# Reclaiming land from urban traffic noise impact zones

"The great canyon"

Evert de Ruiter

# Reclaiming land from urban traffic noise impact zones

"The Great Canyon"

Proefschrift

Ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. dr. ir. J.T. Fokkema,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen, op 10 januari 2005 om 15.30 uur
door Evert Philippus Jan DE RUITER
natuurkundig ingenieur
geboren te Veenendaal

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Distributed by Peutz bv
P.O. Box 696
2700 AR Zoetermeer
Telephone +3179 347 0347
Telefax +3179 3614 985
E-mail info@Zoetermeer.Peutz.nl
ISBN 90-9018 656-5


Printed in The Netherlands.

To my parents

Rijk Hendrik de Ruiter (1904-1979) and

Antonia Leonarda de Ruiter-Knijff (1913-1999)

## Summary

### *Reclaiming land from urban traffic noise impact zones*

Sustainable building implies efficient land use in cities, and elsewhere. Zones with a high noise impact along urban or suburban main roads have been used only for offices and low-grade buildings, because of practical or legal limitations. Bordering these roads with continuous apartment buildings ("canyonisation") can be considered a way to reclaim these zones. The buildings provide noise reduction to the areas in the "backyard" in the first place. In this way they protect land from excessive noise loads. Secondly they offer housing capacity within themselves. Research was aimed at the development of <u>tools</u> to stimulate this approach in a well-considered way. From the experience that acoustical aspects can play an important role, but are often neglected – presumably for lack of easy to handle methods – the focus was set on acoustical tools.

The design process regarding urban canyons embraces the following acoustically important questions.

a) What is the total extent of noise annoyance in the impact area of a stretch of road? How much reduction can be gained?

b) How to achieve the required shielding? What building height is required? Are passageways acceptable?

c) Which special properties are required of the first-line buildings? This concerns the noise-loaded façade in the first place. Secondly, a second (glass) façade can be inserted in front of the building façades, thus creating a buffer space ("atrium") where there is a mild, intermediate climate. This space can be used for circulation (entrances of the apartments); also balconies can be inserted in the atrium. Next to the reduction of external noise, other acoustical aspects of such an atrium are important for the livability of the dwellings and their direct environment: control of noise caused by occupants in the atrium and control of noise nuisance from neighbouring balconies.

Several tools have been developed to facilitate the process, and answer the questions above:

- The Population Annoyance Index (*PAI*), as an indicator for the first question
- The effectiveness of a (continuous) building as a barrier, expressed as the admissible traffic intensity on a road yielding a fixed acceptable sound load at a chosen position in the lee zone behind the building.
- Additional tools, to determine the influence of apertures (passageways) in the buildings and the termination of the buildings on the shielding effect.
- Tools to determine roughly the required measures in the façades, in casu the required types of glazing – the opaque parts are assumed to contain enough mass.
- An approach to control the noise caused by the occupants in the atrium.
- The Required Masking Noise Level ($L_{mn}$), as an indicator for the occurrence of noise annoyance from neighbours residing on their balconies, based on the notion of "speech privacy".

An overview of the tools is added with the most relevant descriptors (output, benefit, and input) and examples to illustrate their use. The tools are regarded in a wider context too, namely as parts of the processes in the design of cities and buildings: learning processes embracing several disciplines. An appropriate model to this end is "double-loop learning".

In the annexes basics of acoustics are given; the phenomenon sound is regarded here at first and in the first place as a kind of energy, which happens to be propagated by means of waves in air.

## Samenvatting

### *Terugwinnen van land in stedelijke verkeersgeluidhinderzones*


Duurzaam[1] bouwen houdt onder meer in, dat de beschikbare grond in steden – maar ook elders – efficiënt gebruikt wordt. Zones langs (voor-)stedelijke hoofdwegen met hoge geluidbelastingen worden veelal alleen voor laagwaardige functies benut, vanwege praktische of wettelijke beperkingen. Het oprichten van ononderbroken woongebouwen direct langs deze wegen ("canyonvorming") kan beschouwd worden als een manier om deze zones terug te winnen. De gebouwen schermen allereerst het geluid in hun "achtertuin" af. Zodoende beschermen zij land tegen zeer hoge geluidbelastingen. In de tweede plaats bieden zij zelf ook woonruimte. Het onderzoek was gericht op de ontwikkeling van "tools " (instrumenten) om deze aanpak op verantwoorde wijze te stimuleren. Vanuit de ervaring dat de akoestische aspecten een belangrijke rol kunnen spelen, maar niettemin vaak genegeerd worden – waarschijnlijk vanwege een gebrek aan eenvoudig bruikbare methoden – is het accent gelegd op akoestische "tools ".

