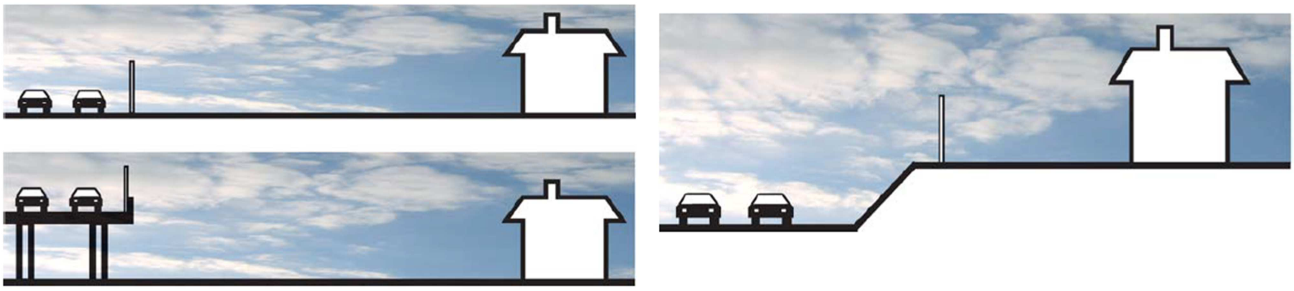


Fig.5.3 Placement of noise barriers (Kotzen& English,2009)

5.2.1 *Theory of Noise Barriers*

A noise barrier protects its surrounding environment by significantly reducing the sound power levels of the disturbing sound source(Lp,dir). However, sound has the property to curl around edges and construction parts, and after this edge or construction the sound propagates. This phenomenon tend to create a difference in the sound affected areas. There where the sound hits directly is called the “illuminated zone”, there where the sounds hit indirectly is called the “shadow zone”(Fig.5.4).

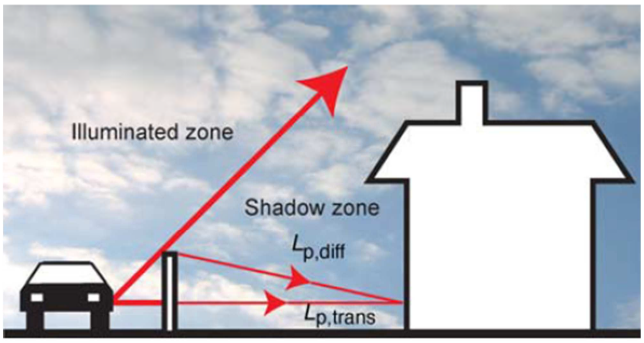


Fig.5.4 Key sound transmission for screened noise source(Kotzen&English,2009, pg43)

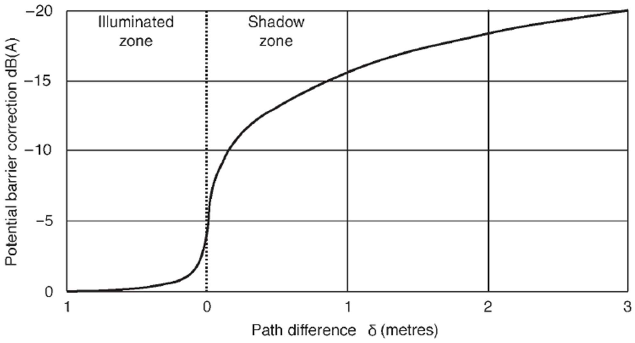


Fig.5.5 Potential barrier correction as a function of path difference(Kotzen&English,1999;2009)

Depending on the shape and materials chosen a noise barrier attenuates the sound from the source in the direction of the protected area. In fig.5.5(Kotzen&English,2009) one can see the values of the sound attenuation of a barrier within the different zones. The graph shows that there is almost no sound attenuation in the illuminated zone. The graph also shows that the maximum sound attenuation in the shadow zone is 20dB(A). However, these values are theoretical. In practice has been shown a maximum sound attenuation of 15dB(A).

The sound energy falling onto the noise barrier can be reflected or absorbed and a small proportion of the sound energy will be transmitted through the noise barrier. How much is depending on the barrier material. Although the real calculations are really complex, the following formulas(Kotzen&English,2009) can be used to calculate the preliminary values of the sound attenuation of a barrier:

- The theory developed to calculate the acoustic performance of a vertical barrier screen is in terms of the Fresnel number N.

This is defined as: $N = 2\frac{\delta}{\lambda}$

δ=Path length difference

λ=Wavelength of sound in air

- For the insertion loss(IL) of a barrier, and a single vehicle at their closest point to the receiver, the following formula is used:

$$IL = 5dB + 20\ Log\ \frac{\sqrt{2\pi N}}{tanh\sqrt{2\pi N}}$$

for $-0.2 < N > 12.5$

For $N > 12.5$ IL=24dB

- The difference in $L_{p,diff}$ and $L_{p,trans}$(fig.12) can be calculated with $L_{P,trans} = L_{p,diff} + 10dB$

A noise barrier should have its height over the total length of the functional design. Beyond this functional length one can design the end parts. Within the noise barrier one can feel as if being in a corridor, with at the endings the open space. Noise barriers normally do not stop abruptly, because in most surroundings one does not accept this visual boundary. To create a transition area between the two areas one can highlight, downplay or disguise these ends. However, in some cityscapes one does accept the abrupt endings. To highlight these endings some designers make use of colors and prints at the end. Most barriers are downplayed at the endings., they taper or have a sloped. Disguising the endings of a barrier is easiest done by enveloping the barrier with plants. A combination of the two is also very possible.

5.2.2 Reflective and Dispersive vs. Absorptive

Noise barriers can have different shapes and can be built up from different materials. All these variables have different effect on how sound propagates around and after the barrier. The main effects of a barrier on the sound rays are that they can reflect, absorb or disperse the sound rays, or they generate energy from it(fig.5.6).

