Building Technology Report
The living bridge
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1. Introduction

The intention of cities is to grow closer and closer to their highways. The positive side is that it increases the mobility of the inhabitants because they are close to the infrastructure. However till now the highway is often not really implemented in the urban plan, but is more a separated element, which cuts through the landscape. This is caused by different reasons, but one of them is that the highway brings noise and pollution problems. Because of these problems there are nowadays even some functions restricted to be built in a band of 300 meters from the highway, like schools, health centers etc. When it’s possible to reduce the pollution and noise significantly by the design, it could be possible to build closer to the highway and create there a pleasant zone where people would like to stay.

The building that will be investigated, is also close to the highway, because it creates a link between two different areas which are separated by the highway. The location is close to the Prins Claus Plein (The Hague, Netherlands), which forms the junction of the highways A4 and A12.

The goal in this research is to find ways to make it possible to build close to the highway by handling with the problems of noise and air pollution. The relationship between the highway and the building is greatest at the edges of the building, so that is an interesting territory to explore.

![Figure 1.1 Situation](image-url)
2. Problem description

2.1 Goals

The design

The highway now is an autonomous world cutting the area surrounding this highway in different parts. Architecture tries to avoid the highway rather than react to it, unless it’s meaning is to attract the attention of the drivers. Therefore it can be interesting to look if and how this highway can be implemented in an urban plan, without separating this plan too much in different areas. The past growth of The Hague shows that the city over time will fill in the empty spaces, which are existing between the highway and the city borders. This means that the parts of the A4 and the A12 close to the Prins Clausplein will be surrounded by urban area. To make an unified whole out of these parts, they have to be connected.

Therefore a design for a building is made which forms a link between Ypenburg and The Hague. This building will act as an bridge connecting the different parts of the city, which are now disconnected by the highway. The reason that there are functions added to this bridge is to make a lively connection between the two areas and to make a continuity in the building landscape. The functions surrounding this inhabited bridge are mainly offices and housing. Therefore the program for this bridge will consist out of functions which are attractive for both the offices and the housing. There will be sport facilities like a gym and a sports hall, cultural facilities like a centre for dance, art etc and a small cinema, shops and as well some offices. Because these facilities are used by the people who work or live there, it can generate a spread out occupation of the buildings during the day.

![Figure 2.1 Local road for vehicles and bicycles](image1)

![Figure 2.2 Highway](image2)

![Figure 2.3 Inner street for pedestrians](image3)

The infrastructure is divided at different levels. At the lowest level the local traffic for vehicles and bicycles perpendicular to the highway takes place. Above this road is the highway where the fast traffic rushes by. On top of this there is an inner street which is connected to the buildings. This inner street is only meant for pedestrians. The main entrances of the different functions are at this street above the highway. A requirement from the design is that the street as well the buildings should have a relationship with the highway. The people who pass the highway with this bridge should be aware that they are crossing a highway. Therefore there are openings made from between the buildings onto the highway. These openings should mainly make the highway visible for the people at the street.

The goal of this research is to create a pleasant zone above the highway for the building and the inner street by dealing with the problems that occur at that site, which are mainly air pollution and noise. To make it an area where people would like to stay and where they don’t suffer from these problems, quite some efforts have to be made. This will be the main challenge and focus of this research.

![Figure 2.4 Location](image4)
2.2 Method

To accomplish the goal of creating a livable zone above the highway, there are several aspects that needs to be researched. First there is the noise, which is caused by the highway. Secondly there is the air pollution, caused as well by the highway, which could make it unpleasant to stay above the highway. Furthermore there should be a good wind climate to create a comfortable zone above the highway. There are two scales on which these topics could be treated. First there is the building scale, where the design of the entire building can ensure a pleasant environment. Further there could be more zoomed in to one aspect of the building, which is the layer between the highway and the building. On the building scale it is the most interesting to research the wind climate and the air pollution and for the layer scale all aspects; noise, wind and air pollution could be researched. This leads to two main questions;

How could the conditions at building scale be optimized so that the nuisance of wind and air pollution will be minimized?

How could the layer between the buildings and the highway contribute in solving the problems that arise at that area?

To research these different topics, a literature study will be done and several tests and calculations will be accomplished, to give an answer to these questions.

2.3 Framework

For this research not all the aspects that occur at this design can be taken into account. For the research at building scale the main focus will be about air pollution. There will be examined how to dilute the contaminated air from the highway and how to bring cleaner air at street level. For the screen the focus will be mainly about acoustics and air pollution. And for example the construction won’t be taken so much in account.
Part I Analysis
3. Air quality

3.1 Introduction

The air contains a wide range of components. Some of these components are harmful while others are not. Sources of pollution include traffic, industry and large-scale agriculture. In the Netherlands, the biggest problems for health occur with nitrogen oxides (NOx), particulate matter (PM10) and ozone (O3). Automobile exhaust gases contain the following key components in high concentrations such as particulate matter, nitrogen oxides (sum of nitric oxide and nitrogen dioxide) and volatile organic compounds. Ozone is formed, under the influence of sunlight, out of nitrogen and other substances that are in the exhaust gases. (Hiemstra, 2008)

Figure 3.1 A traffic jam close to the Prins Clausplein

PM10 (Particulate Matter, ‘fijn stof’)

Particulate Matter (PM), alternatively referred to as particulates or fine particles, are tiny particles of solid or liquid suspended in a gas (or liquid). The sources for these particles can be natural or human related. Natural sources can be volcanoes, dust storms, forest and grassland fires, living vegetation, and sea salt. Examples of anthropogenic aerosols, those made by human activities, are power plants, various industrial processes and as well road traffic is a major source for particles.

The particles are mainly categorized by their size. The notation PM10 is used to describe particles of 10 micrometers or less and PM2.5 represents particles less than 2.5 micrometers in aerodynamic diameter, so the notation PM10 includes as well the PM2.5 particles.

There is as well a distinction between primary and secondary particles. Primary particles are the result of human or natural processes and are created by combustion, friction or evaporation. Secondary particles are the results of chemical reactions and occur when molecules of acidifying substances like nitrogen oxides (NOx), sulfur dioxide (SO2), ammonia (NH3), volatile organic compounds and ozone (O3) commit to solid particles. For example primary gases sulfur and nitrogen oxides into sulfuric acid (liquid) and nitric acid (gaseous).

The composition of aerosol particles depends on their source. But PM10 contains lots of hazardous substances like ammonia, copper, zinc, sulfurous yellow and cadmium. Particles can create respiratory symptoms (cough from irritation, dry throat) or an impaired lung function. For people with heart disease particles may worse the complaints. Particles makes the most victims among people who already have health problems. Respiratory, heart or vascular disease patients can die several month earlier because of particles. Furthermore, (older) people with an impaired physical condition can become victims as well. (MNP, 2005). An estimation of death related to short term exposure to high concentration of these components in the Netherlands is around 2.300-3.500 deaths related to PM10 and 1.100-2.200 deaths related to ozone (Hiemstra, 2008)
Nitrogen oxides (NOx, ‘stikstofoxiden’)

Nitrogen oxides (sometimes abbreviated to NOx) is an collective term for the chemical connections of oxygen and nitrogen. They occur in all types of combustion at high temperatures, for example in a combustion engine of a car. Other examples of combustion processes are domestic heating on gas, oil or coal, industrial processes such as thermal power plants on coal, oil or gas, cement kilns, furnaces for steel production, etc. Nitrogen oxides are among the substances that acidify the environment. Nitrogen oxides are harmful to the respiratory tract of humans and animals and as well for plant growth. Nitrogen oxides also affect the ozone layer in the stratosphere and cause ozone and so smog.

Ozone

Ozone arise naturally in the atmosphere under the influence of electrical discharges (like during thunderstorms) and by ultraviolet radiation in the upper layers of the atmosphere (the stratosphere). At this level ozone is a highly desirable gas, because it stops the harmful ultraviolet radiation from the sun (the “ozone layer”)

At ground level nitrogen dioxide and volatile organic compounds from the exhaust of cars form ozone under the influence of sunlight. Traffic and the industry are the most important sources of NOx and VOC and therefore contribute heavily to the creation of ozone. High concentrations of ozone, particularly occur during the summer (summer smog) cause damage to the public health. (Hiemstra, 2008)

The main focus of this research will be on PM10 and NOx. Because ozone is generated from a reaction with nitrogen oxides, it is particular essential that the NOx will be reduced.
3.2 Requirements

Air quality standards are intended to reduce the risks to human health to a minimum. Exceeding standards is legally not permissible. But meeting the standards does not automatically mean that people no longer suffer from the pollution. By law (Wet Milieubeheer) are some limits established for air quality from the Kaderrichtlijn luchtkwaliteit, which are summarized in the table below.

Limits for the protection of human health

<table>
<thead>
<tr>
<th></th>
<th>μg/m³ as hourly mean concentration (allowable number of times per year exceeded)</th>
<th>μg/m³ as 8-hourly mean concentration (allowable number of times per year exceeded)</th>
<th>μg/m³ as 24-hourly mean concentration (allowable number of times per year exceeded)</th>
<th>μg/m³ as yearly mean concentration</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles(PM10)</td>
<td></td>
<td>50 (35 times)</td>
<td>40</td>
<td>01-01-2005</td>
<td>01-01-2010</td>
</tr>
<tr>
<td>Nitrogen dioxide (NO₂)</td>
<td>200 (18 times)</td>
<td>40</td>
<td>01-01-2010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ozone (O₃)</td>
<td>180 (information) 240 (alarm)</td>
<td>120 (25 per 3 years)</td>
<td></td>
<td>01-01-2010</td>
<td></td>
</tr>
<tr>
<td>Sulfur dioxide (SO₂)</td>
<td>350 (24 times)</td>
<td>125 (3 times)</td>
<td></td>
<td>01-01-2005</td>
<td></td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td></td>
<td>0,5</td>
<td></td>
<td>01-01-2005</td>
<td></td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>10.000</td>
<td></td>
<td></td>
<td>25-08-2005</td>
<td></td>
</tr>
<tr>
<td>Benzene (C₆H₆)</td>
<td></td>
<td>5</td>
<td></td>
<td>01-01-2010</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1  http://www.vrom.nl/Docs/milieu/200711_WijzigingswetWm_luchtkwaliteit.pdf

Inner street

For the street and the buildings the limits for the protection of human health may not be exceeded. Besides this limit it is always better if the pollution levels can be lowered even more, so that a clean environment is created.

Buildings

The air supply in the building can be arranged in two ways, namely mechanical and natural. It is probably practically necessary to use mechanical ventilation because of the depth of the building. This allows the air to be filtered at a central point. Besides these mechanical ventilation it is often still pleasant to be able to open a window. This means that this air must be clean enough to do this. It is probably not feasible to open windows above the highway, but on the side of the street it should be possible.
3.3 Data

PM10

Figure 3.2 PM10 levels in Europe
(http://www.merlin-project.de)

Figure 3.2 shows that looking at the scale of Europe the Netherlands and Belgium have the highest levels of PM10.

 Everywhere in the Netherlands there is a background concentration of PM10 in the air. But not all of these particles are harmful, like for example sea salt. This background concentration consists of domestic traffic, sea salt, earth dust, industrial PM10 and additions from abroad like Figure 3.3 shows. The traffic is a major source of PM10, which is mainly due to combustion engines but as well to brake and tire wear. Passenger cars (and trucks to a lesser extent) contribute most to the total PM10 emissions (both combustion and abrasion of tires, brakes and road surfaces). This is caused by the relatively high wear emissions from passenger cars. The following figure shows that close to and above the highway the traffic gives a major contribution to the total concentration of PM10 in the air.

Figure 3.3 PM10 concentrations
(Kortmann, 2005)
The A4

Figure 3.4 gives the concentration of NO2 and PM10 at various distances from the part of the highway at the building location. In this figure is for every road section a normative cross-section with the concentrations of air pollutants and the number of days exceeding the daily average limit included.

The absolute contributions of most vehicle categories to the NO2 and PM10 concentrations decrease. Exceptions are the contributions of the significantly increasing number of diesel cars on the NO2 concentration and the contributions of all categories to the PM10 emissions from abrasion. The latter is caused by the growth of road traffic in the coming years.

Despite the increase of PM10 emissions by wear, the road contribution on the total PM10 concentrations at all locations decreases. This is because the combustion gases of vehicles progressively get cleaner and because additional policies (ie stimulation of particle filters) are used to reduce PM10 emissions by combustion. The PM10 emissions from abrasion have a growing share of the total PM10 emissions.

(Kortmann, 2005)

Comparison of the requirements and data
<table>
<thead>
<tr>
<th></th>
<th>Limit</th>
<th>Measured value</th>
<th>Excess</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO2 (μg/m³ as yearly mean concentration)</td>
<td>40</td>
<td>63</td>
<td>157.5 %</td>
</tr>
<tr>
<td>PM10 (μg/m³ as yearly mean concentration)</td>
<td>20</td>
<td>40</td>
<td>200%</td>
</tr>
<tr>
<td>PM10 (μg/m³ as 24-hourly mean concentration)</td>
<td>7 days a year exceeded</td>
<td>71 days a year exceeded</td>
<td>1000%</td>
</tr>
</tbody>
</table>

Table 3.2 Comparison of the requirements and data

Table 3.2 shows that despite the prospects that the NO₂ and PM10 concentrations will decrease in the future, they will probably still exceed the limits. Therefore it is necessary that these values at the building location are diminished.

To diminish these values there are several solutions possible. You could either dilute, filter or absorb the pollution in the air. At a building scale the dilution of the contaminated air by a good air flow could be a good possibility, whilst at a smaller scale the filtering and absorption of the pollution is a good manner to reduce the pollution. All these possibilities are further described in chapter 6 and 7.
4. Wind climate

4.1 Introduction

Besides a good air quality it is also important that there is a good wind climate at the building location. You don’t want people to be blown away and hindered by the wind, because this reduces the quality of the space as well. Like explained at the end of the previous chapter the air flow and thus the wind could be used to diminish the pollution in the air by dilution of the contaminated air. Therefore the wind and the air quality have a close cooperation.

Wind climate

Wind affects a person and his surrounding environment. Thus can be hampered when the wind exercises to much force on a human and therefore impedes the movements. These mechanical effects of the wind should also be taken into account in the construction of buildings. Furthermore, the wind affects the comfort of a person. A cool breeze on a hot summer day can be experienced as pleasant, while the same breeze is on a cold day much less welcome. And a child and an elderly man react different on the wind than an adult. Like mentioned before another aspect of the wind is the influence it has on the transport of gases and substances in the air. Especially near a highway that is an important fact. The aim here is to supply enough clean air and to prevent that pollution sticks for a long time, so that dilution of the contaminated air occurs. In order to obtain relatively clean air it is important to catch it not too close to the road but at a higher altitude. By using the wind to dilute the contaminated air, it is important to keep in mind that it should not hinder the people at the streets too much.

Currents

Air flows are on a great height above the earth's surface and at a distance of 10 till 12 km they define as well the climate of a country. The movements of the lower 500 meter, called the boundary layer flow, have a directly impact on humans in the form of wind or storm. The airflow can be distinguished in an "outer flow" ([buitenstroming] and the “boundary layer flow” (grenslaagstroming). The outer flow is caused by thermal and Coriolis forces. The boundary layer is influenced by the outer flow and also by the roughness of the earth surface. This roughness determines the flow velocity profile and the thickness of the boundary layer flow. (van Voorden, 1982)

![Figure 4.1 Layers above the city (Oke, 1988)](image)

Above the city are three air layers (Figure 4.1):
- The atmospheric boundary layer like mentioned before.
- Urban (internal) boundary layer above the roofs of the buildings; here the flow is adjusted to the roughness of the city. The rougher the terrain the higher the boundary layer (though never higher than the height of the mixed layer).
- Urban canopy between the buildings, the flow is now mainly determined by the geometry of the buildings. (Oke, 1988)

Wind Speed

The wind speed appears to vary greatly over time, even in a period of a few seconds there are strong changes. Therefore, the average rate is calculated over a period of eg one minute or one hour. The peaks above this average are called the wind gusts.
There are three average wind speeds of interest for predicting the local wind climate, namely:
- $U_{loc}$: local hourly wind speed at pedestrian height (1.75 m)
- $U_{pot}$: (the potential wind speed) hourly wind speed at a meteorological station, corrected to 10 m height on an uniform grassy plain with roughness length $z_0 = 0.03$ m
- $U_{ref}$: a local reference speed near the location, but outside the zone of influence of individual buildings.

Often the speed at 10 building heights upstream at roof height $U_{ho}$ is taken as the reference speed. Another reference speed is $U_{0(z)}$, which is the wind speed at the same height as $U_{loc}$ if there wouldn’t be a building. (Van Esch, 2009)
4.2 Requirements

Wind discomfort
Wind discomfort depends on many factors, including factors that are dependent on individuals (such as the type of activities that people perform and the psychological state of them) and factors that are dependent on the wind (eg wind and wind gusts). This makes it difficult to find a criterion for wind discomfort in which all factors are incorporated. A way to determine whether an area is affected by the wind, is by looking at the wind speed or the wind discomfort parameter.