Het ontwerpproces van stadscanyons omvat de volgende akoestisch relevante vragen:

a) Wat is de totale omvang van de geluidhinder in de zone langs een bepaald wegvak? Welke verbetering kan bereikt worden?

b) Hoe kan de noodzakelijke afscherming bereikt worden? Hoe hoog moeten de gebouwen zijn? Zijn doorgangen toelaatbaar?

c) Welke bijzondere eigenschappen moet de eerstelijns-bebouwing hebben? Dit betreft in de eerste plaats de geluidbelaste gevel. In de tweede plaats kan een tweede (glazen) gevel voor de gebouwgevel geplaatst worden, waardoor een bufferruimte ( "atrium ") ontstaat, waar een gematigd klimaat heerst. Deze ruimte kan als verkeersruimte gebruikt worden (toegang tot de appartementen); ook kunnen balkons in het atrium toegevoegd worden. Behalve de verzwakking van buitengeluid zijn andere akoestische aspecten belangrijk voor de leefbaarheid van de woningen en hun directe omgeving: beheersing van het geluid van personen in het atrium en beperking van geluidhinder van naburige balkons.


[1] In de betekenis van *volhoubaar* (Zuidafrikaans) of *sustainable* (Engels).

Verschillende gereedschappen ("tools") zijn ontwikkeld om het proces mogelijk te maken, en bovenstaande vragen te beantwoorden.

- De Populatie Hinder Index (Engels: Population Annoyance Index, *PAI*), als indicator voor de eerste vraag
- De afscherming van een doorgaand gebouw, uitgedrukt als de toelaatbare verkeersintensiteit op een weg, die nog een aanvaardbare geluidbelasting oplevert op een gegeven positie in de luwte achter het gebouw
- Hulpgereedschappen ter bepaling van de invloed van openingen (onderdoorgangen) in de gebouwen, en de beëindiging van gebouwen op de afscherming
- Grafieken om de vereiste maatregelen in de gevels te schatten, in het bijzonder het type beglazing
- Een aanpak om het geluid van de (groepen) personen in het atrium te beheersen
- Het Vereist Maskerend Geluidniveau (hier $L_{mn}$ genoemd), als indicator van het voorkomen van geluidhinder ten gevolge van buren op hun balkons, gebaseerd op het begrip "speech privacy "

Een overzicht van de gereedschappen met hun belangrijkste kenmerken (*output, nut* en *input*) alsmede voorbeelden van hun gebruik zijn toegevoegd. Tevens worden de gereedschappen in ruimer verband behandeld, namelijk als onderdeel van de processen die bij het ontwerpen van steden en gebouwen aan de orde zijn: leerprocessen die verschillende disciplines omvatten. Een geschikt model hiervoor is de "dubbele lus" (double-loop learning).

In bijlagen worden akoestische basisbegrippen behandeld, waarbij het verschijnsel geluid in eerste instantie en in de eerste plaats behandeld wordt als een vorm van energie, die zich (toevallig) in de vorm van golven in de lucht voortplant.

## Preface

After graduating in applied physics some thirty years ago, the author has been working as a consultant in noise control and building physics. The emphasis has been on traffic noise and architectural acoustics. The relation with architects, contractors and clients when dealing with matters of acoustics often contains elements of education, because almost all non-acousticians agree that acoustics is a difficult subject. Consultative practice requires a pragmatic approach, including practical aspects like cost and practicability of measures. Another essential aspect of noise control is its societal urgency. Many existing problems ask for a solution, and for the avoidance of new ones. Often problems are so urgent, that a quick realisation of measures takes place. In this way, practical experience increases quickly. On the other hand, the opportunities for reflection and further analysis often suffer from the urgency of daily problem solving.