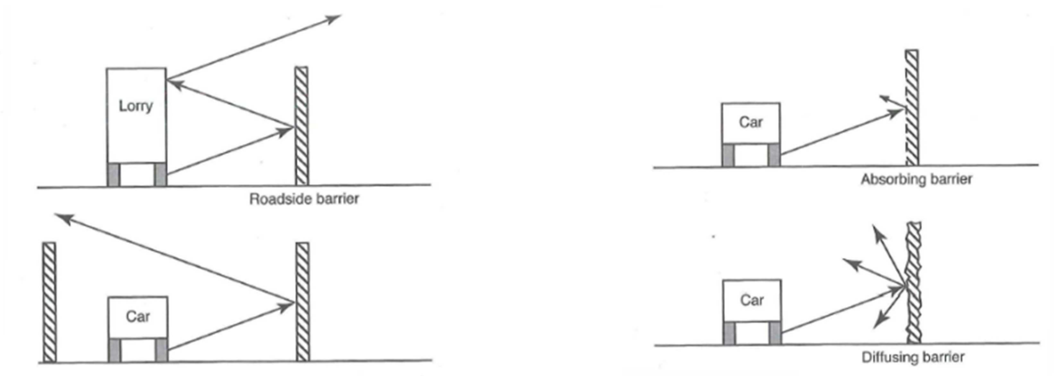


Fig.5.6 Schematic illustrating absorbers and diffusers to reduce reflection problems with noise barriers. (Cox, D'Antonio,2009, pg27)

Sound absorptive barriers contain a porous element that will absorbs the sound. This material could be the outer surface of a barrier, for example made out of concrete woodfibre or granular concrete. If the porous material is less robust, materials like mineral wool, it has to be protected and enclosed with a skin, like a perforated sheet, wood or bricks.
Reactive barriers are barriers that have incorporated cavities or resonators that attenuate particular frequencies.

Like said before the sound energy falling onto the noise barrier can be reflected and only a small proportion of the sound energy will be transmitted through the noise barrier.
To construct the reflected sound ray (Lp,refl.) one can consider the ray coming from a source located at the same distance as the original source from the barrier, but on the far side of the barrier as shown in fig.5.7. But one has to treat this reflective property carefully because it can decrease the performance of a noise barrier when reflective barriers are placed at both sides of the road. For example, for 4,5m parallel reflective barriers that are 34 apart, there can be a loss of 6dB(A)(Tobutt&Nelson,1990). To solve this problem one could increase the height of the barrier, but this also means that the barrier will increase in costs. Another solution is to make sure that the sound rays are reflected towards the sky. This can be done by tilting the barrier as shown in fig.5.8. The last option is to disperse the sound rays by using a profiled reflective surface. However, this has less effect if the sound is coming from a stream of traffic instead of from one car.

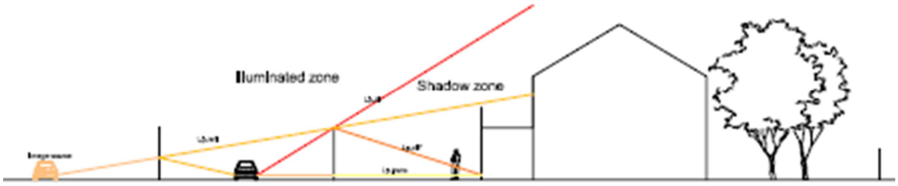


Fig.5.7 Basic principle vertical screen(Author,2013)

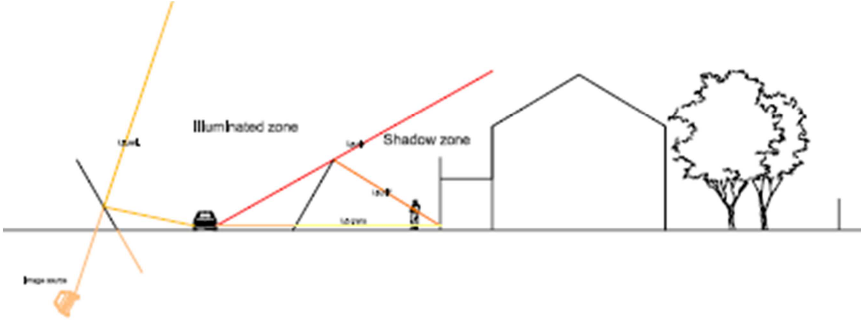


Fig.5.8 Basic principle partially inclined barrier(Author,2013)

The sound rays being reflected between both barriers and therefor decreasing the performance of one barrier not the only problem that tends to happen at reflective barriers. Vehicles have a smooth metal surface which also reflects. Sound can reflect upwards between the car and the barrier and therefor propagate at the top.

5.2.3 Types of Barriers

There are many kinds of barriers. The middle part and the top can be made out of different kind of materials and could differ in shapes. The height of these barriers is higher than most other noise barriers. The shape and the height of the barrier has a big impact on its performance, but also on its visual effect as shown in fig.5.9.

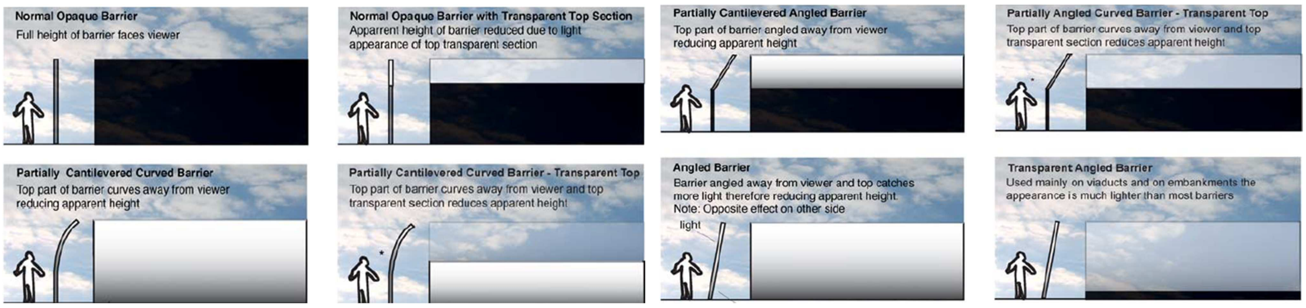


Fig.5.9 Reducing apparent barrier height(Kotzen&English,2009)

The effect of the sound attenuation of these barriers differ for each shape and choice of material. The basic principle effects of these barriers on the ray directions of the incoming sound are shown in fig.5.7-5.8. Here one can see that partially inclined barriers diffract the sound rays upwards instead of towards the protected environment. In this way the barrier prevents the sound rays from hitting any building surface.