- Wind speed

<table>
<thead>
<tr>
<th>activiteitengebied</th>
<th>voorbeeld van gebied</th>
<th>aanvaardbaar</th>
<th>hinderlijk</th>
<th>onaanvaardbaar</th>
</tr>
</thead>
<tbody>
<tr>
<td>doorloopgebied</td>
<td>trottoirs, fietspaden</td>
<td>&lt; 35</td>
<td>35 - 75</td>
<td>&gt; 75</td>
</tr>
<tr>
<td>slentergebied; overdekt doorloopgebied</td>
<td>winkelcentra, gebouwingsangen, treinperrons</td>
<td>&lt; 5</td>
<td>5 - 35</td>
<td>&gt; 35</td>
</tr>
<tr>
<td>verblijfgebied korte duur; overdekt slentergebied</td>
<td>pleinen, overdekte winkelcentra</td>
<td>&lt; 0,1</td>
<td>0,1 - 5</td>
<td>&gt; 5</td>
</tr>
<tr>
<td>verblijfgebied lange duur; overdekt verblijfgebied</td>
<td>terrassen, openluchttheaters</td>
<td>–</td>
<td>0 - 0,1</td>
<td>&gt; 0,1</td>
</tr>
</tbody>
</table>

Figure 4.3 Amount of days a year the hourly wind speed at head height may be more than 5 m/s

Figure 4.3 shows that only a few days a year the wind speed at head height may be more than 5 m/s, if you want to create a comfortable area. The ambition is to ensure that people suffer as few as possible from wind discomfort, so the inner street can be used as well for terraces and other outdoor activities. According to Figure 4.3 it is unacceptable when there are more than 35 days a year, so around 10% of the time, when the wind speed at head height is more than 5 m/s.

- Wind discomfort parameter

With grain erosion tests the wind discomfort is set by the reference speed $v_r$, at which an area with a building is purged. This speed is compared to the reference speed $v_{w,r}$, at which an area without a building is purged. The wind discomfort parameter is $\gamma = v_{w,r} / v$ (Beranek, 1979). Discomfort occurs when the wind discomfort parameter is $\geq 1.6$.

For this research the wind speed is probably the most obvious method to measure the wind discomfort.
4.3 Data

Wind roses
On different KNMI meteorological observation stations in the Netherlands measurements are taken for the wind speed and direction. This is usually done at 10 meter height in little cultivated land and they use the hourly averages for the measurements. The wind rose shows the probability of wind speeds in different directions. In the middle of the rose is the percentage of windless weather indicated.

![Wind roses](image)

Figure 4.4 Wind roses close to the location

Formula
The velocity profile can be described by the following exponential formula. With this formula the average horizontal wind speed at different heights within the boundary layer can be calculated.

\[ V(z) = V_G \left( \frac{z}{z_0} \right)^\alpha \]

- \( z_0 \): height above the earth surfaces of the separation between the boundary layer flow and the outer flow
- \( V_G \): mean wind speed on gradient height
- \( \alpha \): coefficient that depends on the terrain roughness

There are different types of terrain with different wind speed profiles. Figure 4.5 shows the three types of terrains that are normally used.
Figure 4.5 Wind speed profile for three terrain types (van Voorden, 1982)

The measurements of the wind rose are taken on an open field on 10 meters height. Therefore you can relate the measurements to open sea, desert area.

This gives the following values
\[
\begin{align*}
Z_G &= 250 \text{ m} \\
Z &= 10 \text{ m} \\
\alpha &= 0.11
\end{align*}
\]

The wind rose shows that the average from the measurements at \( v(10) \) is 4.5 m/s

Approximately:
\[
V(10) = V_{250} \left( \frac{10}{250} \right)^{0.11}
\]

\[
V(10) = 0.7 \times V_{250}
\]

\[
V_{250} = V(10) / 0.7
\]

\[
V_{250} = 4.5 / 0.7
\]

\[
V_{250} = 6.4 \text{ m/s}
\]

For the location the type; small town, forested area could be applied. When you implement the value from the former formula, you get the following result:

\[
V(10) = V_{400} \left( \frac{10}{400} \right)^{0.25}
\]

\[
V(10) = 6.4 \left( \frac{10}{400} \right)^{0.25}
\]

\[
V(10) = 2.56 \text{ m/s}
\]

However this result of the wind speed at the location is quite general and can’t really predict that the boundary conditions for a good wind climate will be met. Therefore measures need to be taken to provide a good wind climate. In chapter 6 and 7 those measures will be discussed.
5. Noise

5.1 Introduction

The road traffic noise is caused by various sources. For instance, the drive of vehicles produces noise and then especially the engine and exhaust are important noise sources. High noise levels are achieved mainly when accelerating, driving at high speeds and braking.

Another source is the rolling noise of the tires on the ground. Tires get in vibration due to the forces that are exercised on it, which produces the so called "rolling noise. This noise depends on the roughness of the surface of the road, the tire type and the structure of the ground. The rolling noise is for each combination of tire and road surface type different. In general, the wider the band, the coarser the structure and density of the ground, the more noise that is produced.

At lower speeds of vehicles the engine and the exhaust are the main noise sources. At speeds above 30 to 40 km/h (depending on the type of pavement) the rolling noise becomes dominant. Aerodynamic noise plays only a role at speeds above 180 km/h.

In the case of the highway, the road noise is dominant, except when there is congestion. Then the sound of accelerating and braking traffic gets more important.

The effects of road traffic noise

The noise produced by road traffic is in the Netherlands a major source of nuisance, namely, 25 to 30% of the population says to be severely hindered by this noise.

Recent calculations shows that on more than one third of the Dutch surface the quality of the environment is harmed by road traffic noise. This not only affects humans in a negative way but also animals (eg the breeding activities of birds).

Noise during the nighttime has as well adverse effects on sleep, like motility, self-reported awakening, and heart rate increase. The sleep quality decreases when the road and railway noise exposure indoors increases during sleep. (Passchier-Vermeer, 2007)

Road Traffic Noise Spectrum

For cars the dominant noise comes from the vicinity of the tires and therefore the overall source height is at ground level. The same goes for light trucks. For heavy trucks it is a different story, because it has multiple sources. Among the most important are the exhaust noise, engine noise, tire noise, radiated noise from the side panels and the flow noise of the truck itself. (Hayek, 1990)

![Figure 5.1 Normalized noise spectra for cars and heavy trucks (Hayek, 1990)](image-url)
5.2 Requirements

Building
In the Building Act are requirements, concerning sound level, for different functions indicated. (Appendix II). These determinations show that there is a sound level limit of 40 dB for offices. However there is nothing indicated about sport and commercial spaces, but we can hold the same value for these spaces.

Inner street
In the table is indicated what kind of activities belong to the different noise levels.

<table>
<thead>
<tr>
<th>dB(A)</th>
<th>Experience</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Threshold of audibility</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Just audible</td>
<td>Normal breathing, falling leaf</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>Tree leaves in the wind, whispering on 1,5 m</td>
</tr>
<tr>
<td>30</td>
<td>Very quiet</td>
<td>Library (30-40 dB), soft whispering on 5 m, recording studio</td>
</tr>
<tr>
<td>40</td>
<td>Living room, bed room, a quiet office, a quiet neighbourhood, birds at sunset</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Quiet</td>
<td>Light traffic at 30 m, own office room, refrigerator, rain, in the forest</td>
</tr>
<tr>
<td>55</td>
<td></td>
<td>Caffeemaker, electrical tooth brush (50-60 dB)</td>
</tr>
<tr>
<td>60</td>
<td>Intrusive</td>
<td>Air conditioning (50-75 dB), normal conversation, washing machine (50-75 dB), F16 jet at 6000 m (59 dB)</td>
</tr>
<tr>
<td>70</td>
<td>Disruptive at phoning</td>
<td>Crowded office, electric shaver (50-80 dB) vacuum cleaner (60-85 dB), car at 15 m</td>
</tr>
<tr>
<td>75</td>
<td></td>
<td>Elektr mixer, coffee grinder (70-80 dB), crowded restaurant (70-85 dB), F16 jet at 3000 m (74 dB)</td>
</tr>
<tr>
<td>80</td>
<td>Nuisance, annoying</td>
<td>Alarm clock at 0.7 m, hair dryer (60-95 dB), noisy office, heavy traffic (80-85 dB) at 15 m, flushing the toilet (75-85 dB), door bell, ringing phone, machine tools, pneumatic tools at 15 m.</td>
</tr>
</tbody>
</table>

Table 5.1 The experience of different sound levels

For the inner street a sound level of 60 dB seems reasonable. There will be people and activities at the street, so some sound is allowed at the street.

Façade
In the “Wet geluidhinder” there are also regulations for the sound load on a façade of a dwelling. In this project there aren’t any dwellings in the building, but it’s still interesting to keep these regulations in mind. The maximum façade load along a road is 50 dB, but this isn’t feasible in most occasions. Therefore they are exemptions made:
- For a new road and new dwellings in an outside urban situation a load of 55 dB is allowed.
- For an existing road and new dwelling in an inner urban situation a load of 65 dB or even 70 dB is allowed.
5.3 Data

Measurements

At a Monday during the traffic peak hours between 16:30 – 18:00, when the traffic pressure was the highest, the sound level was tested. The highest sound level value that could reach the façade was thus tested. At different places the sound level was tested; two times above the highway (A+D), one time besides it (B) and one time under the highway(C). This was done to see the influence of the relative position to the highway on the sound level.

Locations
A: over the A13
B: besides the A4 at the location
C: under the A4 at the Prins Clausplein
D: under the A4 north of the Prins Clausplein

Figure 5.2 An overview of the measurement locations
Measurement equipment
The test was performed with a sound meter. At first the sound level, averaged over one minute, was measured, which was done five times at each location. With the peak measurement the highest sound level could be determined. The sound level increased for example when a motor or a truck drove by. With the fast measurement you could see the fluctuation of the sound level on the screen.

<table>
<thead>
<tr>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Point</strong></td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>D</td>
</tr>
</tbody>
</table>
The mean of the measurements above the highway is around 80 dB.  

With this data you could also calculate the sound level at various distances from this source.  

The sound power level for a line source in the free field is:  

\[
L_P = L_R - 10 \log \pi R \quad \text{[dB]}
\]

The measurement on the bridge was at a distance of around 6 m from the line source. The sound level of the line source was then:  

\[
80 = L_P - 10 \log 2 \pi 6 \quad \Rightarrow L_P = 95,8 \text{ dB}
\]

When calculated for different heights:

<table>
<thead>
<tr>
<th>The amount of meters above the ground</th>
<th>The amount of meters above the bridge</th>
<th>Sound level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0</td>
<td>80,0</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>78,8</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>77,8</td>
</tr>
<tr>
<td>12</td>
<td>6</td>
<td>77,0</td>
</tr>
<tr>
<td>14</td>
<td>8</td>
<td>76,4</td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>75,8</td>
</tr>
<tr>
<td>18</td>
<td>12</td>
<td>75,3</td>
</tr>
<tr>
<td>20</td>
<td>14</td>
<td>74,8</td>
</tr>
<tr>
<td>22</td>
<td>16</td>
<td>74,4</td>
</tr>
</tbody>
</table>

So upwards there is roughly a difference of 5,6 dB over the facade.

Data

Figure 5.4 Measured sound level around Prins Claus Plein
Figure 5.4 shows the sound level measured by Rijkswaterstaat around the Prins Claus Plein. These values are quite similar to the other measured values. On the highway the sound level is more than 75 dB and close next to the highway it’s around 74/75 dB.

**Calculating sound levels**

There are also possibilities to calculate the noise level on the basis of the class-1-method or the class-2-method. By splitting the traffic into four categories and by classifying and identifying their number on the road per hour, this method can calculate the noise level.

The calculation results between the two methods may differ. SRM-II is more extensive than SRM-I. SRM-I is consistent with the approach that it is an infinitely long straight road (per vehicle category).

At SRM-II the road is divided into road segments and it’s examined for each octave band. SRM-II is not a hand methodology and is only applied when a forecast based on SRM-I is insufficient. SRM-II can be used when there are buildings and screens which can reflect the sound.

The calculation of the sound levels with these methods is not used for this report.

**Comparison of the requirements and data**

The sound level pressure at building level will have a maximum of 80 dB. For the offices the final sound level should be diminished with 40 dB, to reach an 40 dB sound level inside the offices and for the inner street an decrease around 20 dB is required. This gap could be solved with a façade and a sound screen in front of the building. In chapter 8 these possibilities will be tested.
Part II Research
6. Building scale: air quality and wind climate

6.1 Introduction

There are three methods to reduce the air pollution, namely dilution, filtering and absorption of the pollution in the air. With dilution the polluted air is mixed with cleaner air, so the overall concentration of pollution in the air decreases. With filtering the pollution gets attached to a surface and is removed from the air. With absorption, the pollution is absorbed by the material, which happens especially with vegetation.

On a building scale dilution is probably the best way to reduce the air pollution. On such a scale you could influence the wind flow and increase the mixing of the air. By increasing the mixing of the air a good wind climate still needs to be maintained. Therefore it is interesting to research how you could have a cleaner air flow through the street and have a good wind climate as well.
6.2 Wind climate

To provide a pleasant wind climate in the streets the building configuration is researched. The configuration that is tested, consists out of two parallel lying building blocks, on which the wind direction is most of the time perpendicular on the long façade like shown in figure 6.1. To find out what the best configuration and dimensions of these buildings are, a literature study has been done and the wind comfort is tested in Knowind.

![Figure 6.1 The building in the situation and main wind direction](image)

**Literature**

*Wind discomfort for a single building*

Various tests show that when the wind is parallel to one of the main axes of the building, the following symptoms occur:
- The height of the building has a dominant influence
- The length of the facade has a relatively strong influence
- The length of the side has the least impact (Beranek, 1979)

*Wind discomfort for two buildings with their long side in one line*

There is no interaction between the buildings when the areas of influence don’t overlap. This is the case when \( t > 2.5 \) h. When the distance between the two buildings is less than \( \frac{1}{3} \) of the height, the overall image of the wind discomfort is the same as with one continuous building. However in the opening there still will be high wind speeds. This also happens at an opening under the building, where at the underpass a “blowhole” is created with maximum wind discomfort like at building corners. But where the flow (the size of the area over which wind discomfort occurs) is smaller, because the opening is smaller. The size of the underpass has little influence on the wind speed though, but the flow, which is a measure for the discomfort, depends on the width of the opening. The wind discomfort in the opening is the largest at a distance between \( 2h \) and \( h \). At a smaller distance than \( h \) the size of the area where the wind discomfort occurs diminishes (Beranek, 1982).

![Figure 6.2 Two buildings with their long side in one line](image)

![Figure 6.3 Wind flow through a small opening and an underpass](image)
**Wind discomfort for two buildings in a row**

For two buildings in a row the wind speed between the buildings is less than the wind speed behind a single building. When the street width is quite large in respect to the building height and the length is > 3h a skipping vortex may occur behind both buildings at wind directions between 30° and 60°.

At smaller distances between the buildings and with the wind perpendicular to the wall, the corners of the façade, which is in the wind shadow, have significantly smaller discomfort, like shown at Figure 6.4.

By obliquely incident wind, most of the protection is lost and the wind speed between the buildings increases by displaced corner flows. (Beranek, 1982).

**Channelling effect**

The channelling effect are high velocities that are maintained between long, unbroken rows of buildings like in Figure 6.5. This effect occurs when the distance between the rows is less than 2H and when H> 6m. It can be reduced by making "holes" by which the continuous character is disturbed and by placing small building masses against the long rows of buildings (van Voorden, 1982).

**Crossing canyons and streets**

Streets perpendicular to the wind direction are more susceptible to wind nuisance than streets parallel to the wind direction. Like shown in Figure 6.6 this is due to cross currents that occur as a result of varying pressure from turbulence on the streets parallel to the wind direction. This makes the air in the side streets alternately 'sucked' to the left and the right. (Beranek, 1982).

For the occurrence of cross currents and the intensity of them a certain street length is required. At junctions low pressure areas can arise and horizontal vortices can be formed. In relatively short streets these corner vortices can be strong enough to resist the forming of a stable vortex in the canyons and streets perpendicular to the wind direction (Vardoulakis, 2003).

**Conclusions**

- The building should not be too high
- The street should not be too width in respect to the building height
- The street should not be too long without interruption, because of the channeling effect, therefore it’s better to make openings in the building blocks
**Knowind**

The program knowind can give a prediction of wind speeds around maximal two simple geometric shapes. This program was developed by TNO Apeldoorn and is based on the results of numerous wind tunnel studies. Whether wind discomfort occurs is assessed by reference NEN 8100.

With this program an attempt is made to test the impact of the building dimensions and their configuration on the wind climate in the passage. The testing of different heights, lengths and widths of the building and different widths of the passage showed that the wind discomfort was reduced mainly by:
- A lower building
- A wider passage

The influence of the length of the passage was more difficult to determine. An underpass gives worse results than when the passage is open upwards.