In the approach of this research and in this dissertation the elements stated above can be recognised. The outline is aimed at results: solving the parts of the problem that lie within the scope of the research. This may seem a very ambitious goal, but the acoustical part of most problems is small, yet important enough. To contribute to this goal, designers (architects, urban planners) must be given assistance in early stages of design. In these stages, detailed calculations are not possible, instead easy to use indicators and guidelines are required. Those tools have been derived from existing knowledge, and are described here. One problem, the control of noise from (large) groups of people in a room, has been studied in more detail. The outcomes are nevertheless simple and indeed easy to use. Some competition between scientific and practical goals can be noticed. This dissertation contains no trailblazing discoveries in the field of acoustics, but tries to combine existing concepts and new ideas into new tools, aimed at applicability in a field where quantitative tools are not widely used. To that end an Annex A has been added too, containing a quick reference guide to the application of the canyon tools. In Annexes B and C basic elements of acoustics and noise control are treated.

Nootdorp, November 2004

*Evert Ph.J. de Ruiter*

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## Glossary of specific terms

| | |
|---|---|
| acoustical polder | quiet area within a large (closed) perimeter block |
| atrium | (here) room between extra glass façade and inner building façade |
| canyon | narrow chasm with steep cliff walls, cut into the earth by running water |
| coefficient | a numerical measure of a physical property that is constant for a system under specified conditions such as the sound absorption coefficient of a material |
| decade | 1. a period of ten years<br>2. change of a variable by a factor ten |
| EIA | Environmental Impact Assessment |
| hedonic pricing | expressing environmental impact in change of value of property, or the amount people are willing to pay to eliminate the impact |
| hinterland | land near a main road, behind buildings acting as noise barriers |
| Leq or $L_{eq}$ | equivalent (average) sound level |
| $L_{mn}$ | required masking noise level |
| Lombard function | sound level in a room caused by conversations in a group of people, as a function of the amount of sound absorption and the number of persons in the room |
| masking sound | sound that makes other sound indistinct or unintelligible |
| *PAI* | Population Annoyance Index |
| parameter | a constant in an equation that varies in other equations of the same general form, especially such a constant in the equation of a curve that can be varied to represent a family of curves |
| perimeter block | building block shaped as a closed curve bounding a plane area, often rectangular, gridiron |
| $R_{A,tr}$ | A-weighted sound reduction relative to the spectrum of traffic noise |
| speech privacy | the quality that a conversation in an adjacent room (or balcony or otherwise defined position) cannot be understood |
| traffic intensity | number of vehicles passing on a road per hour (hourly intensity), day (daily intensity) or other defined period of time |
| transdisciplinary loop | double-loop learning cycle, used in transdisciplinary projects |
| urban canyon | street in city, enclosed by uninterrupted building façades on each side |
| variable | a quantity capable of assuming any one of a set of values |

# 1. Introduction

## *1.1. DIOC The ecological city*

For times unknown, man has lived on planet Earth under varying circumstances, sometimes with shortage of food, water or materials, or pollution of his environment, but only on a local scale. The developments of the last century have shown an increasing number of messages of concern for global problems: exhaustion of resources, pollution of soil, water and air, climate change et cetera. The World Commission on Environment and Development (Brundtland, 1987) is known for the notion of sustainable development, "that meets the needs of the present generation without compromising the ability of future generations to meet their own needs". Ehrlich and Ehrlich (1990), expressed the necessity of reducing the environmental burden in a metaphorical formula. Starting from estimates of the growth of the world population, the average wealth of people, they state that the (global) environmental burden – whatever that may be, exactly – must be reduced by a factor of 20 towards 2040. Wackernagel and Rees (1996) take a similar position, but express the environmental burden in a square measure: the "ecological footprint". This quantity estimates the area that would be needed to supply the necessary energy, food and materials and other input for living, and the area needed to dispose of waste, both in a sustainable way! The calculation is applicable to individuals, groups, regions or nations. They show that the ecological footprints of most Western countries exceed their actual land areas. Future growth of population and wealth may lead to a global ecological footprint that exceeds the area of the world!