Not only the shape or angle has an effect on the performance of a noise barrier. The shape and material of the top also has a big impact on its performance. The top parts could be made from a rigid, absorptive or soft material. Some shapes of the top part are:

- Plain
- Thick/rectangular barrier
- T-shaped barrier
- Bracket attached to main barrier
- Arrow profile
- Y-profile
- Y-profile with additional edges
- Branched
- U-profile
- Fir tree section
- Double barrier
- Cylindrically
- Double cylindrical
- Mushroom
- Horizontal louvered barrier

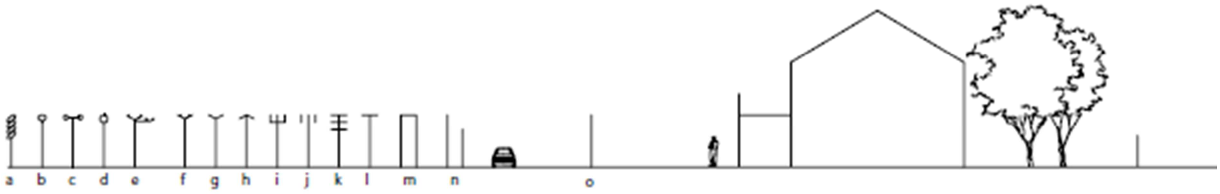


Fig.5.10 a)horizontal louvred b)mushroom capped c)double cylindrically capped d)waterwheel e)branched profile f)Y-profile with additional edges g)Y-profile h)arrow profile i)U-profile j)bracket attached to main barrier k)fir tree section l)T-profile m)thick barrier n)double barrier o)plain

According to the research of Ekici and Bougdah(2003) multiple diffracting edges perform better than a plain barrier. There is supposed to be a gain of sound attenuation of 5dB(A) without an increase of the barrier height. They also found that without the use of an expensive absorptive material there could be a gain of 2.5-3dB(A). Branched barrier tops even found to be 3 to 4dB better than a thin vertical barrier of similar height.

The top does not have to be linear shaped, in some cases it is jagged shaped. According to Ekici and Bougdah(2003) this shape can improve the attenuation by 2.5-5dB. However, they noted that choosing a random-edge fluctuation could result in a worse performance than that of a straight-edge barrier of the same height.

Like mentioned before, the shape and material of the top have a big impact on its performance. The research of Ishizuka and Fujiwara(2003) gives a better insight on this topic. They did a test where the source was positioned 8m from the centerline of the barrier(3m high, 1m wide) on a rigid ground surface. By placing the source on the ground surface, interference effect that arise from sound reflected by the ground on the source side of the barrier was avoided. Such as interference makes the barrier efficiency evaluation more difficult. The broadband insertion loss was calculated at six receivers positioned at heights of 1.5 and 3m above the ground and at distances of 20, 50 and 100m from the centerline of the barrier, on the opposite side to the source. Appendix 4 shows the results of the mean insertion loss of the main barrier shape(the arithmetic average of the broadband insertion loss over these receiver positions) and the change in the mean insertion loss(relative to the 3.0m high plain barrier result) (Ishizuka&Fujiwara,2003). What becomes clear from these graphs is that soft tops perform about 3dB better than absorptive edges and >5dB better than the rigid edges. A 3m high T-shaped barrier with soft top for example performs 8.4dB better than a plain barrier of the same height, but one could also state that this barrier has the same performance of a plain barrier of 10m high.

Another kind of noise barriers would be the sum of barriers that enclose the sound of the highway(Fig.5.11). According to Kotzen&English(2009)this is the most effective visual and acoustic solution, but it is also the most expensive one. A tunnel though, does not necessarily have to be totally covered. It can be open sided or the top part of the tunnel could be made out of absorptive baffles as shown in fig.5.11-5.12.

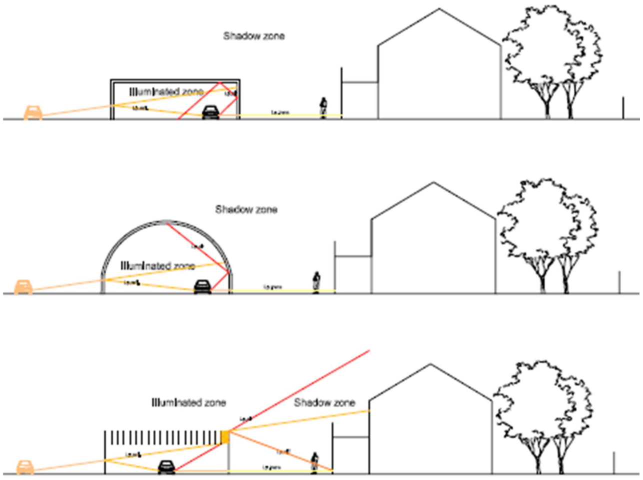


Fig.5.11 Tunnel principles(Author,2013)

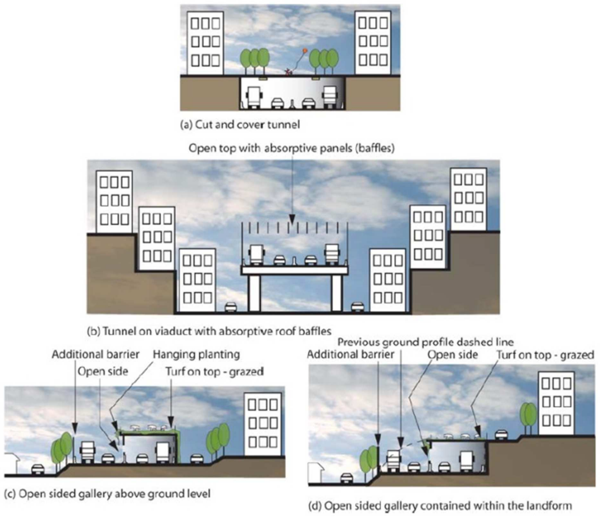


Fig.5.12 Tunnels (Kotzen&English,2009)

5.2.4 Design at the A5

First conclusion for the design task at the A5 would be that the building will got to have the full functional length of the highway and well-designed endings to prevent sound propagation incident on the surrounding areas.

The placement of a noise barrier screen in a high dense area could have several solutions. The noise barrier screen could be placed between the road and a building skin, or the building skin itself can act like a noise barrier screen(integrated barrier).

To make sure that the new building at the A5 will have the best sound attenuation results for the surrounding areas, the noise barrier should be placed as close to the source as possible. However an additional construction onto the viaduct will be needed if a screen would be placed between the road and the building. This is very costly(appendix3) and the building will be placed at several meters from the road, therefore it is more likely to integrate the noise barrier screen in the building skin(fig.5.13).

A building aligning the A5, which will protect the residential areas around it, will have a length of at least 1km. A building of this size will have exceptions in the building shape and facades. For the purpose of urban planning there will be some portals in the plinth of the building to connect the areas on both sides of the building. There also will be openings in the building to create look-outs for the residents as well as for the motorist. On these spots in the building the noise barrier principle cannot be integrated in the façade design. There will have to be an additional noise barrier as described above. Fig. 5.14 are showing which facades in the design task will have to act as noise barriers on several sections of the building.