![Figure 6.7 Knowind test result](image)

Figure 6.7 shows the configuration with the least wind nuisance. The colours show the amount of days a year that the wind speed of 5 m/s is exceeded and the bluer, the less wind nuisance. Especially in the front and the rear of the building the wind nuisance is less than in the passage and at the corners of the building. Directly at the corners of the passage the wind nuisance is also less than in the middle of the passage. However, according to this test the amount of days the wind speed of 5 m/s is exceeded is around 40 / 50 days in the passage, which is more than the 35 days which were set in chapter 4.2 and Figure 4.3. Therefore some additional measures could be taken to improve the wind comfort further.
6.3 Air quality

Like described before, the wind flow could influence the pollution of the air as well. Therefore it is interesting to see how they could positively influence each other.

Literature

The two-dimensional flow pattern
When a street is quite long and narrow, it is also called an urban canyon. In streets where l > 10h, a two-dimensional flow pattern of the wind dominates. Several studies have been done about this two-dimensional pattern, whether or not in relation to the spread of pollution in the canyon. Especially this relation is very interesting for the research. For the canyons a distinction can be made between a symmetrical and asymmetrical canyon. The size of a canyon is expressed as the ratio between height H and width W and the distance between two (major) intersections / side streets is called the length of the canyon.

Symmetrical canyon

Figure 6.8 Symmetrical canyon with different ratio (Xiaomin, 2006)

For wind perpendicular on the canyon the following flow patterns are confirmed at the research of Xiaomin; skimming flow, wake interference flow and isolated roughness flow. As well a link is made with the H/W ratio.

Isolated roughness flow: H/W < 0.1
Wake interference flow: 0.1 < H/W < 0.67
Skimming flow: 0.67 < H/W < 1.57 one main vortex
1.57 < H/W < 3.2 two counter rotating vortices
H/W > 3.2 three counter rotating vortices

At Figure 6.8 these different vortices are shown.
An obliquely incident wind can, by reflection of the wind from the windward wall of the canyon to the sides, create a spiral flow in the canyon.

Asymmetric canyon
The canyon can also be asymmetric, when the facades don’t have equal heights. So there can be a step-up canyon, when the second wall is higher and a step-down canyon when this wall is lower.
The distribution of the pollution in the canyon varies, depending on the geometry of the buildings. For a symmetrical canyon the most pollution is formed at the lower left corner of the building. The pollution levels can rise to 27% from the upper corner of the wall to the bottom. When the left building height is reduced and a step-up notch is created, the pollution levels reduce as well. For a step-down notch pollution levels rise on both sides. In the case of a step-up notch the ventilation in the canyon is reduced, because the interaction with the wind flow above the canyon is weaker. (Assimakopoulos, 2003).

Table 6.1 shows that the higher and the further away from the highway you catch the air, the cleaner it will be. A good possibility could be to catch this air from a higher altitude and bring it into the streets. This idea resembles the idea of a “wind catcher”, like at figure 6.10, which is used in the Middle East to bring a wind flow into the houses. In this case the wind could be brought in the streets by creating a difference in height of the building blocks, like a step-up notch.

Table 6.1 Calculated fine dust concentrations µ g m⁻³ next to a four-lane highway with 100,000 vehicles a day and 14% freight for average neutral conditions. As background concentration 20 µ g m⁻³ is taken

![Figure 6.9 The different canyons (Assimakopoulos, 2003)](image)

![Figure 6.10 An Iranian wind catcher](image)

Conclusions
The research of Xiaomin and Assimakopoulos show that a step up notch creates the lowest pollution levels in the street. Therefore a step-up notch directed to the main wind direction is a good possibility. It is as well a good manner to catch the air not too close to the highway and bring it from a higher altitude into the streets. However a step-up notch also reduces the ventilation in the canyon, but the air shouldn’t stay too long at the same place in the streets. A good possibility is to create openings in the street wall, to improve the wind flow through the streets, like shown at Figure 6.6. Like mentioned in the former paragraph, openings in the street also prevent the channeling effect.
**Ecotect**

Using the programs ECOTECT and Winair CFD calculations can be made and different mass configurations can be tested on their wind patterns. With these programs it can be considered whether it is better for the building to perform as a long strip or that openings in the strip yield a better flow pattern. When openings perform better, the place of the openings could also be tested.

**Ecotect and Winair**

The software ECOTECT is an instrument developed by Dr Andrew Marsh, a former lecturer at the University of Cardiff, Wales. Like any other simulation software, ECOTECT cannot claim that it can do all the built environment simulations, but ECOTECT can import and export other data files from other software such as Energy Plus and Radiance. A software that is needed to simulate air movement, should be a CFD (computational fluid dynamic) software. Winair is such a software and is only developed for research purposes within the University of Cardiff (it is not commercially available). Data from CFD results can then be imported into ECOTECT and is presented in a graphical interface. As this program is produced within a university and is used also for research purposes, it can be regarded as somewhat reliable.

The program has as well its limitations:
- At a wind calculation only one wind direction and wind speed at a time can be analyzed.
- Probably the application is primarily for projects on a small scale.
- There are some tests with wind flow through an urban environment. However, the wind direction and the initial wind speed are determined by the user. This can roughly be estimated at a more exposed terrain, but it is harder to assess in a complex urban area.
- Using speed and direction from a wind rose that can be accessed in the program also has its limitations because wind is measured primarily on a high altitude where the speed is faster and is not yet destabilized by ground-borne turbulence. (www.csupomona.edu California State Polytechnic University Pomona)

The computational domain for CFD calculations

In the COST Action C14 is a recommendation prepared for the computing domain with CFD calculations. Here, the inlet and the sides of the domain should be 5 (maximum) building heights away from the front and sides of the buildings and the outlet should be 15 (maximum) building heights away from the rear of the buildings. The field is 6 (maximum) building heights high (see Figure 6.11). The barrier percentage - the part of the diameter of the domain perpendicular to the wind direction that is occupied by buildings - should be less than 3 percent. This may mean that the domain must be higher than 6H. (Franke et al, 2004)

![Figure 6.11 Domain of the CFD calculations (Franke et al, 2004)]
**Method**

These rules are also applied to the domain for the CFD calculations in ECOTECT. The total masses together have a size of b x l x h; 160 x 60 x 16.

Here the inlet and the sides of the domain are 5 x 16 = 80 m away from the front and sides of buildings. The exhaust is 15 x 16 = 240 m away from the back of the building. Because the barrier percentage should be less than 3 percent, the height of the computing domain becomes larger than 6H. The barrier surface is 16 x 160 = 2560. By this the diameter of the domain is least 2560 / 0.03 = 85,333. The height of the domain is then 85333 / 320 = 266.7. What means it is 266.7 / 16 = 16.7 = 17 H.

**Results**

**Variant 1**

![Figure 6.13 Flow rate on 1,75 m](image1)

![Figure 6.14 Flow vector on 12 m](image2)

**Variant 2**

![Figure 6.15 Flow rate on 1,75 m](image3)

![Figure 6.16 Flow vector on 12 m](image4)

**Variant 3**
Conclusions

The results show that with openings in the blocks the flow through the side streets increases. When the openings are shifted from each other, the flow through the street perpendicular to the wind flow also increases (see Figure 6.17 and 6.21). The study does not clearly show the “wake effect” (zogeffect) of the side streets, which is discussed in the literature at paragraph 6.2. Probably the program is not advanced enough to take these kind of effects in their calculations.
6.4 Conclusions and recommendations

The research is split into two aspects, which is the wind climate and the quality of the air.

The research for the wind climate showed, that the buildings shouldn’t be too high and the street shouldn’t be too width in respect to the building height. Another aspect was that the street shouldn’t be too long without interruption to avoid the channeling effect, which are high air speeds between long, continuous rows of buildings. Therefore it is better to make openings in the street wall.

Knowind showed that in the passage between two buildings the wind climate was at some places still uncomfortable and therefore additional measures needs to be taken to improve the wind climate at that spot. A possibility could be a screen which is placed at the opening which still allows the air to flow through. These options will be further discussed in chapter 7.

The research for the air quality showed that the further away from the highway you catch the air, the cleaner it will be. Therefore it will be better to catch the air from a certain height. This could be done by creating a step-up notch (Figure 6.9) which brings the air from a higher altitude to street level. A step-up notch creates as well the lowest pollution levels in the street (Assimakopoulos, 2003). But on the other hand the ventilation in the canyon is reduced by a step-up notch. For the improvement of the air flow through the street and the increase of dilution of the air, it is also better to make openings in the street wall. Like mentioned before openings in the street also prevent the channeling effect.

Figure 6.23 Air flow through a street with a closed street wall

Figure 6.24 Air flow through a street with openings in the wall

Ecotect showed that when the openings are shiftet from each other the air flow through the side streets improves.

As well from an architectonic point of view it is desirable to make openings in the street wall to have a (visual) connection between the street and the highway. People become aware that they are actually crossing a highway at that point.

Because of these openings there is the risk that the air that comes through these openings is more polluted than the air you catch from a higher altitude. So it is important that the air which enters the street in this way is filtered before it enters. A screen in front of the openings could be used to filter the air. Like mentioned before such a screen could also improve the wind climate at the opening. Another advantage is that these screens can function as well as noise barriers. In chapter 7 the screen will be further discussed.
7. Screen: Air quality and wind climate

7.1 Introduction

Like discussed in chapter 6 is dilution of the air a way to diminish the pollution. The other possibilities are filtering and absorption of the pollution, which will be discussed in this chapter. In chapter 6 was stated that a screen in front of the openings in the street could improve the air flow behind it and could as well be used to clean the air further by absorption and filtering of the pollution. Therefore the main focus in this chapter will be on the screen and how it contributes to a liveable area above the highway, where it is pleasant to stay and where it’s possible to open a window to the street, without being hindered too much.
7.2 Means to clean the air

There are different means that contribute in cleaning the air from PM10 and NOx. These means can mainly be divided in:

- natural materials (like plants, moss and coconut shells)
- stone materials (like granules and aggregates)
- additions to a material (like paint)
- water
- air flow

Fine particles (PM10) need to be attracted and captured to get them out of the air. To make nitrogen (NOx) harmless it needs to be totally converted into nitrate (NO3) or nitrite (HNO2)

Natural materials

1. Vegetation

Plants affect the air quality because particulates and gaseous pollution are effectively removed by vegetation. Also the wind speed changes by the planting and turbulence can occur especially by trees. The greater the range of pollution, the more the vegetation absorbs or captures. For the vegetation it is however important that they receive sunlight. Gaseous pollutants and particulates are absorbed and captured in different ways by the vegetation.

Gaseous pollutants

Gaseous pollutants are only taken in by the leaves of the vegetation and this is done through the stomata and the cuticle.

- Stomata

The stomata are lockable openings in the leaf through which continuous gas exchange between leaf and environment occurs. Through these stomata a large network of internal cavities is in contact with the outside air. These cavities increase the surface of the leaf and hence the capacity of the gas exchange. From these cavities, carbon dioxide (CO2) is absorbed into the cells of the leaf and water (H2O) and oxygen (O2) are issued to the air (Figure 7.1). Also ozone and nitrogen oxides enter the leaves mainly through the stomata, which is called absorption. These gases are very soluble and absorbed quantities can be processed well in the leaf. Nitrogen (NOx) is converted into nitrite/nitrate, which is as well food for the plants. Nitrogen oxides can also be harmful to plants, therefore the sensitivity of plants must be taken into account when trees and shrubs are planted to reduce the concentrations of nitrogen oxides. Usually the stomata are open during the day and closed at night.

- Cuticle

The cuticle is the outermost layer of the leaf which is a fatty substance that protects the plant for example from dehydration. For many volatile organic compounds such as PCBs, dioxins and furans the cuticle is the main route of intake. This process is called adsorption. These substances are often insoluble in water but are soluble in the fatty components of the cuticle. The uptake through the cuticle has the advantage that it continues during the night, when the stomata are closed, and in the winter months when the green plants are little active. After the intake in the cuticle, the volatile organic compounds are gradually issued to the interior of the leaf. (Hiemstra, 2008)

Particulates (PM10)

Unlike gaseous pollutants where only the leaves are important, the whole plant or tree plays a role with particulates. By gravity or impaction particulates come in contact with the vegetation. With impaction the particles ‘collide’ on the plantation. The particles should therefore come directly into contact with the vegetation or should be close enough to the vegetation to be electro statically attracted. Unevenness on the
leaf as a rough surface and leaf hairs enhance this process. Also the degree of moisture and "stickiness" of the leaf is an influence. The particles remain on the outer surface of the plant or tree. For the capture of particles it doesn’t matter in principle whether or not the leaves and needles of trees are dead or alive, as long as they come into contact with the polluted air. An average city tree captures each year around 100 grams of particles. A mature tree captures net 1.4 kilograms per year. After the capture a part of the particles remains attached. Another part comes off the leaf by relatively strong wind or is washed from the leaf by rainwater. Once on the ground, the particulates are washed into the drain by water or is attached to the bottom where it is stored for a long time. Some compounds that are attached to the particulates, can be inactivated in the soil.

![Figure 7.2 Particles on the leaf of a virginia creeper in June (Hiemstra, 2008)](image1)

![Figure 7.3 and in October](image2)

Different types of vegetation are effective for different pollutants. The following division could be made:

**Particulates**
- Conifers
- Deciduous trees: trees with rough and hairy leaves
- Evergreen species
- Species with a large leaf surface

**Nitrogen oxides (NOx)**
- Deciduous trees and then especially trees with smooth and flat leaves
- Species with a large leaf surface

Besides the criteria that the vegetation should either capture particulates or absorb nitrogen oxides and ozone well or even better do both, there are also other criteria which should be considered when incorporating plants and trees in this environment:

- Location; they should for example be placed at a spot where they receive enough sunlight
- Climate; they should be able to grow in our climate
- Evergreen; to be able to neutralize the polluted air all year
- Ability to withstand the polluted air; besides filtering the air, they shouldn’t suffer too much from this polluted air and then particularly from NOx
- Speed of growth; a fast growing plant needs a lot of trimming and therefore a lot of maintenance
- Available space (above and below); the spatial dimensions of the vegetation should fit properly the available space. As well by placing trees in the streets above the highway, there won’t be soil to plant them, so they should be placed in some sort of box. Therefore the roots of those trees can’t be too big.
- Human allergic reactions to some sort of plants
- Inconvenience of dropping leaves or fluff
Vegetation on the screen

Creepers are at the screen the most suitable plants to grow (Figure 7.4). Different types of creepers could be used (see Appendix III).

Some of the creepers that perform well are shown in Figure 7.5

- **Fallopia**
  - Good for absorbing nitrogen oxides (NO + NO2) and ozone (O3)

- **Hedera - Ivy**
  - Good for capturing particulates (PM10)

- **Pyracantha**
  - Good for absorbing nitrogen oxides (NO + NO2) and ozone (O3)

The ivy (Hedera helix) for example can have per square meter wall three to eight square meter leaves and up to six grams of particulates (Hlemstra, 2008). In addition, this plant is as well evergreen so it functions as an filter the whole year. This feature is especially important for removing particulates. Compared with bare walls ivy means a great increase of the filtering surface.

An example of a product that could be made for vertical vegetation is from wallflore.

The plants are placed on horticultural rock wool (Figure 7.6) which is also a sound absorbing material. Furthermore it’s built out of light weight modular panels with a built-in irrigation system.
2. Coconut shells:
Another material which can be used in as a material in the screens are coconuts.
PM10: these are very fibrous and porous with a large contact surface, fine particles will stick to the diffuse surface, which is called adsorption
NOx: coconut has the ability to bind nitrates permanently to the porous material between the fibers (called kokospeat) through a complex exchange of ions.

Stone materials:

1. Polypropylene granules;
PM10: after the transformation of the granules, the filter is electrostatically charged. The positive and negative charge ensure that the small particles are attracted and captured.

2. Wood fiber concrete:
PM10: it contains fine pores and small cavities, which are surrounded by cement. In this microstructure turbulence of the polluted air occurs. Because the fine particles can’t follow the air flow, they “go off the road” and are captured. (Innovatie Programma Luchtkwaliteit, 2007)

3. Stony residue:
PM10: a good capture occurs by filtration and absorption
NOx: it converts NO and NO2 into nitrate and nitrite

Additions to a material

1. Titanium dioxide (TiO2) also called photocatalytic paint.
NOx: The paint can be applied to buildings, roads, noise barriers and can degrade the nitrogen dioxide (NO2). Using sunlight, the resulting nitrogen oxides (NOx) are converted to relatively harmless nitrate. The coatings will be particularly effective in environments where a high concentration and low air currents are present (e.g., in tunnels is the case). It also lowers the levels of PAHs and benzene

2. Ionizing agent:
PM10: by ionization fine particles are bound to relatively larger particles that precipitate.

3. sticky mineral (for example glue)
PM10: Fine particles get stuck on the material.

4. Electrostatic precipitation:
PM10: this can be divided into active and passive precipitation of aerosol. With passive precipitation a plastic filter material is used, which gets a charge by the flow of air or the dipping in a liquid. With active electrostatic precipitation the aerosol is directed between loaded electrodes. The required voltage is in this case ten kilo Volts and is dependent on the electrode gap. The efficiency of both types of electrostatic filters can be high (> 95%). However, there are some disadvantages too, for example; the passive filters have a certain pressure drop, so pumps are needed. In addition, high voltages are required for the active filters, which may pose a safety risk for people and animals. (Hofschreuder, 2005)
Water

Within the wet deposition two processes can be distinguished; “raining out” (uitregenen) and “washing out” (uitwassen).