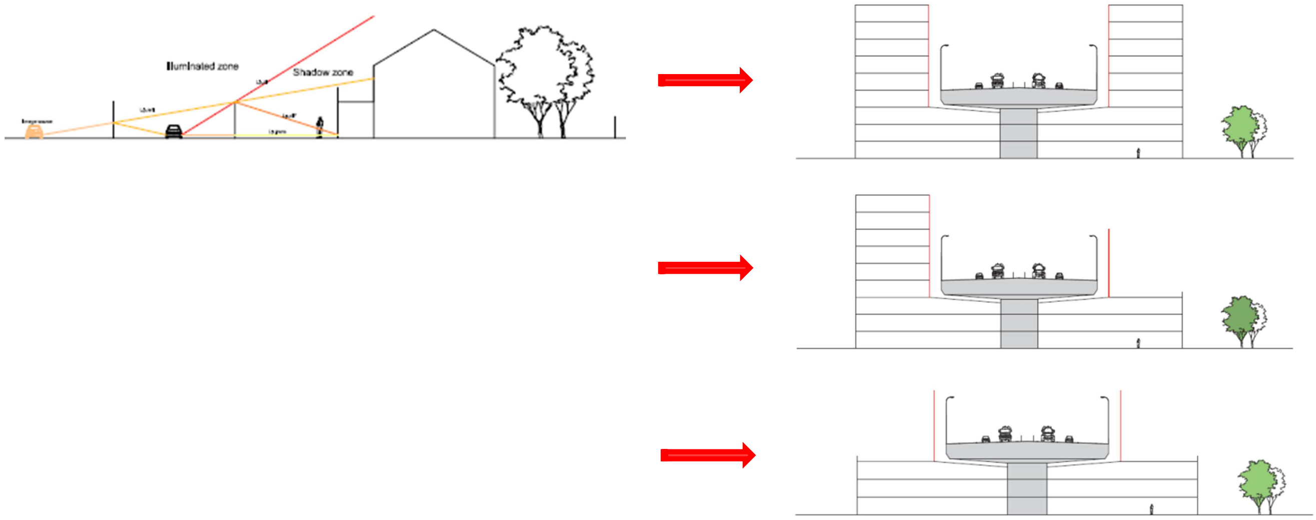


Fig.5.13 Noise barrier principles translated to building design at the A5

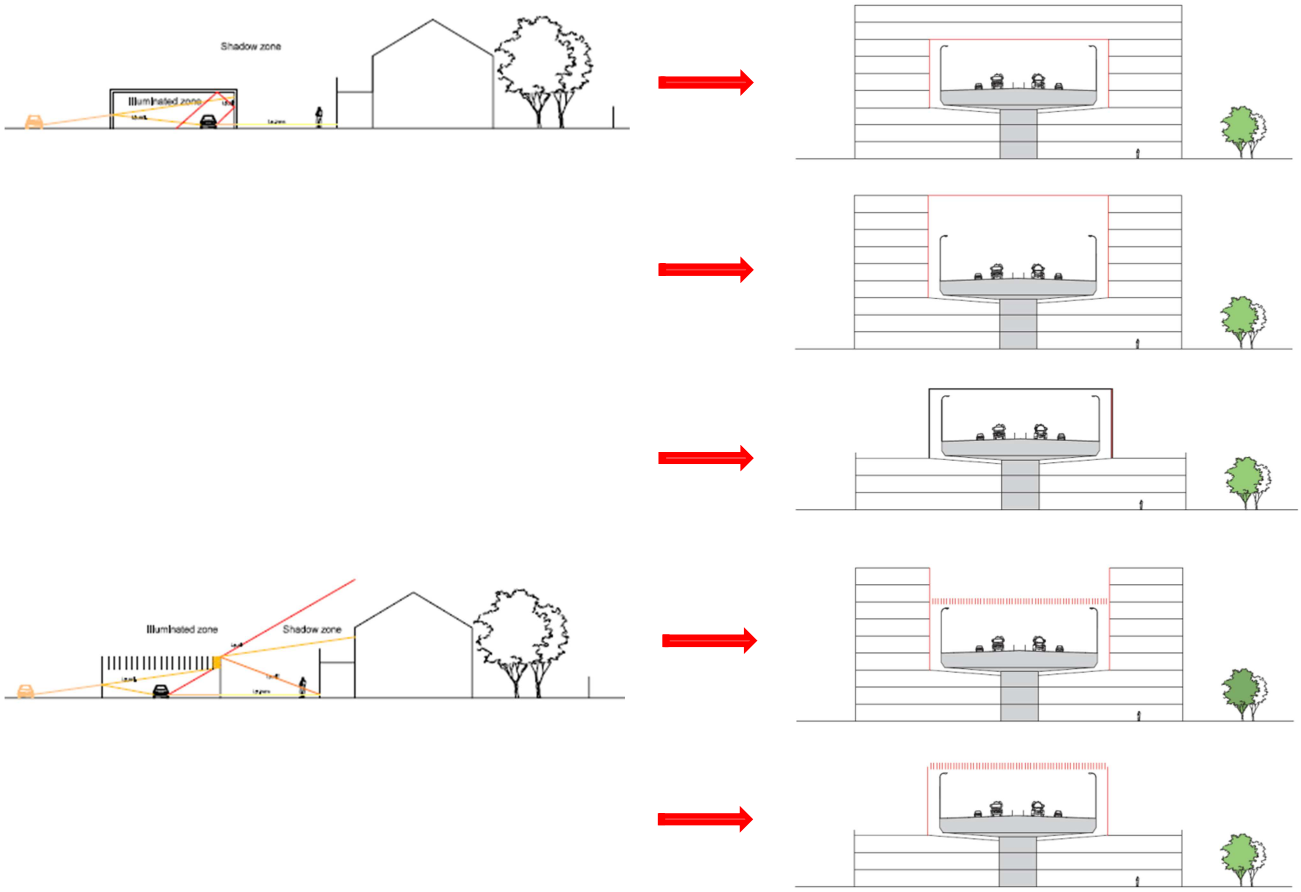


Fig.5.14 Tunnel principles translated to building design at the A5(Author,2013)

5.3 Solutions at building level

5.3.1 Airtight, Zoning & Second skin façade

At the level of the resident itself, the receiver, one could use proper insulation or use a zoning principle within the residential building. For the right insulation McMullan(2012) gives the following principles:

- Heaviness

With a high mass transmit less sound energy than lightweight structures. In practice McMullan(2012) states that the sound insulation increases by 5dB whenever the mass is doubled. He also states that sound insulation increases by 5dB whenever the frequency is doubled. The sound attenuation of a partition at a frequency of 500Hz can be calculated by the use of the formula: $R = 14.5 log_{10} M + 10$

- Completeness

Completeness of the insulation structure depends on the airtightness and the uniformity of it.

- Flexibility

High stiffness and the elasticity of a material a partition can cause a partition to decrease the loss of insulation at certain frequencies because resonance and coincidence effects can occur.

- Isolation

Discontinuous construction can be effective in reducing the transmission of sound through a structure. As the sound is converted to different wave motions at the junction of different materials, energy is lost and a useful amount of insulation is gained. Sound insulation is easily ruined by strong flanking transmissions through rigid links, even by a single nail. Cavity constructions must be sufficiently wide for the air to be flexible, otherwise resonance and coincidence effects can cause the insulation to be reduced at certain frequencies.

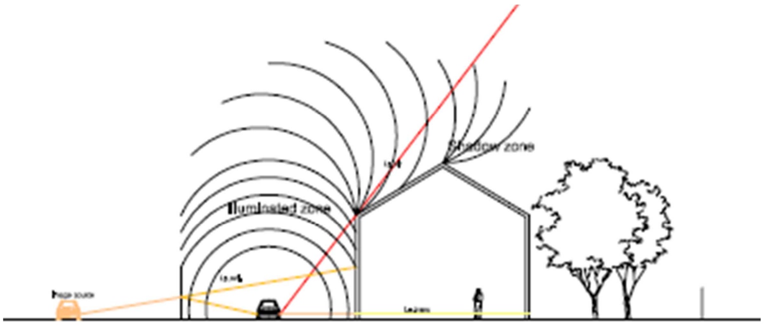


Fig.5.15 Sound propagation after noise barrier(Author,2013)

A second principle at the level of the resident itself is zoning. This can be interpreted in different ways. One is to place sound insensitive functions at the façade incident with sound waves. In this way the sound sensitive functions within a resident are protected by the buffer zone.

A third option would be to apply a second façade skin to a building. The size of the cavity determines whether the cavity can be used for residential purposes or not.

5.3.2 Design at the A5

For this particular design task at the A5 solutions like creating distant to the road do not apply, because there is no space to create distance. The solutions possible to attenuate sound power levels are using the principles of noise barriers integrated facades, and the insulation and zoning principles at the level of the building itself. A buffer zone will be created by the placement of sound insensitive functions at the façade incident with sound waves, which thereby will protect the sound sensitive functions within a resident. Fig. 5.16-5.17 are showing which facades in the design task will have to act as noise barrier zones on several sections of the building design at the A5.

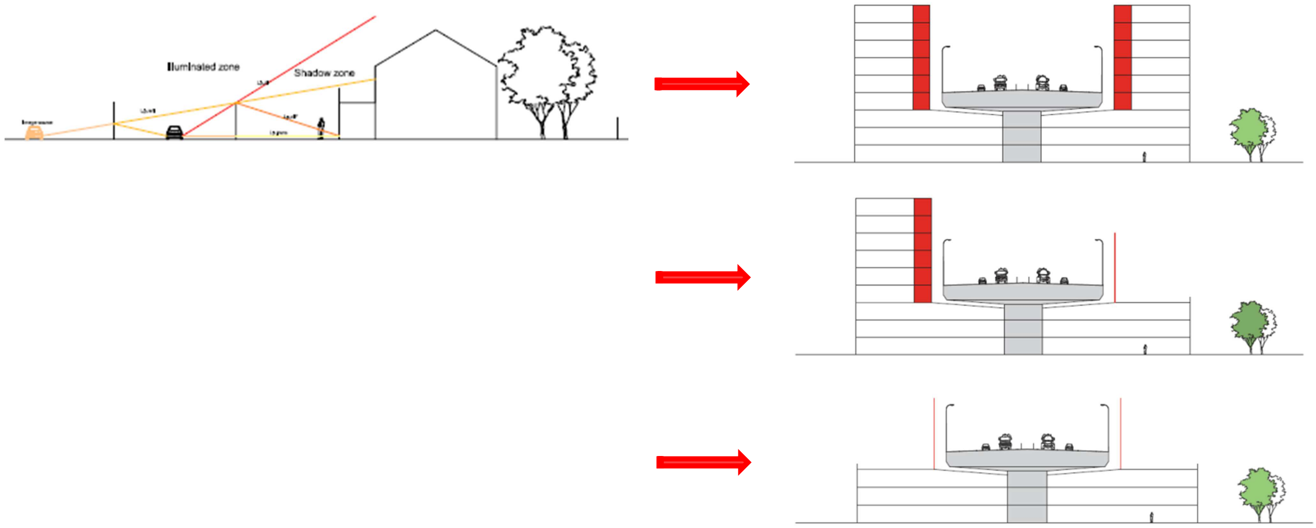


Fig.5.16 Noise barrier zone principles translated to building design at the A5(Author,2013)