PM10: With “raining out” the air is saturated with water vapor, which condenses on aerosols and gas molecules. By growth of the droplets or ice particles, the hydro meteors with solutes can rain out. This process is important in cleaning the air (especially of small particles (0.1-1.0 mm)). It occurs however particularly at altitude in the atmosphere where cloud formation occurs and this process will therefore play no role at short distances to a road.

The second process is the washing out. The pollution is included in the descending rain drops. Because the air flows around a falling drop (including pollutants gases and small particles), this mechanism is ineffective. Removal rates are estimated at 0.1-10% per cent per second. In the Netherlands wet deposition is at about 30% of the estimated dry deposition for soluble compounds. The washout process contributes 10-15% to the wet deposition.

The wet deposition of emissions of traffic in the vicinity of the road is insignificant (less than 3-4%). When water spray is used, a wet road should be avoided in relation to the danger of slipping.

NOx: is not very soluble and has therefore an even lower proportion washed out. (Hofschreuder, 2005)

Air flow

PM10 en NOx: The flow of the air could be used to maximize the filtering of the air. A method, for example, could be to place a porous screen in front of the actual screen to slow the wind down before entering the screen. In this way the fine particles inside the screen could be captured better.

Finally it is important that the deposited material won’t come off again, which won’t happen when the deposited material is tied up by chemical reactions at the surface, absorbed by active elements such as the stomata of plants, dissolved in water, tied up by surface roughness elements and electrostatic powers.

Conclusion

Like discussed in this paragraph, there are several means to clean the contaminated air. Some of them are a bit more effective than others. Especially vegetation is a very effective mean because it deals with particulate matter (PM10), nitrogen dioxides (NOx), carbon dioxide CO₂ and even ozone (O₃).
7.3 Effectiveness of the screen

**Air quality**

There are several ways to increase the effectiveness of screens including the increase of the surface. Trying to increase the surface of the screen by adding different ribs on the screen is limited. Also most of the air would flow over the screen without coming in contact with the screen. Therefore the most effective way to reach an increase in the surface is to allow the air to go through the screen. In this way the screen should be made porous, allowing the contaminated air to enter the screen and create a larger contact area. It can be increased by the use of vegetation or passive constructions. Hereby the dry deposition of gases and aerosols can be increased.

![Figure 7.9 Wind flow over and through a screen](image)

However for NOx, surface enlargement has little effect, because the surface resistance of this substance is very high. Surface enlargement is only useful if the surface is treated with a catalyst (TiO2) or other surfactant, allowing the boundary layer resistance to be reduced. Because at a bare screen the maximum deposition is 2-4% of the total flux (traffic emissions plus background flux). Therefore surface enlargement is necessary to get an appreciable effect. Besides the use of surfactants only increase (read: improve) of turbulent interference with cleaner air has a positive impact on air quality for NOx. (Hofschreuder, 2005)

The fact that it's better to let the air flow through the screen instead of only along the screen also correspond with the conclusions from Chapter 6.

**Wind climate**

It is important that the screen in the opening doesn’t impaire the flow behind the screen. Some options are;

![Figure 7.10 Different options for placement of the screens](image)

From an architectonic point of view, option 2 would be less attractive because it can give an oppressive, culminating feeling. Option 3 would also be less attractive because it doesn’t allow the wind to flow through the screen, but can only flow along it before passing over the screen. Furthermore it probably it enhances the wind nuisance.

To prevent that people are blown away by the wind that enters the street through the openings, measures should be taken to regulate this. There are several studies done about the effect of a windbreak on the mean
wind speed and the turbulence behind such a screen. These studies are related to the porosity of such a screen and the influence of an inclination of a screen.

- The best windbreak porosity for an efficient downwind shelter in these conditions is ϕ= 0.35 (Figure 7.11). It provides the best shelter at large distance and, in short and intermediate distances, it produces a similar protection to a fence with less porosity. (Santiago, 2007)

- For providing significant (10-30%) reductions in mean wind speed near the ground for the largest distance, solid or very dense barriers are apparently less effective than medium-porous barriers, although the difference in protected distance between very dense and medium-porous barriers usually has been exaggerated
- The horizontal extent of wind protection is generally proportional to windbreak height
- Turbulent energy in the lee of windbreaks generally decreases with increasing barrier porosity.
- Dense barriers (with artificial structures, ϕ < ~ 30%) result in a ‘recirculation bubble’ in their lee with increased vertical flow between x~8h and x= 10h and flow toward the barrier near the ground. (Heisler, 1988)

- Inclined screens with the same vertical height as a vertical screen will be more effective than vertical screens.
- A 30° windward inclined windbreak with an open area of about 50% is a better shelter than its vertical position (Dierickx, 2003)

**Conclusions**

A porous screen, where the air can flow through, improves the effectiveness of a screen, because the surface is enlarged and the contaminated air has a larger contact area. A porous screen creates as well a better wind climate behind the screen than a closed one.
7.4 Comflow: air flow calculations

Comflow is a CFD (Computational Fluid Dynamics) program for the design of process equipment. This program will be less accurate than calculations using the large 'scientific' CFD codes, but more accurate than calculations based on the various empirical and heuristic design rules in common use. The calculation parameters are based on the Navier-Stokes equation. Therefore it is a good program to perform some simulations about air flow through screens set against the information about screens out of the literature. This program is a two-dimensional flow calculation program, so it can’t calculate intrinsically 3-dimensional flow problems. Therefore the research needs to be simplified to an 2-d simulation. With this program you can’t exactly make a wind simulation, but you can predict in some way what the effect of openings in a screen will be and if the porosity of an opening will allow the air to flow through or not.

Goal

With this research the flow through a screen in front of the street openings can be examined. The purpose is to maximize the contact of the air with the cleaning devices and to minimize the mean air speed behind the screen.

Method

For the inlet an uniform profile with a mean velocity of 2.5 m/s was used. With the Viscosity ratio eff/lam = Re/100 you can give a scale to the tested area. For this research are different screen configurations tested. First is tested what the influence of porosity is on the flow through the screen, than different configurations and opening forms are tested and finally the influence of different porosities on the flow through the screen is researched. To obtain more reliable results the dimensions of the flow area should be large.

Results

- Different porosities of a screen

Figure 7.14 Different porosities of the screen

Like shown in Figure 7.14, when the porosity of a screen decreases, the flow goes rather over the screen than through it, because there is too much resistance. This creates turbulence at the top of the screen.
- Different openings and screen models

Figure 7.15 Air flow through a screen

To give a better view on what happens behind the screen, there’s zoomed into the results

Figure 7.16 Model 1: the screens are behind each other with a height of 1.5 m and openings of 1 m

Figure 7.17 Model 2: the screens are alternated with a height of 1.5 m and openings of 1 m

Figure 7.18 Model 3: the screens are alternated with a height of 1.5 m and openings of 1 m with a resistance block in the openings, with a volume porosity of 0.12

Figure 7.19 Model 4: the screens are alternated with a height of 1.5 m and openings of 1 m with a resistance block two times as wide as the former model in the openings, with a volume porosity of 0.12.
And a bit more zoomed out for model 1 and 5

![Figure 7.20 Model 1](image1)  ![Figure 7.21 Model 4](image2)

When the thickness of a resistance block increases, the speed of the air directly behind the screen diminishes (Figure 7.18 and 7.19). When the flow through the screen is hampered because the porosity of the openings is very low, the flow over the screen and therefore the turbulence at the top of the screen is increased (Figure 7.20 and 7.21).

- Different porosities in the openings

![Figure 7.22 Different porosities in the openings](image3)

With a difference in volume porosity, increasing from the bottom to the top, you decrease the turbulence at the top of the screen and the flow through the screen will be more uniform.

**Conclusions**

- With a higher resistance, the direct speed behind the screen diminishes, but on top there’s turbulence. This turbulence causes finally a worse flow pattern behind the screen.
- The porosity and thickness of a resistance block has an influence on the air flow.
- An increasing porosity from the bottom to the top of the screen gives an more uniform air flow.
- The program doesn’t show the effect that wind at an closed screen because of eddies comes down at an area behind the screen.
7.5 Comparison of the programs

For the different wind simulations different programs and methods were used. To be aware of the shortcomings of each of these methods a short overview of these programs is made. Each program has its own possibilities and limitations.

<table>
<thead>
<tr>
<th>Program</th>
<th>Possibilities</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>- reliable program, because it is based on wind tunnel study</td>
<td>- the amount of configurations that can be tested are limited</td>
</tr>
<tr>
<td></td>
<td>- it shows in a fast way which configurations will work</td>
<td>- it’s 2D and only in floor plan the results can be showed</td>
</tr>
<tr>
<td>Knowind</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ecotect</td>
<td>- 3D</td>
<td>- doesn’t take some effects in account like the “wake effect”</td>
</tr>
<tr>
<td></td>
<td>- results are shown in a very graphic way</td>
<td>- the results have to be treated carefully</td>
</tr>
<tr>
<td>Comflow</td>
<td>- The effect of different porosities could be tested</td>
<td>- 2D</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Based on the flow through an pipe</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Doesn’t take into account the turbulence behind a closed screen</td>
</tr>
</tbody>
</table>

Table 7.1 Comparison of the different programs used in chapter 6 and 7

7.6 Conclusions

There are different means to filter and absorb the pollution in the air. One that is very effective is the use of vegetation to clean the contaminated air, because it deals with particulate matter (PM10), nitrogen dioxides (NOx), carbon dioxide (CO₂) and even ozone (O₃). To increase the effectiveness of a screen for the cleaning of the air, the wind should be able to flow through it. As well as an wind break it’s better when the wind isn’t totally blocked by a screen but could flow through a porous screen. Further from an architectonic point of view it’s recommended to provide a view from the street and the buildings onto the surroundings. The program Comflow showed that when the porosity of the screen decreases, the direct speed behind the screen diminishes, but the turbulence at the top of a screen increases. This turbulence finally causes a worse flow pattern behind the screen.
7.7 Recommendations for further research

The focus in this chapter was on the screen and the influence it can have on the wind climate and air quality in the street. The filtering and absorption of the pollution in the air could however also happen at different places in the design, which are shown at Figure 7.23 and Table 7.2. An + and an – shows whether it is effective to clean the air at this place or not.

![Figure 7.23 Different places in the design for filtering and absorption of the pollution](image)

| Screen in front of the openings | + The screen could be very effective in cleaning the air which reaches the street. | + For the windows that can be opened in the street the cleaning of the air at this place could be very useful. |
| Outer facade | + / - Because of the turbulence at the facade it is doubtful whether the air that reaches the street could be cleaned by this facade. It could be useful however when the screen is extended to the roof. | - Because there probably will not be any window that can be opened above the highway, it is not necessary to clean the air at that spot. |
| Inner facade | + The air that finally reaches the street could be further cleaned by the inner facade | + For the windows that can be opened in the street the cleaning of the air at this place could be very useful. |
| Roof | + The air that reaches the street over the roof could be effective cleaned at the roof. | + For the windows that can be opened in the street the cleaning of the air at this place could be very useful. |
| Street | + In the street itself the air could be even further cleaned | + For the windows that can be opened in the street the cleaning of the air at this place could be very useful. |

Table 7.2 Different places in the design for filtering and absorption of the pollution

Like shown at Table 7.2 there are more places where a cleaning device could be effective. Especially for the vegetation it could be very effective used at other places at the design (Figure 7.24, 7.25 and 7.26)
- At the street walls
The same type of vegetation could be used at the street walls as at the screen. These types are already mentioned at Figure 7.4.

- In the streets
Different trees are effective for different pollutants. For each type of pollution you could chose a different tree (Appendix III).

**Taxus**
Good for capturing particulates (PM10)

**Aesculus (paardenkastanje)**
Good for absorbing nitrogen oxides (NO + NO2) and ozone (O3)
(they decrease the concentration of ozone effectively in a city)

**Prunus**
Good for absorbing nitrogen oxides (NO + NO2) and ozone (O3)

- On the roof
Vegetation on the roof has other advantages too besides the purification of the air:
• the increase of the temperature accumulation capacity of the roof, which can lead to cooling in the summer.
• the relieve of the drainage sewer systems through a shorter cycle of the rain water. The rain water stays longer on the roof and gets the change to evaporate.
• new habitat for birds and insects
• Improved sound insulation (Hout, 2005)

A distinction can be made between extensive and intensive vegetation. An extensive vegetation is low maintenance and usually consists of low requirement vegetation as moss, sedum species and low herbs. Intensive vegetation requires regular maintenance and a good foundation and can exist of grass roofs or vegetation composed of border plants, shrubs and even trees (Figure 7.28).
Moss roof (Icomoss)    Sedum roof (height 8cm)
Figure 7.28 Different types of roof vegetation

Permanent plant roof (height 25 cm)
8. Screen: Noise

8.1 Introduction

There are actually two types of screens in front of the building. The first one is the one in front of the openings in the street and the second one is the one in front of the building.

Like discussed in the previous chapter the screen in front of the opening should have openings or be porous to enable the wind to flow through it. Furthermore an open screen provides a view to the surroundings, which from an architectonic point of view is desired.

The main function of the screen in front of the building is to diminish the sound level behind the screen. The air though is not cleaned at this place. It is however important that the screen provides sunlight and a view to its surroundings for the building behind it. A totally double glass façade is an option to provide sunlight and a view. This option is however not chosen, because such a façade heats up in the summer and so the second skin still needs to be opened to ventilate the cavity as much as possible. For that reason is chosen for a screen with openings in it.

There are several definitions related to sound, which will be explained shortly

- **Insulation**
  Sound insulation prevents that sound can travel from one place to another. Heavy materials such as concrete or masonry are most effective for sound insulation. Good sound insulating materials should as well be completely airtight. A doubling of the surface mass improves the sound insulation by 6 dB. Examples of sound insulating materials: concrete, double glazing (glass only is less effective), masonry, wood (without cracks)

- **Absorption and reflection**
  Sound waves deform a material, but the deformation of the material requires energy. Depending on the type of material a part of the energy will be refunded in the form of reflected sound. The other part, which will not be returned, will be stored in the form of heat in the material and that’s called absorption. The amount of absorption is a property of a material and is expressed as the absorption coefficient, which is the part of the incoming sound power that is absorbed. The rest of the sound is reflected. The absorption coefficient depends on the frequency of the sound, and is usually measured in any octave band between 125 and 4000 hertz. The absorption coefficient has a value between zero (no absorption, all the sound is reflected) and 1 (complete absorption, there is no reflected sound). Sound absorbing materials are generally lightweight and have an open structure. Examples of sound absorbing materials: curtains, carpet, rock wool, hole ceilings.

- **Diffraction of sound**
The wavelength of a sound wave is equal to the distance between two consecutive highest (or lowest) sound pressures in the wave. The wave length has the following formula

\[ \lambda = \frac{v}{f} \]

\(\lambda\) = wave length  
\(v\) = speed of sound (343 m/s at room temperature and atmospheric pressure)  
\(f\) = frequency

For a frequency of 200 Hz, the wavelength is \( \lambda = \frac{343}{200} = 1.7\) m

For a frequency of 1000 Hz, the wavelength is \( \lambda = \frac{343}{1000} = 0.34\) m

So the lower the frequency, the larger the wave length.

If this wavelength is comparable to or greater than the size of the object that it affects, the waves are mainly diffracting around it, and the reflection is weak. The smaller the object is compared to the wavelength, the better the bending around it goes, and the stronger the sound behind the object, this is called diffraction. So especially at low frequency diffraction occurs, which is important because traffic noise is especially at low frequencies.
8.2 Materials

To reduce the noise different measures can be taken at several different levels, namely at the source, in the transfer area and at the receiver. Measures at the source consists of quieter tires, quieter vehicles and a quieter road surface. At the source the quiet roads have the greatest potential to reduce the noise. Traffic measures like speed reduction can have an impact as well. In the design of the building there can’t be any influence on the measures at the source and the traffic, but on the contrary there can be influence at the transfer area and at the receiver.

The solution can be divided in two areas, namely the façade of the building and the screen which will be in front of the building and the openings in the street.

Figure 8.3 Screen in front of the building and screen in front of the openings

Like described in the paragraph 8.1 you could either make the screen and façade from sound insulating or absorptive materials.

Facade

There are several materials which can be used in the façade to reduce the incoming sound level.

Glass

With the program VABI several different glass facades are tested at their soundproofing at various frequencies. These frequencies are summed up into a total sound insulation of that façade.