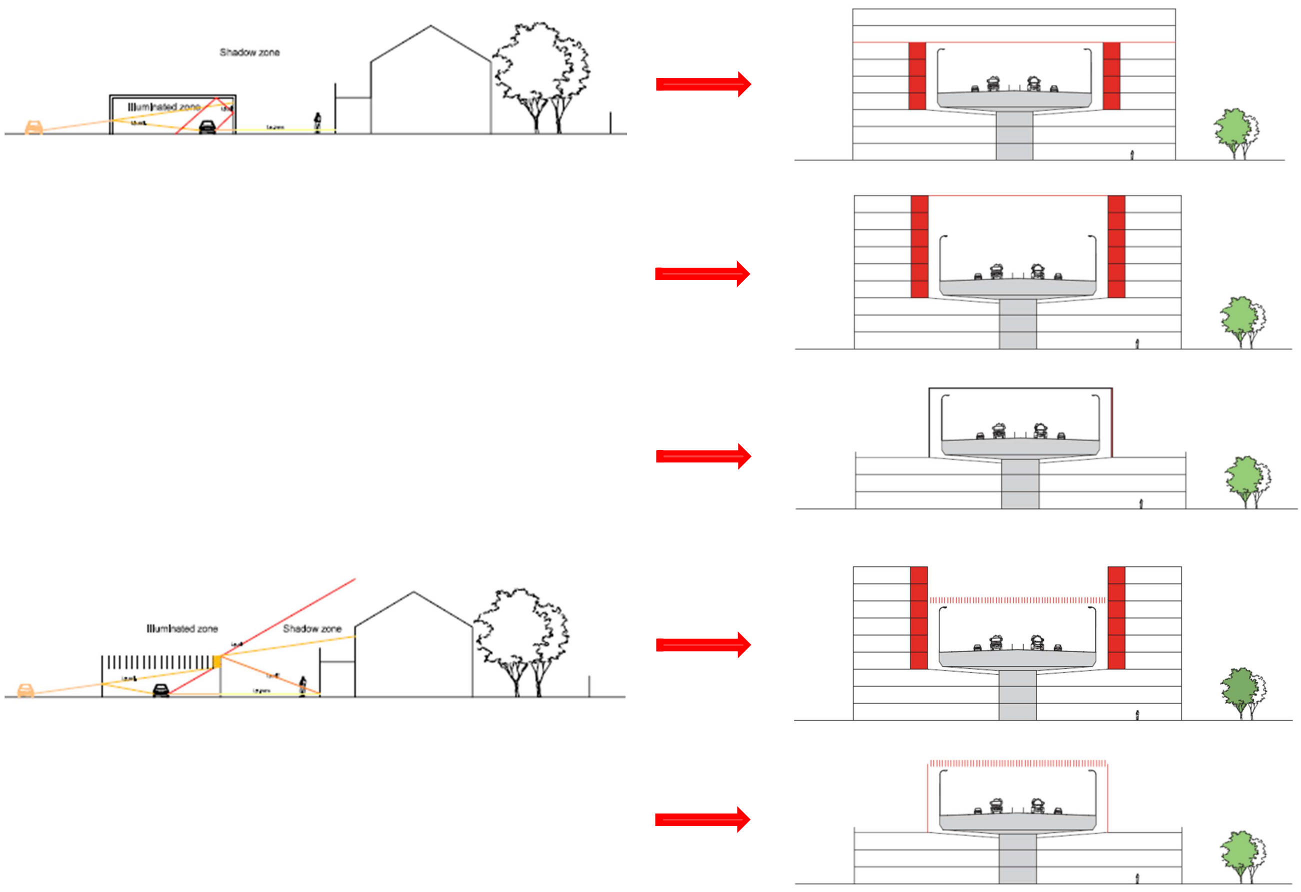


Fig.5.17 Tunnel principles translated to building design at the A5(Author,2013)

6. Building Skin Design nearby a Highway

When behind the façade, facing the radiating sound waves, sound sensitive functions are placed there are several kind of regulations a building skin has to measure up to.

6.1 Regulations and Calculations

A dwelling can be made sound proof by the use of the right insulation. The Dutch Building regulations article 22 on sound mitigation states that the outer building skin and the roof should attenuate at least 20dB(SBR,2013a). The exact attenuation is described as: $GA_{;kg} \geq L\ bu_{;A} - Lbin_{;A}$

$G_{A;kg:}$ characteristic sound attenuation of the inside area dB(A)
$L_{bu,A:}$ Sound power level incident on the façade, A-weighted, dB(A)
$L_{bin;A:}$ maximum admittable sound power levels at the inside area, dB(A).

$$GA_{;kg} \geq 20$$

According to the Dutch Building Regulations the sound insulation of a new dwelling should be 35 dB(A) and new offices 40 dB(A).

The characteristic sound attenuation of a façade for a sound sensitive area has to be less than the minimum value calculated by:

$$GA_{;kr} \geq GA_{;kg} - 2$$

$G_{A;kr}$: characteristic sound attenuation of a façade for a sound sensitive area, dB(A) (AV-Consulting B.V,2012)

6.2 Detailing

To accomplish the demanded sound mitigation a building skin(façade and roof) is build up from several layers of different materials. The total sound mitigation depends on which combination of loadbearing structure, insulation and kind of cladding material is used.
The thickness of layers of the skin in their turn depend on their characteristics regarding for example their manufacturing sizes, insulation values and combination of materials and placement in the façade.
Next to the choice of materials the connecting parts of the separate building components are important. The way of connecting can improve or worsen the sound mitigation tremendously. If a façade is facing high sound power levels exceeding 60dB special building methods will have to be applied. Like mentioned before, completeness of the insulation structure depends on the airtightness and the uniformity of it. Even if the proper sound insulation material is used, sound waves can propagate through the smallest openings in façades. Therefore designing and detailing a dwelling nearby a highway takes great care for these sound leakages. The relatively biggest sound leakages in practice are(SBR,2012b):

- Draft proving of the windows and doors
- Connection of window in façade
- Connection of roof on façades
- Connection of the façades on the ground floor construction
- aansluitingen met de begane grondvloer
- Roof cams
- Roof penetrations
- Mailboxes
- Corner connections

By designing air tight details of these connections one does not only increase the sound insulation, it also influences the thermal performance, water tightness, rain retardency and fire safety. Therefore SBR(2012b) highly recommends this way of building.

However there are several gradations in building an airtight building skin (SBR,2012b):

- Classification 1 Basic
- Classification 2 Good
- Classification 3 Excellent

There are also some classifications for the ventilation systems according to NEN 1087:

- Natural supply and discharge of air (system A)

Natural supply and mechanical discharge of air (system C)

- Mechanical supply and natural discharge of air (system B)

Mechanical supply and discharge of air (system D)

- Mechanical supply and discharge of air (system D) in combination with passive building concepts.

6.3 Measures

For the design task at the A5 the sound power levels exceed the limits of 60dB. This means that classification 3, excellent, has to be achieved. When designing to achieve classification 3 one has to take in count all the design steps of the other two classifications plus additional design steps. These design steps are(SBR,2012c):

- Point out the airtightness of window clinks
- Point out the airtightness in one surface
- Point out the airtightness as far to the inside as possible(inside of insulation surface)
- Good gagging 2 and 3 point locking
- Cuffs placed in the roof and façade penetrations
- Correctable locksmithing
- If possible prefabricated air seals
- Unilateral sloping hooks H & S work
- Where possible taping seams and cracks
- Double air tightening in rotating elements
- Wet glazing in wooden frames and quality demands for plastic and aluminum window frames
- Cable and pipe penetrations (lights outside and outside taps): use prefabricated cuffs, taping and in case of the use of electricity pipes also seal within the pipe
- Tape overlap and connections of the vapor barrier (foil)
- No breakthroughs of the vapor barrier(foil), if necessary use a double constructed wall for the electra and plumbing
- Control focused on the affixed air seals and control measurements (possibly in combination with infra-red measurements)

However, there are many ways of constructing a façade or building skin and every kind needs different attention to the detailing. In appendix 4 there are a few ways of constructing an airtight façade.

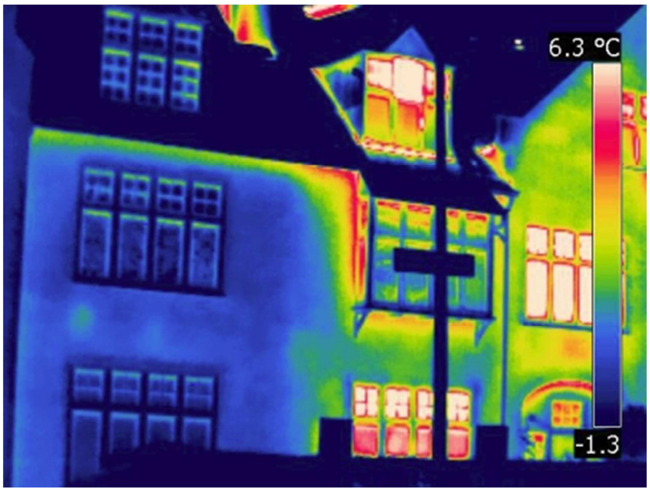


Fig.6.1 Control focused on the affixed air seals and control measurements (SBR,2012b)

6.3 Design at the A5

If less sound sensitive functions can be placed at the façade facing the radiating sound waves, one can make use of the zoning principle. As mentioned before this can be interpreted in different ways. One is to place sound insensitive functions at the façade incident with sound waves that will act like a buffer. In this way the more sound sensitive functions within a resident are protected.