<table>
<thead>
<tr>
<th>Material and Thickness</th>
<th>R total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminated glass, single, 10 mm</td>
<td>29,8 dB</td>
</tr>
<tr>
<td>Laminated glass, single, 15 mm</td>
<td>30,3 dB</td>
</tr>
<tr>
<td>Laminated glass, single, 20 mm</td>
<td>31,6 dB</td>
</tr>
<tr>
<td>Double glazing, 8-10-7mm with 1,5 mm synthetic resin</td>
<td>31,5 dB</td>
</tr>
<tr>
<td>Double glazing, 8-35-7mm with 1,5 mm synthetic resin</td>
<td>34,7 dB</td>
</tr>
<tr>
<td>Laminated glass, single, 15 mm with 1,5 mm synthetic resin</td>
<td>33,8 dB</td>
</tr>
<tr>
<td>Laminated glass, single, 20 mm with 1,5 mm synthetic resin</td>
<td>35,6 dB</td>
</tr>
<tr>
<td>Laminated glass, 20 mm with 1,5 mm soft resin - 500 mm cavity - laminated glass, 10 mm with 1,5 mm soft resin</td>
<td>53 dB</td>
</tr>
<tr>
<td>Laminated glass, 20 mm with 1,5 mm soft resin - 100 mm cavity - laminated glass, 10 mm with 1,5 mm soft resin</td>
<td>44,3 dB</td>
</tr>
<tr>
<td>Laminated glass, 20 mm with pvb - 500 mm cavity - laminated glass, 10 mm with pvb</td>
<td>50,3 dB</td>
</tr>
<tr>
<td>Laminated glass, 20 mm with pvb - 100 mm cavity - laminated glass, 10 mm with pvb</td>
<td>50,3 dB</td>
</tr>
</tbody>
</table>

Table 8.1 The sound proofing of different types of glass facades

The outcome of these tests show that a high sound insulation can be achieved when a very special glass or a cavity is used. Without these extras a glass facade has a sound insulation around 30 dB.
Screen

Because the screen is open, it is more logical to make it out of absorptive materials than sound insulating materials. Because sound rays will be able to pass the screen because of the openness, the energy of the incident rays can be reduced with an absorptive material.

The effects of absorption

Figure 8.4 shows the decrease in sound pressure level, at various absorption coefficients. With an absorption coefficient of 0.99 a reduction of 20 dB could be achieved.

![Image of Figure 8.4 showing the decrease in sound pressure level](image)

This is related to the following formulas:

\[
L_p = 10 \log \frac{I}{I_0}\text{ dB}
\]

\[
a = \frac{I_{\text{absorption}}}{I}
\]

Where:
- \(L_p\) = Sound pressure level (dB)
- \(I\) = incident sound
- \(I_0\) = reference intensity
- \(I_{\text{absorption}}\) = absorption intensity

So when \(a=0.5\), then \(I_{\text{absorption}} = 0.5 \times I\) than \(I_{\text{reflection}} = 0.5 \times I\)

When \(L_p = 70\) dB \((= 10\log I/I_0)\), the difference after reflection will be \((= 10\log0.5 I/I_0) = 3\) dB

The same for \(a=0.9\), the difference after reflection will be \((= 10\log0.1 I/I_0) = 10\) dB

And for \(a=0.99\), the difference after reflection will be \((= 10\log0.01 I/I_0) = 20\) dB

When a ray reaches a façade after four times being reflected at a surface with an absorption coefficient of 0.5, the total diminishing in the sound level of the ray will be \(4 \times 10\log0.5 = 12\) dB

The absorption coefficient of different materials

1. MDF boards faced in wood grain with different perforation patterns

![Image of Figure 8.5 showing different perforation patterns and amount](image)
Figure 8.6 shows that overall a higher perforation gives a better absorption coefficient. It also shows that at higher frequencies the absorption coefficient diminishes.

2. Different wall and ceiling finishes

These images show that especially a resonator absorbs well at lower frequencies. Porous materials absorb the best around a frequency of 1000 Hz.
8.3 Case studies

There are already several researches done about the screen effect of balconies and parapets by using computer models and scale models and there are projects with sound barriers.

The influence of ceilings

In the study of Hossam El-Dien and Woloszyn (Hossam El-Dien, 2004), the acoustic performance of three different inclined angles (5°, 10°, 15°) of the ceiling of the balcony in a 17-storey building is tested using a computer simulation. Besides the different angles it was also tested with various balcony depths, namely 1, 2 and 3 meter.

![Figure 8.8 The image before and after changing balcony ceiling form and a schematic representation of the reception surface (Hossam El-Dien, 2004)](image)

This research shows that the inclined form of the ceiling changes the direction of reflected rays away from the openings located at the balcony back wall (Figure 8.8). Because the sound ray makes multiple reflections before reaching the back wall, the power of the sound ray is decreased. So the protected surface over the balcony back wall increases by comparison of the protected surface gained from the classical form as a consequence of ceiling reflected area.

The average noise reduction provided by that configuration with reflective surface (α = 0.07 at 1 kHz) was about 0.5–6 db (A). The higher the floor level and the deeper the balcony, the greater the sound reduction. For the floors on a lower level a greater angle was more effective (10° en 15°), whilst on a higher level a smaller angle was more effective (5°).

The influence of parapets

In another study (Hossam El-Dien, 2005) the influence of balcony depth and the angle of the parapet is tested at an eight-storey building using computer simulations and scale models. The different depths of the balcony were 1, 2 and 3 meter and the angle of the parapet was 15° of 30°.
The basic idea of increasing balcony’s depth and inclining balcony’s parapet is to decrease the contributions of the reflected and diffuse energy components by increasing the shielding zones. The inclined parapet increases the shielding zone over the balcony back wall in comparison with the classical parapet form (Figure 8.9). This is due to the screening of that surface from direct rays and the increasing of the path between the source and the reception points.

The sound proofing that was achieved with a reflective surface ($\alpha = 0.07$ at 1 kHz) differed at different depths varying between 4 and 8 dB (A) and an additional protection between 0.5 and 4 dB (A) could be achieved by inclining the parapets. An angle of 30° performed better than one of 15°.

**Influence of different forms**

There is also a study done about different balcony configurations with or without the addition of absorptive material (Lee, 2006).

Figure 8.10 (a) lintel, (b) parapet, (c) inclined ceiling, (d) inclined ceiling and an absorbing surface, (e) inclined ceiling, an absorbing surface, and a parapet, (f) inclined ceiling, parapet and absorbing surfaces (Lee, 2006).
The addition of the lintel (a) increased the noise level and had therefore a negative effect on the sound proofing. This is because the longer lintel generated far more reflected sound rays from the ceiling and thus functioned as an extended ceiling (Figure 8.11).

![Figure 8.11 Increased reflection from the lintel (Lee, 2006)](image)

The effect of the parapet differs at the different levels (Figure 8.12). Without a parapet on the lower floors of the building the effect of the direct sound is most dominant and on the upper floors the reflected sound from the ceiling is most dominant. By addition of the parapets the path of the propagating sound is blocked and therefore the sound pressure levels are decreased. For the middle floors however the parapet could not block the path for the reflected sound from the ceiling to the back wall. Therefore, the sound pressure levels at the middle floors increased, because the reflected sounds from the ceiling could not escape from the balcony.

![Figure 8.12 The effect of the parapet at various levels (a) low levels; (b) middle levels; (c) high levels. (Lee, 2006)](image)

The parapet works on almost all levels better than the lintel and the noise reduction that was achieved ranged between -1 and 5.7 dB (Figure 8.13).

![Figure 8.13 Noise reduction of treatment (a) and (b), •: lintel 50 cm, o: lintel 100 cm, ∆: parapet 50 cm, ∆: parapet 100 cm](image)

The parapet and absorptive material were added with $\alpha = 0.67$ at 1 kHz. The results of the variants are shown in the graph. This shows that the addition of a parapet and absorptive material gives the greatest sound reduction (Figure 8.14).

![Figure 8.14 Noise reduction of treatment, o (c), ∆ (d), • (e), ∆ (f)](image)

For the variants d, e and f sound absorbing material was added with $\alpha = 0.67$ at 1 kHz. The results of the variants are shown in the graph. This shows that the addition of a parapet and absorptive material gives the greatest sound reduction (Figure 8.14).
Coulisse screen

The consultancy Cauberg Huygens has done research about the performance of open sound barriers. The main reason to make an open sound barrier is because of the view it creates. Another point is that in this way the space between the screen and building could be regarded as outside air and then ventilation through the facade is possible. The depth of the coulisses as well as the distance between them is 0.5 to 1 meter and the thickness of the coulisses is 0.2 meters. They are made of perforated steel or aluminum plate containing a core of heavy mineral wool. The sheet material is approximately 20% open to mute the sound in a good manner. Because of the sound absorbing effect of the coulisses the sound is hardly reflected through other openings and what remains is the sound that bends around the coulisses. Reducing the distance between the coulisses is good for the screening effect, but impedes daylight. The screening effect is 8 dB for a road parallel to the building. When approximately half of the openings between the coulisses are closed with a transparent material, a reduction of approximately 11 dB could be achieved at all levels. For a road perpendicular to the building, a reduction between 12 and 16 dB could be achieved. For low frequency the reduction is limited because the size of the coulisses are small compared to the wavelength. In the midrange of 500 to 2000 Hz the effect is optimal. For high frequency the noise is reduced by the so-called irradiation.

Open sound screen

This is a sound barrier of laminated glass that is open for one-third. The sound that comes through the open sections is partly absorbed by the acoustic coating of the ceiling and parapets. Before the approach there was a sound pressure level of 72 dB and afterwards the maximum was 70 dB. There is an open strip along the ground floor, an open roof and there are open strips at each floor, which are situated along the gallery floor. The incoming sound falls on the parapet and never reaches directly the inner facade. On the parapet the sound is partly absorbed and partly diffused. The inside of the parapet and the bottom of the galleries are covered with absorbing material and therefore the sound pressure level is brought under the maximum allowed 70 dB (A). After measuring the noise barrier had finally a performance between 2 and 7 dB.
8.4 Hand calculations: The screening effect of two types of barriers

With these hand calculations the road is simplified to a point source. By calculating this point source at different distances from the building, you can model a line source. The diffraction of the sound is taken into these calculations.

**Goal**

With this calculation the screening effect of two types of horizontal barriers could be calculated. The first type are multiple small screens which are vertical equally divided over the façade and the second type is one larger screen at the bottom corner of the building.

**Method**

Distance

The decrease of the sound energy is $1/r^2$ for a point source and $1/r$ for a line source, where $r$ is the distance between the source and the microphone. For this calculation a point source will be used. In principle the road (and thus the line source) goes underneath the building and is thus perpendicular to it. But using a line source in this calculation means that it will be projected parallel to the building. The measurements show that the noise level 6 meters above the highway is 80 dB. So formula 1a can be written as 1b:

$$L_p(r) = L_p(s) - 20\log(r/s) \quad (1a)$$

$$L_p(r) = 80 - 20\log(r/6) \quad (1b)$$

In some cases it is only a comparison of two situations with a point source. Then it is often more convenient to express the formula 1a in a delta-value which gives this difference:

$$\Delta L(r > s) = 20\log(r/s), \quad (2a)$$

In which $\Delta L$ is positive as $r > s$ and negative for the opposite case. The formulas for distance influence are not depending on the frequency.

Screening

The screening is calculated as a difference in sound pressure levels between the situations with or without a screen. First the path length difference $\delta$ will be defined between the source and the microphone in accordance to the following figures as:

$$\delta = d_1 + d_2 + d_3 - r \quad (3)$$

![Figure 8.17 The path between source and microphone](image)

Purely mathematically $\delta$ is always positive, by convention, the symbol gets a minus as the source and receiver are in each others sight line ("above the line of sight"). Therefore the sight line must be determined separately.

Now the “Fresnel number” is calculated by

$$N = 2\delta f/c \quad (4)$$
In which \( f \) is the frequency and \( c \) the propagation speed of sound. We always work with \( c = 340 \text{ m/s} \), the frequencies for traffic noise are from 50 Hz to 5000 Hz. The human hearing system runs from 20 to 20,000 Hz.

According to the theory provides a larger value of \( N \) a greater shielding. Formula (4) shows that \( N \) (and thus the impact of screening) increases as the path length difference and / or the frequency increases.

Using the acoustic theory it is possible to make a very accurate estimation of the noise reduction by shielding. This requires fairly complicated integrals and therefore in most practical cases a series of formulas based on a large number of Japanese scale measurements from the early sixties will be used. The formulas are in Table 8.2. There are four distinctive areas of \( N \). \( \Delta L \) is the searched difference in the noise levels with and without screen.

<table>
<thead>
<tr>
<th>Fresnelgetal ( N )</th>
<th>Point source</th>
<th>Line source</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N &lt; -0.3 )</td>
<td>( \Delta L(\text{schermer}) = 0 )</td>
<td>( \Delta L(\text{schermer}) = 0 )</td>
</tr>
<tr>
<td>(-0.3 \leq N &lt; 0 )</td>
<td>( \Delta L = 56(N + 0.3)^2 )</td>
<td>( \Delta L = 52(N + 0.3)^2 )</td>
</tr>
<tr>
<td>( 0 \leq N &lt; 1 )</td>
<td>( \Delta L = 8\sqrt{N} + 5.0 )</td>
<td>( \Delta L = 5.4\sqrt{N} + 4.7 )</td>
</tr>
<tr>
<td>( N \geq 1 )</td>
<td>( \Delta L = 10\log(N) + 13.0 )</td>
<td>( \Delta L = 8\log(N) + 10.1 )</td>
</tr>
</tbody>
</table>

Table 8.2 Screening (\( \Delta L \)) by adjusting a screen at a given fresnel number \( N \) (Practicumstructies geluidhinder bij bebouwing boven een spoorlijn of Weg)

**Input**

Using this equation there are two different configurations tested at a varying distance from the point source to the building. Variant 1 consists of horizontal screens of one meter long, that are placed along the entire facade with a distance of 1 meter between them. In variant 2 is a horizontal screen of 3.5 meters long at the bottom of the building.

The calculations are performed at a frequency of 400 Hz. In the first test is the microphone placed at a height of 1.5 m and a depth of 0.5 m from the bottom edge of the building. At the second test it is at 5.5 m height and 0.5 m depth. The height of the noise source is based on the overall source height of a normal vehicle, which is at ground level.

Test 1

**Variant 1**

**Variant 2**

Test 2

Figure 8.18 The orange line shows the sight line from the microphone via the screen to the road.
Results

Microphone at 1.5 meters height
At a height of 1.5 meters from the bottom edge variant 2 appears to work better than variant 1. The path length difference $\delta$ for this variant is larger. The drawing also shows that the projection of the sight line on the road for variant 2 is horizontally two times further from the building than variant 1 (Figure 8.19).

![Figure 8.19 The screening effect of screen 1 and 2 with the microphone at 1,5 m height.](image)

Microphone at 5.5 meters height
This test shows that variant 2 works better on a smaller horizontal distance from the building. This is because the path length difference $\delta$ is still larger for these distances. For a larger horizontal distance, the roles are reversed and variant 1 appears to perform better (Figure 8.20).

![Figure 8.20 The screening effect of screen 1 and 2 with the microphone at 5,5 m height.](image)

Conclusions

The results show that when the microphone is close to the bottom of the building, than screen 2 performs better, because it has a larger path length $\delta$. However when the microphone is placed higher, than screen 1, which are smaller screens equally divided over the façade, performs better from a certain distance from the building.
8.5 Program Traffic Sound: The screening effect of different types of screens

The Program Traffic Sound
This program makes it possible to take the influence of the absorption into the calculations. The difference with the former calculations is that the road is modelled as a line source and that the measurements are taken with a microphone at different heights in front of the facade. Different configurations are tested.
This program has as well its limitations.
- It is two-dimensional
- The diffraction that occurs at the screens especially at lower frequencies is not taken into account in the calculations.
- Reflective program, not all obstacles in the array generate a new radio item, as a branched structure calculation results can be very complicated.

Goals

The goal of this research is to compare the sound level in front of the facade when there is no screen with the sound level when there is a screen. There are different types of screens tested.

Method

Input

Figure 8.21 Different types of screens
ST1: without sound screen
ST2: horizontal sound screen of 3 m at the bottom edge
ST3: horizontal sound screen of 1 m wide placed with an interval of 1 m over the entire façade
ST4: vertical sound screens with a length of 2 m and a gap of 2 m between placed at 1 m from the façade
ST5: horizontal sound screen of 1 m (with an angle of 14 degrees with the horizontal plane) wide placed with an interval of 1 m over the entire façade
ST6: horizontal sound screens of different sizes, where the extended sight line between the microphone and the screen crosses the road at a horizontal distance of 20 m from the building.
ST7: vertical sound screens with a length of 2 m (inclination of 15°) and a gap of 2 m between placed at 1 m from the façade
ST8: vertical sound screens with a length of 1 m (inclination of 15°) and a gap of 1 m between placed at 1 m from the façade

There are also different reflection coefficients assigned to these configurations.
A : rc = 0,794 (default setting of the program) , B : rc = 0,4 , C : rc = 0,1, D : rc = 0,01 and E : rc = 1

Results

Figure 8.22 The reflection coefficient: 1

With a reflection coefficient of 1 the noise levels of the different configurations are quite similar (Figure 8.22). One on hand the screens create a shielding effect and increase the path between the source and the reception points, but on the other hand also provide additional reflection. Therefore there is little difference between the situations with or without screen.
With a reflection coefficient of 0.01 the differences between the configurations become clearer (Figure 8.23). This shows that at microphone height of 7 m variant 2 works the best. This is because this point is immediately above the wide screen. Overall variant 5 works the best. This variant is similar to variant 3, only the screen of variant 5 makes an angle of 14° with the horizontal plane. The projection of the sight line on the road is for variant 5 further away from the building than with variant 3. Also is the path between the source and the microphones increased. For variant 6, the noise level over the entire facade is more or less the same. In this case the extended sight lines between the microphones and the screens crossed the road at the same place. This resulted in an almost identical noise level. Variant 7 and 8 perform at some points better and at others worse, because some points are screened and others aren't. When you take the mean of graph 5, 7 and 8 then that would be approximately the same.

**Conclusions**

Especially the graph with reflection coefficient 0.01 shows the lowest sound pressure level that could be achieved with different screens. According to these graph the band width is around 10 dB between a façade with a screen and a façade without a screen.
8.6 Ecotec: The screening effect of different types of screens

The software ECOTECT is an instrument developed by Dr Andrew Marsh, a former teacher at the University of Cardiff, Wales. With this program a simulation of the sound rays of a microphone can be performed. In this way you can test how many rays reach the façade and how the reflections will occur. Subsequently, the façade can be optimized, by minimizing the direct radiation and maximizing the amount of reflections at the screen before a ray finally reaches the façade.

By simulating the sound in this way means that it will perform like a light ray. However this comparison only counts for the higher frequencies starting from 1000 Hz. For noise with a lower frequency this comparison isn’t totally the same. At a low frequency the diffraction of sound plays a bigger role. These results also have to be taken into account.

- In test 1 there is tested which configuration works best in order to ensure that as little as possible rays reach directly the façade.
- In test 2 the amount of rays that reach the façade by reflection are tested. The influence of the form of the screen on the amount of total reflection that reach the façade can be checked and the purpose is to minimize that amount of rays

Goals

With this test the screening effect for different types of screens is tested. When it is assumed that only the rays that reach directly the façade determine the final sound level, it can be determined what the maximum possible sound reduction value of the screen will be. Thus you assume that reflections from the screen to the façade don’t have any influence on the final sound pressure level. In this fictive case the screen would be 100% absorptive and absorb all the energy from a sound ray.

Method

There are different types of screen tested. To give a value to these façade, the following method is used.
- The building is schematized to the figure below

![Figure 8.24 Schematization of the building and with rays spread on it](image)

The building is schematized to one bridging of the highway (Figure 8.24). In this way you can look at the façade above and next to the highway, but the test time is shortened, since not all four bridgings are taken into account.

Further are the different highway sections, schematized to one line source, as well to shorten the calculation time and to prevent the model from becoming to chaotic.

The microphone is tested at different distances from the building to simulate a line source. The microphone sprays as one fourth of a sphere rays all over the façade and shows how many rays has hit each part.
- First the amount of rays without a screen before the façade are calculated
- Than the amount of rays that hit the façade with a screen in front of it
- With the ratio between these tests (with a screen/without a screen), the following value can be calculated \( \Delta L = -10 \log \text{(ratio)} \). This gives an value for the performance of the screen.
- Then the sound level at various distances from the façade without screen is calculated.
- When you diminish the sound level with \( \Delta L \), you get the sound level with the screen (Figure 8.25).

\[
\Delta L = 10 \log \left( \frac{S_{\text{without screen}}}{S_{\text{with screen}}} \right)
\]

The screen is supposed to be completely absorptive.

- Both values then need to be converted into the sound pressure, with the following formula \( 10^{L/10} \) (Figure 8.26 and 8.27).

- By calculating the integral under these graphs, you can calculate the overall \( \Delta L \) with the following formula:

\[
\Delta L = 10 \log \left( \frac{S_{\text{without screen}}}{S_{\text{with screen}}} \right)
\]

- The screen is supposed to be completely absorptive.
Figure 8.30 Model 3 Vertical and horizontal strips in front of the façade, but with an inclination of 15° away from the highway.

Figure 8.31 Model 4 Vertical and horizontal strips in front of the façade, but with a curve away from the highway.

Figure 8.32 Model 5 One screen with openings (25% of the total façade) in front of the façade.

Figure 8.33 Model 6 Two screens with openings (25% of the total façade) in front of the façade.

Figure 8.34 Model 7 Three screens with openings (25% of the total façade) in front of the façade.

Figure 8.35 Model 8 One screen with openings (12.5% of the total façade) two times as small in front of the façade.

Figure 8.36 Model 9 Two screens with openings (12.5% of the total façade) two times as small in front of the façade.
Results

<table>
<thead>
<tr>
<th>Type of screen</th>
<th>ΔLp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Vertical and horizontal strips in front of the facade</td>
<td>9 dB</td>
</tr>
<tr>
<td>2. Strips in the form of an arch over the highway</td>
<td>10 dB</td>
</tr>
<tr>
<td>3. Vertical and horizontal strips in front of the façade, but with an inclination of 15° away from the highway.</td>
<td>11 dB</td>
</tr>
<tr>
<td>4. Vertical and horizontal strips in front of the façade, but with a curve away from the highway.</td>
<td>15 dB</td>
</tr>
<tr>
<td>5. One screen with openings (25% of the total façade) in front of the façade</td>
<td>4 dB</td>
</tr>
<tr>
<td>6. Two screens with openings (25% of the total façade) in front of the façade</td>
<td>8 dB</td>
</tr>
<tr>
<td>7. Three screens with openings (25% of the total façade) in front of the façade</td>
<td>9 dB</td>
</tr>
<tr>
<td>8. One screen with openings (12,5% of the total façade) two times as small in front of the façade</td>
<td>5 dB</td>
</tr>
<tr>
<td>9. Two screens with openings (12,5% of the total façade) two times as small in front of the façade</td>
<td>8 dB</td>
</tr>
</tbody>
</table>

For a more detailed explanation on the results see Appendix IV: Results Ecotect

Conclusions

The maximum sound proofing value the screen could reach is calculated. According to this simulation type 4 seems to work much better than all the other types. Because of the curve in the screen, this screen has a larger screening effect. The screens with openings in it seems to perform the worst, though the results get better, when two of the same screens are placed in front of each other. The performance of this screen is as well very dependent on the size and placement of the openings and a better arrangement for this can improve the situation a lot.
8.7 Ecotect: Reflection behavior of different shapes of screens and different positions relative to each other

Goals

Besides the foreclosure effect of the screen, it is also the intention to minimize the reflections between the screen and the wall. By giving the screen different shapes, the influence of a form on the reflections could be tested. With minimizing the amount of reflections, the final sound pressure level could be lowered.

Method

For this test the amount of reflections on the façade above the highway are tested (Figure 8.37). The increment between the rays is 0.1° and up to 5 reflections are included into the calculation. The results of this test won’t give numbers about the final sound pressure level on the façade, but it gives an insight into the performances of the different screens.

There are two different configurations tested
- the shape of the screens
- the position of the screens relative to each other

The shape of the screens

![Figure 8.37 The red part is the façade above the highway](image)

![Figure 8.38 Model 1](image)  ![Figure 8.39 Model 2](image)  ![Figure 8.40 Model 3](image)
The position of the screens relative to each other

These two configurations are combined tested. Therefore a speaker was positioned at different distances from the building to approach a line source. The distance between the points is smaller closer to the building than further away.

The curve is constructed out of 8 separate segments in Ecotect (Figure 8.46).
Results

Figure 8.47 Total rays on the façade

Figure 8.47 shows the total amount of rays on the façade above the highway after five reflections for the different configurations. In this graph can be seen that especially model 3 where the front screen is 20 cm up and model 2 with the front screen 20 cm down have a lower amount of total rays. Further the amount of rays only by reflection are calculated by diminishing the total amount of rays after five reflections with the amount of direct rays (0 reflections) on the façade. This results in the following graph (Figure 8.48).

The influence of the amount of reflections on the total amount of rays on the façade: Therefore are for the following two configurations (Figure 8.49 and 8.50) the total amount of rays tested after 0, 1, 2, 3, 4 and 5 reflections.
This resulted in the following ratio (Figure 8.51)

![Graph showing the ratio for amount of reflections](image)

Figure 8.51 Amount of reflection

This graph shows in ratio for example that at the second reflection an large increase in the amount of rays on the façade occurs. This counts as well for the fourth reflection. But the part of the third reflection is not so high, which means that there isn’t so much difference between two or three reflections on a façade. This is probably because many second reflections take place on the façade, whilst a third reflection probably occurs more at the screen. At paragraph 7.3 was explained that in theory for every reflection at an absorptive surface the sound pressure level of the sound ray diminishes. It could be calculated by the following formula:

\[
\Delta L = L_{p1} - L_{p2} \\
\Delta L = 10\log \left( \frac{l_1}{l_2} \right) - 10\log \left( r^* l_1/l_o \right) \\
\Delta L = 10\log \left( l_1/l_o \right) - 10\log \left( l_1/l_o \right) - 10\log (r) \\
\Delta L = -10\log (r)
\]

Example:
When we assume that the first incident ray has a sound pressure level of 80 dB and the absorptive surface has a reflection coefficient of 0.5, than \( \Delta L = 3 \) dB. The more reflections occur the lower the final sound pressure level of that ray will be. In Table 8.3 also the ratio of the reflections are showed. (This is a mean of the examples calculated for model 1 - The front screen 20 cm up and model 4 – In front of each other, because they were quite the same).

<table>
<thead>
<tr>
<th>Reflections</th>
<th>( \Delta L )</th>
<th>( L )</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>After 1 reflection</td>
<td>3 dB</td>
<td>80-3= 77dB</td>
<td>0,0701</td>
</tr>
<tr>
<td>After 2 reflections</td>
<td>6 dB</td>
<td>77-3= 74dB</td>
<td>0,5874</td>
</tr>
<tr>
<td>After 3 reflections</td>
<td>9 dB</td>
<td>74-3= 71dB</td>
<td>0,0619</td>
</tr>
<tr>
<td>After 4 reflections</td>
<td>12 dB</td>
<td>71-3= 68dB</td>
<td>0,2263</td>
</tr>
<tr>
<td>After 5 reflections</td>
<td>15 dB</td>
<td>68-3= 65dB</td>
<td>0,0544</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Table 8.3 The final sound pressure level and the ratio
To give a value to the screens, you can look at the ratio of the amount of rays that reaches the facade with a screen divided by the amount of total rays that reaches the facade without a screen. With this ratio you can calculate $\Delta L$ according to the following formula.

$$\Delta L = -10 \log \left( \frac{\text{with a screen}}{\text{without a screen}} \right)$$

- $\Delta L$ could be calculated for the rays that reach the façade without any reflections (so direct), and as well for the rays that reach the façade after 1, 2, 3, 4 or 5 reflections. Every ray that is reflected could actually be seen as a new “sound source” only with a diminished sound pressure level. A ray that reaches the façade after 5 reflections has a lower sound pressure level than a ray that hits the façade directly without any reflections.
- With the ratio from the table above the amount of rays at each reflection could be calculated.
- Then $\Delta L$ could be calculated for the situations with 0, 1, 2, 3, 4 and 5 reflections.
- Subsequently the total sound pressure level could be calculated by summing up all these “sound sources” with the following formula : $10 \log \left( 10^{L_{p1}/10} + 10^{L_{p2}/10} + 10^{L_{p3}/10} + 10^{L_{p4}/10} + 10^{L_{p5}/10} \right)$
- Finally $\Delta L$ could be calculated again by diminishing the initial sound pressure level (in this case 80 dB) with the total sound pressure level at the façade.

<table>
<thead>
<tr>
<th>Amount of rays</th>
<th>$\Delta L$</th>
<th>$L_{p1}$</th>
<th>$L_{p2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct on the facade</td>
<td>31320</td>
<td>0,139</td>
<td>8,56</td>
</tr>
<tr>
<td>After 1 reflection</td>
<td>1820</td>
<td>0,008</td>
<td>20,92</td>
</tr>
<tr>
<td>After 2 reflections</td>
<td>15247</td>
<td>0,068</td>
<td>11,69</td>
</tr>
<tr>
<td>After 3 reflections</td>
<td>1607</td>
<td>0,007</td>
<td>21,46</td>
</tr>
<tr>
<td>After 4 reflections</td>
<td>5874</td>
<td>0,026</td>
<td>15,83</td>
</tr>
<tr>
<td>After 5 reflections</td>
<td>1412</td>
<td>0,006</td>
<td>22,02</td>
</tr>
<tr>
<td>Total sound pressure level</td>
<td></td>
<td></td>
<td>72,12</td>
</tr>
<tr>
<td>$\Delta L$</td>
<td></td>
<td></td>
<td>7,88</td>
</tr>
</tbody>
</table>

Table 8.4 The sound proofing $\Delta L$

For all these types of screens you will get the following results, which are shown in Table 8.5 with reflection coefficient 0,5 )

<table>
<thead>
<tr>
<th>$\Delta L$</th>
<th>Model 1</th>
<th>Model 1 (20 cm up)</th>
<th>Model 1 (20 cm down)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>7,88</td>
<td>7,63</td>
<td>7,44</td>
</tr>
<tr>
<td>Model 2</td>
<td>8,68</td>
<td>8,52</td>
<td>8,51</td>
</tr>
<tr>
<td>Model 3</td>
<td>8,63</td>
<td>9,48</td>
<td>7,59</td>
</tr>
<tr>
<td>Model 4</td>
<td>7,57</td>
<td>7,54</td>
<td>7,06</td>
</tr>
<tr>
<td>Model 5</td>
<td>7,36</td>
<td>7,42</td>
<td>7,30</td>
</tr>
</tbody>
</table>

Table 8.5 The sound proofing $\Delta L$ of all models

However, these results about the performances of the screens may not be totally correct, because the distance in which it was calculated was only between 5 and 50 meters from the façade. A more important feature about this data is how the screens perform relative to each other. When you diminish $\Delta L - \Delta L_{max}$ out of this table you can see what the band width is in which these screens perform (Table 8.6).
When you compare this with the graph that shows the total amount of rays on the façade, you can see that like in the graph model 3 with the front screen 20 cm up performs the best. From this table you can also extract that the band width of performances of the screens is around 2,43 dB.

With a reflection coefficient of 0,01 (a.c.:0,99) the differences in performances of the screen will be 2,95 dB and with a reflection coefficient of 1 (a.c.:0) the difference is 2,14 dB.

In these calculations the influence of the direct rays on the façade is taken into account whilst these rays give the highest sound pressure level and plays the biggest part in the calculation of the total sound pressure level with this formula $10 \log (10^{L_0/10} + 10^{L_1/10} + 10^{L_2/10} + 10^{L_3/10} + 10^{L_4/10} + 10^{L_5/10})$. When you for example look at the graph of the total rays on the façade, you wouldn’t say that model 4 (20 cm down) would perform worse than model 4 (20 cm up). This is because model 4 (20 cm down) has a larger part of direct rays on the façade than model 4 (20 cm up) which brings up the total sound pressure level at the façade.

When you only look at the rays at the façade caused by reflection (like shown in the graph rays only by reflection), you can see what the effect is if you don’t take the direct rays into account. This result would occur if the screens all would have the same screening effect and the only difference would be in the amount of reflections (Table 8.7).

<table>
<thead>
<tr>
<th></th>
<th>Model 1</th>
<th>Model 1 (20 cm up)</th>
<th>Model 1 (20 cm down)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta L$</td>
<td>-1,20</td>
<td>-1,59</td>
<td>-1,28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Model 2</th>
<th>Model 2 (20 cm up)</th>
<th>Model 2 (20 cm down)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta L$</td>
<td>-1,44</td>
<td>-1,81</td>
<td>-0,78</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Model 3</th>
<th>Model 3 (20 cm up)</th>
<th>Model 3 (20 cm down)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta L$</td>
<td>-1,98</td>
<td>-0,86</td>
<td>-2,18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Model 4</th>
<th>Model 4 (20 cm up)</th>
<th>Model 4 (20 cm down)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta L$</td>
<td>-1,76</td>
<td>-3,24</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Model 5</th>
<th>Model 5 (20 cm up)</th>
<th>Model 5 (20 cm down)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta L$</td>
<td>-1,66</td>
<td>-0,83</td>
<td>-1,35</td>
</tr>
</tbody>
</table>

Table 8.7 The band width of the different models only by reflection

The band width is 3,24 dB and the numbers don’t change with different reflection coefficients. From this table you can clearly see that if you only look at the reflections model 4 (20 cm down) would perform better than model 4 (20 cm up). This could also be seen in the graph (rays only by reflection). Model 3 (20 m up) which performed the best in the former table, is now on a fourth place.
Conclusions

The shape and the position of the screens have an influence on the total amount of rays on the façade and therefore on the sound proofing value of the screens. However no clear statement could be made about the performance of either a shape or a position because they seem to randomly perform well or bad. The band width of variations of the performances of the screens when you look at direct and indirect rays is 2,4 dB and when you only look at direct rays this band width is 3 dB.
8.8 Ecotect: The influence of the width of the cavity and the form

Goals

The influence of the width of the cavity between the screens on the amount of rays on the façade was tested as well. There is looked at the total number of rays that reach the façade after five reflections, which could be split up into the number of rays that reach directly the façade, so without reflections, and the number of rays that reach the façade only by reflections. With this information you can see if the variants differ mainly in the amount of rays that reach the façade directly, the amount of rays that reach the façade by reflection or both.