Another option is to apply a second façade skin to a building. Cavity constructions must be sufficiently wide for the air to be flexible, otherwise resonance and coincidence effects can cause the insulation to be reduced at certain frequencies. The size of the cavity determines whether the cavity can be used for residential purposes or not.

If sound sensitive functions will be placed at the façade facing the road, the façade will have to be airtight and well-designed to be able to guarantee the right sound attenuation levels.

For the design task at the A5 these design steps would merely, depending on building shapes ,cut outs and functions, have to be applied to the facades facing the highway. The building itself can (again depending on the building shapes) protect its other facades from incidental sound rays. The building as a whole in its turn will act like a noise barrier to its surrounding areas by:

- its shape which will diffract the sound rays coming from traffic
- its sound absorbing materials used in the inner façades
- the distant it creates by its size to the nearby dwellings

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Fig.5.13 *Noise barrier principles translated to building design at the A5*. Author, 2013

Fig.5.14 *Tunnel principles translated to building design at the A5*. (Author,2013)

Fig.5.15 *Sound propagation after noise barrier*. Author, 2013

Fig. 5.16 *Noise barrier zone principles translated to building design at the A5*. Author, 2013

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Appendix 1

For tires of class C1 the road-tire noise is not allowed to exceed the values as described down below. These values are revering to the in 2.17.1.1 of the regulations nr 30 mentioned section width	
Fase 1	
Nominal section width	Limit dB(A)
≤145	72
> 145 ≤ 165	73
> 165 ≤ 185	74
> 185 ≤ 215	75
>215	76
Limits mentioned above increase 1dB(A) if the tires have a higher carrying capacity or are reinforced and 2dB(A) if special tires are used.	
Fase 2	
Nominal section width	Limit dB(A)
≤185	70
> 185 ≤ 245	71
> 245 ≤ 275	72
> 275	74
Limits mentioned above increase 1dB(A) if the tires are winter tires, tires with a higher carrying capacity or are reinforced and 2dB(A) if special tires are used or a combination of these categories.	
For tires of class C2 the road-tire noise per use category is not allowed to exceed the limits as described down below.	
Fase1	
Use category	Limit dB(A)
Normal	75
Winter*	77
Special	78
*Limit also count for tires with the inscriptions M+S	
Fase2	
Use category	Limit dB(A)
Normal	72
Winter	73
Special	74
Limits mentioned above increase 1dB(A) for traction tires for normal and special use and 2dB(A) for winter.	
For tires of class C3 the road-tire noise per use category is not allowed to exceed the limits as described down below.	
Fase1	
Use category	Limit dB(A)
Normal	76
Winter*	78
Special	79
*Limit also count for tires with the inscriptions M+S	
Fase2	
Use category	Limit dB(A)
Normal	73
Winter	74
Special	75
Limits mentioned above increase 2dB(A) for traction tires.	
(UNECE,2013)	

Appendix 2

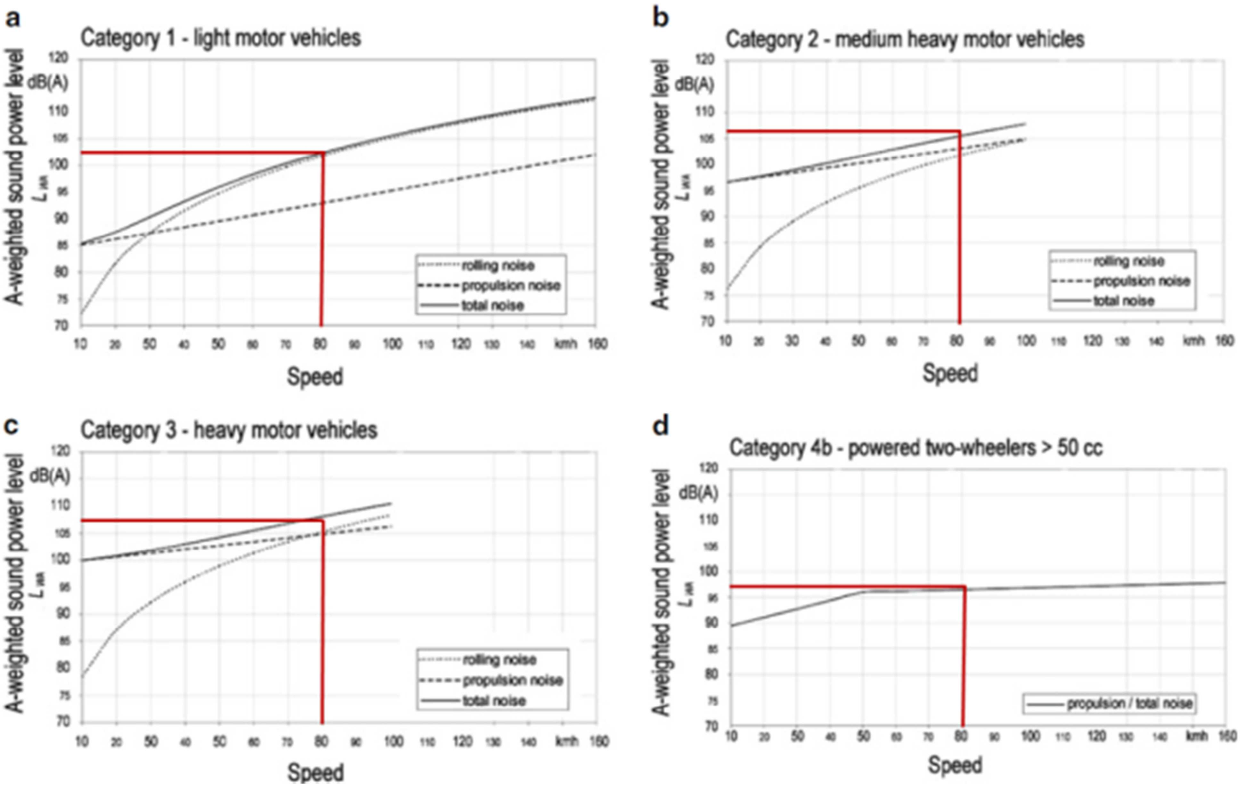

Fig.8 These values represent average values for the European vehicle fleet in different vehicle categories. At the new A5 in Amsterdam the top speed will be 80km/h. The red line in the figures are showing the total sound power levels at 80km/h(Beckenbauer,2013).