Method

There are five different cavity widths tested, namely 0.5, 0.75, 1, 1.25 and 1.5 m (Figure 8.52)

And this is done for three different configurations, two straight screens and a curved one (Figure 8.53)

Figure 8.52 The different cavity widths

Figure 8.53 The different configurations
Results

- **Straight screens**

![Figure 8.54 Amount of rays (model 1- screens in front of each other)](image)

Figure 8.54 Amount of rays (model 1- screens in front of each other)

![Figure 8.55 Amount of rays (model 1- front screen 20 cm up)](image)

Figure 8.55 Amount of rays (model 1- front screen 20 cm up)

Like shown in Figure 8.54 and 8.55
- The first peak of the graph shifts from left to right (from close to further away from the façade) when the cavity gets wider.
- The smaller the cavity the greater the amount of rays on the first peak.
- The total amount of rays on the façade minimizes when the cavity gets wider

![Figure 8.56 Amount of direct rays (model 1- screens in front of each other)](image)

Figure 8.56 Amount of direct rays (model 1- screens in front of each other)

![Figure 8.57 Amount of direct rays (model 1- front screen 20 cm up)](image)

Figure 8.57 Amount of direct rays (model 1- front screen 20 cm up)

The total amount of direct rays on the façade doesn’t differ that much for the different cavity widths. (Figure 8.56and 8.57).
With a curved screen the results are a bit different than the straight screens, but still resemble in some way the previous results (Figure 8.60).
- The first peak of the graph shifts as well from left to right when the cavity gets wider.
- But the total amount of rays on the façade are the least when the cavity is one meter width. The wider or the narrower the cavity, the worse the performances.
Conclusions

- Straight screens
  The diminishing of the total amount of rays on the façade when the cavity gets wider is due to the diminishing of the total reflections on the façade.

- Curved screen
  There is no clear conclusion in the diminishing in the amount of rays. For this variant the cavity width with the least amount of rays is 1 m (as well for the direct as the reflected rays). However this doesn’t mean directly that this counts for all types of curved screens.


8.9 Comparison of the different methods

Like for the wind simulations in the previous chapters, there are also different programs and methods used for the sound simulations. For these methods as well a short overview of their possibilities and limitations is made to get a sense of the value and shortcomings of the results.

<table>
<thead>
<tr>
<th>Acoustics</th>
<th>Possibilities</th>
<th>Limitations</th>
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</thead>
<tbody>
<tr>
<td>Hand calculations</td>
<td>- The diffraction is taken into account</td>
<td>- 2D</td>
</tr>
<tr>
<td>Program traffic sound</td>
<td>- A line source could be modeled</td>
<td>- 2D</td>
</tr>
<tr>
<td></td>
<td>- The calculation is faster than a hand calculation</td>
<td>- The diffraction is not taken into account</td>
</tr>
<tr>
<td></td>
<td>- The sound pressure level is modeled by the road data you put in</td>
<td>- The forms are limited to straight lines</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- The reflection coefficient is applied to all the materials</td>
</tr>
<tr>
<td>Ecotect</td>
<td>- 3D</td>
<td>- It is in essence not a sound calculation program, but with different</td>
</tr>
<tr>
<td></td>
<td>- More form freedom is possible</td>
<td>calculations you can get valuable results</td>
</tr>
<tr>
<td></td>
<td>- The influence of amount of reflections could be tested better</td>
<td>- The diffraction is not taken into account</td>
</tr>
</tbody>
</table>

Table 8.8 Comparison of the different methods
8.10 Diffraction

At lower frequencies the diffraction of sound around objects plays a bigger role and the assumption that sound behaves like light is less relevant. When diffraction occurs the screening effect of objects is diminished. There are already a lot of studies done about the phenomenon of diffraction and how to diminish this effect.

**Literature**

In this study of Pirinchieva they determined the minimum barrier length for which the influence of the side edges diffraction may be neglected, so that the barrier may be considered as infinitely long. When only diffraction over the horizontal edge exists, the sound field is formed mainly by the waves diffracted from the central part which is up to about 6 to 8 wavelengths long. (Pirinchieva, 1991)

Single diffraction occurs on thin sound barriers like a screen. However when sound propagates over a thick barrier or polygonal-like obstacles, multiple diffractions occur. The sound attenuation increases with multiple diffractions and is therefore a good principle, to diminish the effect of diffraction. (Kim, 2005)

![Graph showing insertion loss predictions](image)

The graph in Figure 8.63 shows the effect of the multiple barriers on the insertion loss. Insertion loss is the attenuation caused by the insertion of a device. The double screen and the two wedges have a slightly higher insertion loss than the thick barrier.

![Graph comparing insertion loss predictions](image)

Figure 8.64 The influence of different forms on the insertion loss (Kim, 2005)
Figure 8.64 shows that the Y-shaped barrier has overall a higher insertion loss than the other two barriers. Especially around the frequency of 1000 Hz this barrier had a higher insertion loss.

Numerical examples such as double wedges and doubly inclined barrier show that when there exist several diffraction paths for given source and receiver positions, the insertion loss is dominated by the diffraction associated with the shortest propagation path. It is also found that although the partially inclined barrier increases the shadow zone as compared to the simple screen type of the same total height, it does not necessarily increase the insertion loss at all heights. (Hyun Sil Kim, 2006)

Figure 8.65 Insertion loss behind a thin screen
The thicker barrier (Figure 8.66) shows a higher insertion loss behind the barrier than the thin screen (Figure 8.65) (Kawai, 1981)

Conclusions

When you compare a single barrier with a multiple barrier, the multiple barrier performs on one hand better because the shadow zone is increased. The other reason that it performs better is that multiple diffractions at the screen increases the sound attenuation. This principle could be used in the design.

An idea for implementation
8.11 Conclusions

Several tests with different methods have been done to research the value of a screen in front of the façade. Especially the screening effect of a screen is important for the performance of a screen.
- Several smaller screens which are vertical equally divided over the façade perform better at a higher altitude than one large screen at the bottom of the building.
- When a screen makes an angle away from the road, than the screening of the façade from direct rays increases and the path between the source and reception point increases as well, therefore such a screen performs better.
- When a screen is made out of reflective materials, the sound level in front of the façade is almost equal as without a screen. On one hand a screen creates a shielding effect and increases the path between the source and the reception points, but on the other hand also provide additional reflections.
- Two screens with openings in front of the façade perform twice as good as one screen, whilst three screens only give a little more improvement. The minimization of the openings give less improvement than the increase in number of screens.
- The shape and the position of the screens have an influence on the total amount of rays on the façade and therefore on the sound proofing value of the screens. However no clear statement could be made about the performance of either a shape or a position because they seem to randomly perform good or bad.
- When a cavity gets wider with a straight screen, the total amount of rays on the façade diminishes. This is mainly due to the diminishing of the total reflections on the façade.
9. Conclusions

At the end of this research report the two main questions which were proposed in the beginning could be answered.

*How could the conditions at building scale be optimized so that the nuisance of wind and air pollution will be minimized?*

The research at building scale was focused on two aspects, which is the wind climate and the quality of the air. The requirements and data from chapter 3 and 4 showed that some effort had to be made to meet the requirements for a comfortable wind climate and a healthy environment with reduced pollution.

The research for the wind climate showed some design rules which could be applied to ensure a better wind climate in the street. So should the building not be too high and the street not too width in respect to the building height. Another aspect is that the street shouldn’t be too long without interruption to avoid the channeling effect, which are high air speeds between long, continuous rows of buildings. Openings in the building row should be made to avoid this effect.

The requirements for the wind climate showed that there is a maximum of 35 days a year that a wind speed of 5 m/s at head height may be exceeded. The testing of the wind climate in the passage between two buildings with the program Knowind showed that even with the most optimized circumstances the wind climate was still uncomfortable at some places. Therefore additional measures needs to be taken to improve the wind climate at that spot. The screen, which will be discussed later, is a good device to improve the wind climate in the passage.

The research for the air quality showed as well some design rules for the building to create a better environment above the highway. On a building scale is dilution of the contaminated air with cleaner air the best way to reduce the air pollution. The further away from the highway you catch this air, the cleaner it will be and so it will be better to catch the air from a certain height. This could be done by creating a step-up notch, which is a height difference in the building rows perpendicular to the main wind direction. This step-up notch leads the air from a higher altitude to street level. A step-up notch creates as well the lowest pollution levels in the street. On the other hand the ventilation in the street is reduced by a step-up notch. For the improvement of the air flow through the street and the increase of dilution of the air, it is better to make openings in the building row. Like mentioned before openings in the building row also prevent the channeling effect. Tests with the program Ecotect showed that when the openings are shifted from each other the air flow through the street improves.

Because of the openings in the street wall, which should be made to create a better wind climate and to improve the dilution of the air, the risk that the air that comes through these openings is more polluted than the air you catch from a higher altitude arises. Like mentioned before the wind climate in such an opening is as well still uncomfortable at some places. For the wind climate and the air pollution it is important that an extra device is created for the improvement of the wind climate and the air quality. This could be done in the form of a screen in the openings, which could function as well as a noise barrier. This brings us to the next main question.

*How could the layer between the buildings and the highway contribute in solving the problems that arise at that area?*

The research for the screen was focused on three aspects, namely the improvement of the wind climate, the air pollution and noise.

For the wind climate it is better when the wind isn’t totally blocked by the screen but could flow through a porous screen. The program Comflow showed as well that when the porosity of the screen decreases, the direct speed behind the screen diminishes, but the turbulence at the top of a screen increases. This turbulence finally causes a worse flow pattern behind the screen.

For the air pollution there are different means to filter and absorb the pollution in the air. One that is very effective is the use of vegetation to clean the contaminated air, because it deals with particulate matter (PM$_{10}$), nitrogen dioxides (NOx), carbon dioxide (CO$_2$) and even ozone (O$_3$). For the air pollution it is as well better when the contaminated air can flow through the screen because it increases the effectiveness of a screen.
For the noise there are several tests with different methods done to research the sound level reduction of a screen in front of the façade and the openings. Especially the shielding effect of a screen is important for the performance of a screen. The several tests resulted in the following conclusions:

- Several smaller screens which are vertical equally divided over the façade perform better at a higher altitude than one large screen at the bottom of the building.
- When a screen makes an angle away from the road, than the screening of the façade from direct rays increases and the path between the source and reception point increases as well, therefore such a screen performs better.
- When a screen is made out of reflective materials, the sound level in front of the façade is almost equal as without a screen. On one hand a screen creates a shielding effect and increases the path between the source and the reception points, but on the other hand also provide additional reflections.
- Two screens with openings in front of the façade perform twice as good as one screen, whilst three screens only give a little more improvement. The minimization of the openings give less improvement than the increase in number of screens.
- The shape and the position of the screens have an influence on the total amount of rays on the façade and therefore on the sound proofing value of the screens. However no clear statement could be made about the performance of either a shape or a position because they seem to randomly perform good or bad.
- When a cavity gets wider with a straight screen, the total amount of rays on the façade diminishes. This is mainly due to the diminishing of the total reflections on the façade.

The exact wind climate and wind speeds at a design are very difficult and complicated to simulate. Therefore it can’t be stated with complete certainty that the requirements for a good wind climate at street level are met. But the measures that this research showed are at least a good way to provide a comfortable wind climate.

For the air pollution it is as well very difficult and out of the reach of this research to calculate how much pollution is absorbed and filtered and what the exact effect of dilution is on the pollution in the air. But the measures show here as well a good manner to reduce the pollution as much as possible.

For the noise it is easier to give an indication of the sound level reduction caused by the screen. Like showed in paragraph 8.6 the different types of open screens could give a maximum sound level reduction between 4 and 15 dB, when the material of the screen has an absorption coefficient of 1. In combination with a façade it is feasible to achieve a sound level reduction of 40 dB. At street level it is less likely that a reduction of 20 dB only by an open screen could be received. Therefore some additional measures could be taken at the screen to improve the sound level reduction of the screen more. The options will be further discussed in the recommendations.
10. Recommendations

For the design some recommendations can be made.

For the air quality
- Building scale
Create an step-up notch towards the main wind direction and make openings in the large building block to enhance the air flow through the streets.
- Screen
To increase the effectiveness of a screen for the filtering of the air, the wind should be able to flow through it.

For the wind climate
- Building scale
Openings in the large building block improves the wind climate, because it avoids the channeling effect.
- Screen
As an wind break it is as well better when the wind isn‘t totally blocked by a screen but could flow through a porous screen.
Further from an architectonic point of view it is also recommended to provide a view from the street and the building onto the surroundings.

For the noise
- Screen
An open screen could give a sound level reduction at street level and in front of the façade. The amount of direct sound rays and as well reflected sound rays should be diminished by the design of the open screen. When multiple diffractions occur at the screen a sound attenuation takes place as well.

The screen
When the screen is in front of the façade, it is important that noise is reduced as much as possible. When the screen is however in front of an opening in the street, than it is on one hand important that the noise is reduced, but as well that the air can flow through the screen and that the pollution will be captured. At this point the acoustic and cleaning properties of the screen meet each other. There are some variants created and compared on their applicability.
Like shown in Figure 10.1 variant 1 and 2 are horizontal screens and variant 3 till 7 are two vertical screens placed in front of each other. In the research of chapter 8 the gaps in the vertical screens where always placed in front of each other. For the air flow it is however not necessary that these gaps are in front of each other. By alternating the openings the sound reduction could be improved more because the sound rays can most of time not directly go through the screen, but is first reflected in the gap between the screens. A sound ray also needs to diffract multiple times before it is behind the screen, which improves the sound reduction as well. To maintain the view a transparent surface could be used at the place where the gap used to be. This is because Variant 4 till 7 show the possibilities of alternating opening, where the thin line indicates a transparent surface and the hatched section shows the sound absorbing screen. At all variants the place where the cleaning material could be placed is colored green, which could be vegetation, but as well other materials, like discussed in paragraph 7.2.

As discussed in paragraph 7.3 it is more effective for the cleaning of the air to let it flow through the material instead of just along it. In variant 2 and 3, the air flows only along the material, which reduces the change of intensive contact between the contaminated air and the cleaning device. At the variants 5 and 6, where the air actually flows through the cleaning material, a piece of the acoustic screen is replaced by the porous cleaning material so the air can flow through it. This however decreases the sound-proofing effect of the screen. It is an advantage when the air speed is reduced at the moment the air flows through the material. The reduction of the speed has as well positive influence on the wind climate behind the screen. This is especially the case with variants 4 and 7, because the air flow needs to make a turn at these screens, and less with variant 1. Variant 4 or 7 would therefore be a good recommendation to continue with for the design.
11. The integration of the research and the design

This research project of Building Technology was performed and finished one semester before the design of the Architectural Engineering was completed. Because this graduation project is a combined project of Building Technology and Architectural Engineering it is interesting to see how the research finally is integrated in the design.

At a building scale
• There is a height difference created between the two building rows as could be seen in Figure 11.1, so the wind can be captured at a certain height and brought to street level.

![Figure 11.1 The height difference and the moss roof](image)

• There are openings made in the street, which functions as squares. These squares break an otherwise long building row into different smaller buildings, which improves the air flow. The squares are as well for the design very important because they create different spaces along the street which makes the route over the highway more interesting.
• There are trees placed in trays in the street and between the offices to filter and absorb the pollution in the air (Figure 11.2). There is as well moss on the roof to clean the air which flows over the roof into the streets (Figure 11.1).
Screen
- There are two screens placed in front of each other with openings which increases in size from bottom to top (Figure 11.3). This is done partly functional, because closer to the road there is more noise, so the smaller the gaps should be and partly for the aesthetics because it results in an interesting pattern. The screens are made of perforated steel sheet containing rock wool which ensures that the sound is absorbed. The increasing porosity from bottom to top also has a positive influence on the air flow through the screen, because it reduces the turbulence at the top of the screen.

Figure 11.3 The pattern of the screen

- The screen is curved according to a certain pattern, which creates an interesting view when you face the screen from the side (Figure 11.4). The test of paragraph 8.7 showed that the form of a screen has an influence on the performance, but that no clear statement could be made about the performance because they randomly seem to perform good or bad. Some curved screens performed better than the straight screens, but as well some curved screen performed worse. Therefore the curvature of the screen was based on design preferences.
In the screen there are no gaps placed directly in front of each other. Like discussed in chapter 10 it is not necessary for the air flow that the gaps are in front of each other. The gaps are alternately closed with polycarbonate, which is a transparent material. It is also flexible, so it could be bend in the curved shape of the screen. Because the air cannot directly flow through the gaps, but only by an alternately path (Figure 11.5), the wind speed behind the screen is reduced and therefore the wind climate improved. The sound-proofing of the screen improves because the sound rays can most of time not directly go through the screen, but hits the second screen first (Figure 11.5). A sound rays also needs to diffract multiple times before it is behind the screen, which improves the sound reduction as well.
• Between the screens vegetation is applied as a cleaning device, which should purify the contaminated air which flows through the screen (Figure 11.6). The plants don’t receive a lot of light, because they are in between two screens, but they do receive light from the gap above the plants. However the plants that will be placed should be able to live in darker circumstances.