Appendix 3

	Sound reduction on façade	Features	Indication of costs	Indication of life
Quiet Road Surfaces				
ZOAB	2-3 dB	Sound reduction depends on speed limit and vehicle type	10-30% higher than DAB	10-12 years
2-layered ZOAB	4-7dB	Sound reduction depends on speed limit and vehicle type	20-40% higher than ZOAB	7-11 years
Thin coatings	2-4dB	Sound reduction depends on speed limit and vehicle type	10-30% higher than DAB	8-15 years
Quiet element hardenings	0-1dB	Sound reduction depends on speed limit and vehicle type	10-20% higher than normal element hardenings	Comparable with normal element hardenings
Noise Barriers				
(Modular) screens	0-15dB	Sound reduction depends strongly on height of screen and exact location behind the screen	± E 300-600m^2	± 30 years
Additional top part on a noise barrier	0-3dB	Sound reduction depends strongly on height of screen and exact location behind the screen.	Unknown	Unknown
Screen at central part of traffic lanes	0-3dB	Sound reduction depends strongly on height of screen and exact location behind the screen.	± E 400-700 m^2	± 30 years
Vehicle and tires				
Quiet tires	0-3dB	-	Not higher than regular tires	Comparable to regular tires

(CROW,2012) http://www.stillerverkeer.nl/index.php?section=general&subject=geluidmaatregelen

Appendix 4

4.1 *(Ishizuka&Fujiwara,2003)*

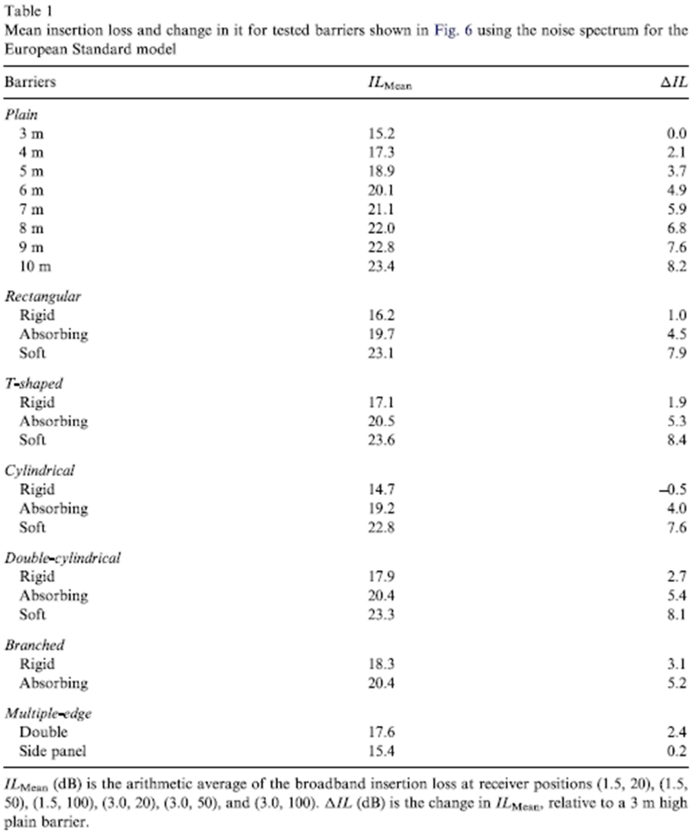

Table 1
Mean insertion loss and change in it for tested barriers shown in Fig. 6 using the noise spectrum for the European Standard model

Barriers	IL_{Mean}	ΔIL
Plain		
3 m	15.2	0.0
4 m	17.3	2.1
5 m	18.9	3.7
6 m	20.1	4.9
7 m	21.1	5.9
8 m	22.0	6.8
9 m	22.8	7.6
10 m	23.4	8.2
Rectangular		
Rigid	16.2	1.0
Absorbing	19.7	4.5
Soft	23.1	7.9
T-shaped		
Rigid	17.1	1.9
Absorbing	20.5	5.3
Soft	23.6	8.4
Cylindrical		
Rigid	14.7	–0.5
Absorbing	19.2	4.0
Soft	22.8	7.6
Double-cylindrical		
Rigid	17.9	2.7
Absorbing	20.4	5.4
Soft	23.3	8.1
Branched		
Rigid	18.3	3.1
Absorbing	20.4	5.2
Multiple-edge		
Double	17.6	2.4
Side panel	15.4	0.2

IL_{Mean} (dB) is the arithmetic average of the broadband insertion loss at receiver positions (1.5, 20), (1.5, 50), (1.5, 100), (3.0, 20), (3.0, 50), and (3.0, 100). ΔIL (dB) is the change in IL_{Mean}, relative to a 3 m high plain barrier.

4.2 *(Ishizuka&Fujiwara,2003)*

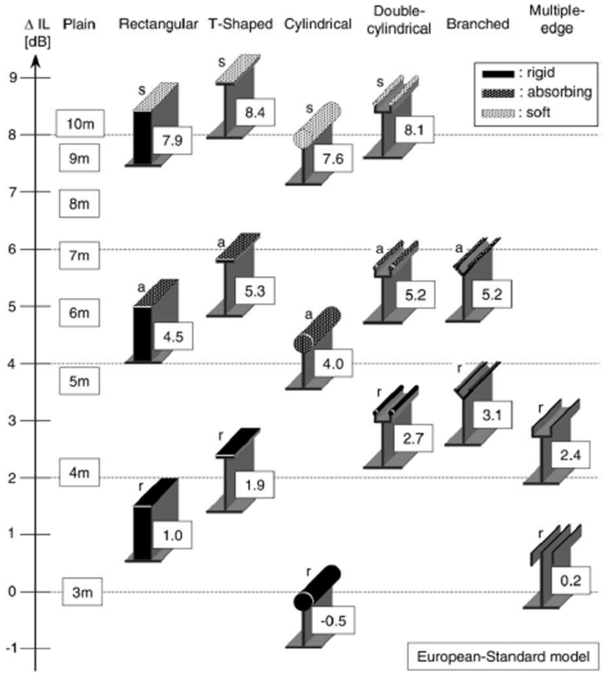

Fig. 8. Comparison of performance of barriers with various shapes and acoustical conditions for the European Standard noise source model. Barriers are presented with ΔIL, change in the mean insertion loss relative to a 3 m high plain barrier. Plain barriers of various height plotted in left-end column represent the equivalent height.