Figure 11.6 The air flow through the screen and the vegetation indicated in green.

• The façade itself consists of precast concrete panels with natural stone plates placed upon it and with windows made out of double glazing. The concrete in combination with an insulated cavity and the natural stone will give a good sound proofing. However the windows will be normative for the sound-proofing of the façade (which is roughly calculated 36 dB), which makes it necessary to place a screen in front of the façade.

For further explanations of the design see Appendix V : Design
12. Sources

Books


Lord, Peter (1996), 'Detailing for acoustics'. (Londen: Spon), 200


Articles


Dierickx, W., Cornelis, W.M. and Gabriels, D. (2003), ‘Wind tunnel study on rough and smooth surface turbulent approach flow and on inclined windscreens’, Biosystems Engineering 86, 151-166

Franke, J. et al. (2004), 'Recommendations on the Use of CFD in Wind Engineering', COST Action C14


Kawai, T., (1981), ‘Sound diffraction by a many-sided barrier or pillar’, 79, 229-242


(Practicum instructies geluidhinder bij bebouwing boven een spoorlijn of Weg)

Internet
www.knmi.nl
www.bouwbesluit.nl
www.chri.nl
http://www.lml.rivm.nl/data/histo/446-168.html
http://www.merlin-project.de
www.rijkswaterstaat.nl
www.wallflore.nl
Appendices
I. Appendix: Influences on the final sound pressure level

Before a sound from a source reaches a perceiver different factors have an influence on the diminishing of the sound emission. These factors are:

- distance
- air
- ground
- meteo (atmospheric influence like wind)

All these factors together give the following formula for the final sound pressure level.

\[ L_{\text{Aeq}} = \text{Emission} - D_{\text{distance}} - D_{\text{air}} - D_{\text{ground}} - D_{\text{meteo}} \]

This formula is for a road parallel to the observer.

**The influence of the distance**

The formula is based on a logarithmic scale

\[ D_{\text{distance}} = 10 \log r \]

<table>
<thead>
<tr>
<th>Distance [m]</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1 km</th>
<th>10 km</th>
<th>100 km</th>
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<tr>
<td>( D_{\text{distance}} ) [dB(A)]</td>
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<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
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</table>

**The influence of the air**

Because of friction by the water molecules in the air, loss of energy occurs.

Measurements give the following formula:

\[ D_{\text{air}} = 0.01r^{0.9} \]

<table>
<thead>
<tr>
<th>Distance [m]</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1 km</th>
<th>10 km</th>
<th>100 km</th>
</tr>
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<tr>
<td>( D_{\text{air}} ) [dB(A)]</td>
<td>0.1</td>
<td>0.6</td>
<td>5.1</td>
<td>40</td>
<td>316</td>
<td></td>
</tr>
</tbody>
</table>

**The influence of the ground**

Reflection to the ground has an influence on the final sound pressure level. There are two types of ground layer, namely absorbent and non-absorbent. The effect of a non-absorbent ground layer is 0, as it is already taken in the emission measurements, because they are also above the ground. Examples of these layers are roads, water, etc. The absorbent ground layer has an effect compared to the non-absorbent ground layer. In theory the effect of an absorbent surface could be tens of dB’s, but it is limited around 6 dB because of atmospheric influences.

![Graph showing the influence of the ground](image)

Figure I.1 The influence of the ground On a height of 1 m and on a height of 4 m

The influence of the absorbent ground decrease at a greater height (Figure I.1)

**The influence of wind**

The sheltering effect of a screen is impeded when wind is blowing from the source across the barrier towards the protected area. The air flow is accelerated above the obstacle and a vortex is formed in its wake. Due to
enhanced vertical wind gradients above the top of the screen additional downward refraction is caused which diminishes the sound attenuation

Figure I.2 Results of the acoustical simulations vertically averaged between ground and screen top level. R01-R00: effect of ground, R02-R00: effect of ground and wind, R11-R00: effect of screen and ground, R12-R00: effect of screen, ground and wind (Heimann, 2003)

At 250 m range the wind effect amounts to 3 dB without screen and 5 dB with screen (Figure I.2) (Heimann, 2003). When a porous screen is used, the downward refraction could maybe be diminished.

The effect of turbulence
The effect of screen-induced turbulence on the sound level behind the screen is negligible. Values of 0.2 dB (at 250 m range) where found. (Heimann et al., 2004)

Wind influence on hard ground
Situation without wind 65 dB(A)
At cross wind ca. 45 dB(A)
At tailwind ca. 67 dB(A)
Like

Wind influence on absorbent ground
Situation without wind on hard ground 65 dB(A)
Without wind on grass 50 dB(A)
Tailwind on grass 60 dB(A)
So tail wind bypasses absorption
(Lau Nijs)

In this situation the ground layer will be non-absorbent as it is a road surface. The influence of wind should be taken into account, as the direction of the highway is a prevailing wind direction. But the distance on which it occurs is short (60m) and therefore the diminishing of the sound attenuation under influence of tailwind is smaller.

So the following values can be concluded

- $D_{\text{distance}}$ -10 dB on 10 m / -20 dB on 100m
- $D_{\text{air}}$ -1 dB on 100 m
- $D_{\text{ground}}$ 0 dB
- $D_{\text{meteo}}$ -2 dB on 60 m

So the biggest impact comes from the distance on the sound pressure level.
## II. Appendix: Building Act

<table>
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### Artikel 3.2 Industrie-, weg- of spoorweglawaai

**Lid 3.**

Een uitwendige scheidingsconstructie die de scheiding vormt tussen een verblijfsgebied en de buitenlucht, heeft een volgens NEN 5077 bepaalde karakteristieke geluidswering die niet kleiner is dan het verschil tussen de geluidsbelasting zoals gedefinieerd in de Wet geluidhinder en bepaald volgens reken- en meetvoorschriften van de Wet geluidhinder van die scheidingsconstructie en 40 dB in geval van weg- of spoorweglawaai, met een minimum van 20 dB, of 40 dB(A) in geval van industrielawaai, met een minimum van 20 dB(A).

**Lid 4.**

Indien krachtens de Wet geluidhinder in het verblijfsgebied een hogere geluidsbelasting is toegestaan dan bedoeld in het eerste lid heeft de uitwendige scheidingsconstructie volgens NEN 5077 bepaalde karakteristieke geluidswering die niet kleiner is dan het verschil tussen de geluidsbelasting van die scheidingsconstructie en het krachtens de Wet geluidhinder toegestane geluidsniveau.

**Lid 5.**

Op een inwendige scheidingsconstructie van een verblijfsgebied als bedoeld in het eerste en derde lid, die niet de scheiding vormt met een aangrenzend verblijfsgebied van een andere gebruiksfunctie die gevoelig is voor industrie-, weg- of spoorweglawaai, zijn de eerste, derde en vierde lid van overeenkomstige toepassing.

**Lid 6.**

Een scheidingsconstructie als bedoeld in het eerste en het derde tot en met vijfde lid van een verblijfsruimte heeft volgens NEN 5077 bepaalde karakteristieke geluidswering die maximaal 2 dB(A) lager ligt dan de karakteristieke geluidswering als bedoeld in het eerste en het derde tot en met vijfde lid, van het verblijfsgebied waarin die verblijfsruimte ligt.

---

**Building Technology Report – Susanne Rolaff – 1186396 – 02/07/2010**
III. Appendix : Vegetation

The effectiveness of vegetation
They are several studies done on the effect of vegetation on air quality.
- Overall
All forests in the Netherlands together remove estimated 7200 tons particulates per year (Houben et al., 2006). This is 17% of the total amount of particulate matter which is emitted annually in our country.
Green elements capture estimated in average meteorological conditions maximum 15-20% of the total particulate matter (PM10). The concentration of nitrogen dioxide can be reduced up to 10% by a green element with a proper porosity (Wesseling et al., 2008).
- Near a source of air pollution
Near a source, such as a busy road, greenery can help reduce the concentration at the spot (local protection). The possible reduction of the concentration is very local and would particularly take place on the leeward side of the tree. The protective effect could be repeated by planting a second line of trees at some distance.
- The green tunnel effect
However not always leads the filtering through the trees to lower concentrations at the site where the tree grows. Trees next to the road filter the air but they also reduce the wind speed. As a result of this attenuation of the wind speed, the exhaust gases are mixed with less air than in a situation without trees. The net effect of the concentration increase by the attenuation of the wind speed and the concentration reduction by filtration of the green is often an increase in the concentrations at the site where the tree stands. This is the case for PM10 when the porosity of the plants is less than 40%. The "green tunnel effect" occurs only within 100 to 150 meters from the road where the exhaust is not fully mixed with the air.

Effectiveness of various plants and trees, where ■ means least effective and ■■■ means most effective in the catching of particulates and absorbing of nitrogen dioxides and ozone.

<table>
<thead>
<tr>
<th>TABLE 8</th>
<th>Schatting van de effectiviteit van de belangrijkste soorten om de concentraties van fijn stof, stikstofoxiden en ozon in de lucht te verlagen.</th>
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<td>KOLOM SOORT</td>
<td>Genoemde eigenschappen gelden ook voor de cultivars van de genoemde soort.</td>
</tr>
<tr>
<td>KOLOM FIJN STOF (AFVANGEN), STIKSTOFOXIDEN (ABSORPTIE) EN OZON (ABSORPTIE)</td>
<td>☐ : Minst effectief  ■■■ : Meest effectief</td>
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<tr>
<td>KOLOM STIKSTOFOXIDEN</td>
<td>☐ : Soorten die veel stikstofdioxide absorberen en hier niet gevoelig voor zijn (op basis van Japans onderzoek)</td>
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<tr>
<td>KOLOM OZON</td>
<td>☐ : Soorten die de ozonconcentratie effectief doen dalen in de stad (op basis van Engels onderzoek)  ■ : Geringe emissie  ■■ : Veel emissie</td>
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<td>KOLOM EMISSIE VAN VLUCHTIGE ORGANISCHE STOFFEN</td>
<td>☐ : De emissie van vluchtige organische stoffen is bij deze soorten niet meetbaar.</td>
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### Figure III.1 The effectiveness of various plants and trees (Hiemstra, 2008)

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<th>OZON</th>
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IV. Appendix: Results Ecotect

The following Excel sheet shows how the calculations of Paragraph 8.6 for Model 1 in Ecotect are made.
At 6m from the highway the sound level is 80 dB

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Integrate without a screen

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V. Design

Construction

The construction which needs to carry the building also needs to span the highway with quiet large spans, because the largest span is 34 meters. For that reason is chosen for a division in an understructure, which makes the large spans possible and a superstructure, which is placed upon the understructure and which is more adapted to the smaller grid of the spaces above the highway.

Materials

For the understructure which is next and directly above the highway concrete is used as a material (Figure V.1). It carries like a table the superconconstruction which is placed upon this concrete structure. It is made out of concrete because it:
- captures collisions better
- succumbs slower at fire
- is less affected by the weather
For the superstructure steel is chosen as a material (Figure V.2), because steel:
• is flexible and makes a change of building afterwards possible
• is stronger than concrete, so a slimmer dimensioning is possible
• can be integrated with the floor
• by a slimmer dimensioning the total construction becomes lighter, which is good for the total loads

As a floor is chosen for a steel-concrete floor (Comflor 210), because it has a
• has a low weight. The profile of the steel plates reduces the concrete volume and creates an efficient diameter. Compared to traditional concrete floors, steel-concrete floors are slim and light performed.
• makes a large span possible
• makes a rapid construction possible
• makes an overhang possible

Grid

Use structure
On top of a part of the building are offices. Office sizes are often based on 1.8 m or a multiple of that. For example a size of 3.6 m is common in office buildings.

Installation structure
This installation structure frequently enters well with office sizes and is therefore often based on a grid of 1.8 or 3.6 m. In respect to costs is 3.6 m often used.

Supporting structure
For floors often the width of 0,6m or a multiple of that is used. In this case the Comflor210 has a width of 0,6m.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Grid 3600 mm</th>
<th>Grid 5400 mm</th>
<th>Grid 7200 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,6 m</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>1,8 m</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>3,6 m</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table V.1 Grid and structure matches

Table V.1 shows that the structures both fit in a grid of 3,6 and 7,2 meters. But with a larger grid size the building could be built faster, because the amount of connections is reduced. Therefore the grid size of 7,2 m is chosen.

The transition from a small grid to a large grid.
The transition from two different grid sizes is under the floor of the street. In this way, users do not suffer from the transition structure. Most of the columns of the superstructure are not directly placed at a column of the understructure and these columns are carried by the concrete beams of the understructure.

Stability

Stability of the understructure in longitudinal and transverse direction
Since concrete is the selected material for the substructure, the portal is made stable as is common with concrete. Namely by clamping the bottom of the columns in the foundation and to hinge the beams to the columns. (Walraven et al, 2004)
Stability of the superstructure in longitudinal and transverse direction

For the superstructure a braced structure with k-connections has been chosen. The reason that a k-connection (Figure V.3) is preferred above an cross connection (Figure V.4) is the following. The columns shorten by the vertical load on it, which introduces compressive forces in the connections. This means that a connection always should be dimensioned as a compressive bar. You can’t make a cross connection which is only dimensioned on tension. In a k-connection both diagonals pushes the beam up, which bends then. The force needed for this will be much smaller than the force that occurs when applying a cross connection. This is because a k-connection is less inclined than a cross connection (Gerrits, 2002). Openings are as well easier to make under a k-connection (Figure V.5).

Figure V.5 Stability of the building

**Climate design**

The ambition for the climate concept is to make a pleasant and healthy environment for the people that work, do sports and spent their free time at the living bridge. The heating, cooling and ventilation should be realized in a energy efficient way and should be adjustable to changing needs.

**The course of the ducts and pipes**

The air ducts and water pipes are above a suspended ceiling. The mechanical ventilation is based on a CAV system. The air is blown into the room through an air supply grill. The drainage of this air is through open fittings which are also located in the ceiling. At the offices, the exhaust air above the suspended ceiling of the office goes to the suspended ceiling in the corridor by a tube. Eventually at the end near the air shaft the air is drained through a large drain.
There are three shafts on each side (Figure V.6) and in these shafts is the vertical transport of air ducts and water pipes. On top of each shaft at the roof is an air handling unit. Each side has one boiler room and chiller room with condenser. The pipes that come from here, are divided over the three shafts. The plant rooms are on the roof because the air handling unit can properly supply fresh air in this way, the boiler room can lose his harmful gases instantly and the central cooling can be placed by its condenser, which has to stand on the roof anyway (Figure V.7).

It is decided to place three vertical shafts on each side because in this way:

- The ducts and pipes are not too long
- The horizontal and vertical ducts and pipes don’t get a too large diameter, which restricts the height of the suspended ceiling.

The ducts and pipes are horizontally above a suspended ceiling. In this way you don’t lose any valuable floor space, which you have by placing the pipes space at the facade and you will have no problems with height differences per floor, which you have if you install the pipes beneath a raised floor (Figure V.8).
The transport of heat and air

The space is heated and cooled with a climate ceiling. The ventilation is controlled with a constant volume system (Figure VII.9). The advantage is that the heating and cooling can be independently regulated from the ventilation. This means you no longer need to vent than is necessary for the fresh air supply. This creates less draft in the space.

A climate ceiling is chosen for the following reasons:

- Heating and cooling ventilation is independent of the ventilation
- Low air displacement -> Better comfort
- Good sound absorption
- Saves a constructional ceiling
- Energetically favorable (due to temperature trajectories of heated and cooled water that can be kept low)
- In the winter radiation compensation of cold surfaces
- Easy maintenance
- High cooling capacity

Sound insulation of the façade

The façade panels consists out of a prefab concrete slab with natural stone placed upon it and windows in it to provide a view. The sizes of such a panel is shown in Figure V.10. The sound insulation of double glass was
showed in table 8.1 and is 31.5 dB. With the practical mass law the sound insulation of concrete plus natural stone could be calculated. The concrete slab has a thickness of 12 cm and the specific gravity is 2400 kg/m$^3$, which makes the weight of the panel 288 kg/m$^2$. The natural stone plates have a thickness of 3 cm and their specific gravity is 2600 kg/m$^3$, which adds another 78 kg/m$^2$ to the weight of the panel. The total weight is 366 kg/m$^2$ combined. The practical mass law is $R_m = 15 \log(4*m)$, which gives a value of 47.5 dB. The glass in the façade is however normative for the sound insulation value of the total panel, which could be calculated by the following formula: $R_{\text{surface}} = -10 \log \left( \frac{1}{S_{\text{surface}}} \right) \times \left( S_1 \times 10^{R_1/10} + S_2 \times 10^{R_2/10} \right)$

Like shown in Figure V.10 the total surface of the panel is $4 \times 3.6 = 14.4$ m$^2$, the surface of the glass is $2 \times 1.5 \times 1.5 = 4.5$ m$^2$ and the surface of the concrete and natural stone is $9.9$ m$^2$.

This results in an $R_{\text{surface}}$ of 36.3 dB.