A dramatic reduction of the use of exhaustible resources and of the emission of pollutants, as indicated above, cannot be effected in a short time. Research is needed to answer the very complex question of how to achieve this reduction. The Delft Interfaculty Research Project – Sustainable Built Environment, "The Ecological City", (DIOC-DGO is the Dutch acronym) was started by the Delft University of Technology in 1997 to bring together several disciplines involved in the built environment. The participants include architects, urban planners, civil engineers, policy analysts, biologists and others. The scientific group consisted of graduated researchers, some as Ph.D.-students (backed by their supervisors), and some supervising post-docs. The set of individual research subjects can give an impression of the working area of DIOC-DGO; the descriptions are preceded by their DIOC-tags:

A1 *Sustainable urban traffic and transport*

A2 *Livability in the ecological city; development of design guides for a livable and sustainable built environment*

A3 *The role of water in urban restructuring*

A4 *The Ecological Main Structure as a cultural challenge*

A5 *Strategies for planning based on flows and networks*

A6 *Sustainable urban (re)structuring related to a "Sustainable Implant "*

B1 *Building in environmental impact zones*

B2 *Sustainable urban planning*

C *Sustainable housing management*

D1 *Development of an Integral Decision Support System for office Buildings*

D2 *Demountable building in precast concrete*

E1 *Environmentally-conscious design of infrastructural services*

E2 *Integral chain management*

F1 *Environmental qualification systems in the construction sector at city/regional planning level*

F2 *Environmental qualification systems in the building industry: costing models*

G *Towards a sustainable built environment: policy and instruments.*

H *Scenario analysis 2040*

Besides the individual research, integration projects were done, like "Sustainable renovation of the Poptahof-district in Delft" and "Comparison of Effect Tools" by Müller et al. (2005). During the research period, the notion arose that most of the research results of the whole DIOC-group would fall in the category of "tools": *design tools, effect tools* and *communication/decision tools.* Moreover, those tools would be subject to a developing process that can be described as a transdisciplinary cycle of learning, in which all three types of tools are included, as described by Müller et al. (2004) as follows.

"*Simplified, we can distinguish three steps: normative, creative and descriptive.(…) The normative step of the cycle includes the "inner world" of thoughts, concepts, values and norms. This normative step is followed by a creative or expressive step, in which the thoughts and concepts are expressed in the physical world (e.g. speaking, painting, writing or constructing a house). The thoughts and concepts are translated into action in a concrete situation. The physical products and consequences of this expressive step can be observed in a descriptive step. In this step we can collect quantitative and qualitative data by observing. The data gained in this step are the basis for an integration, which leads to a change in the view of problems and concepts. Therefore a second translation has to be made from the physical world to the inner world of thoughts.*

*The three-step learning cycle (normative – creative – descriptive – normative or interpretation – action – observation –*

*interpretation) serves as a basis for a double-loop learning cycle, which we call transdisciplinary learning cycle* (Figure 1). *The single-loops represent learning cycles with a focus on the creative/expressive, the descriptive or the normative step. The learning cycles with strength in the creative step, we call design cycle, where design tools are developed and applied. The learning cycles with a focus on the descriptive step, we call modelling cycle. In the modelling cycle, effect tools are developed and applied. And the learning cycles with an end in the normative step, we call actor cycle. In the actor cycle, communication tools are developed and applied. It is important to see that all tool groups or disciplines follow the same sequence of normative-creative-descriptive-normative for progressing in their discipline. Design is not pure creative, but also descriptive and normative. Modelling is not pure descriptive, but also normative and creative. And communication is not only normative, but involves also creative and descriptive steps. The three tool groups are essentially the same; they have just different ends.*
*The transdisciplinary learning cycle integrates the three tool groups in a double-loop learning process."*

Each step of the outer learning cycle uses specific tools, varying from simple schemes to complex computer programs. The development of these tools themselves can be regarded as learning cycles again: the small inner circles in Figure 1. The *act*-step depends on the type of tool; the other steps are equal. The figure also means that the development of tools (the three inner circles) is a process in the first place; this process takes place in connection with and within the framework of the spatial design process.

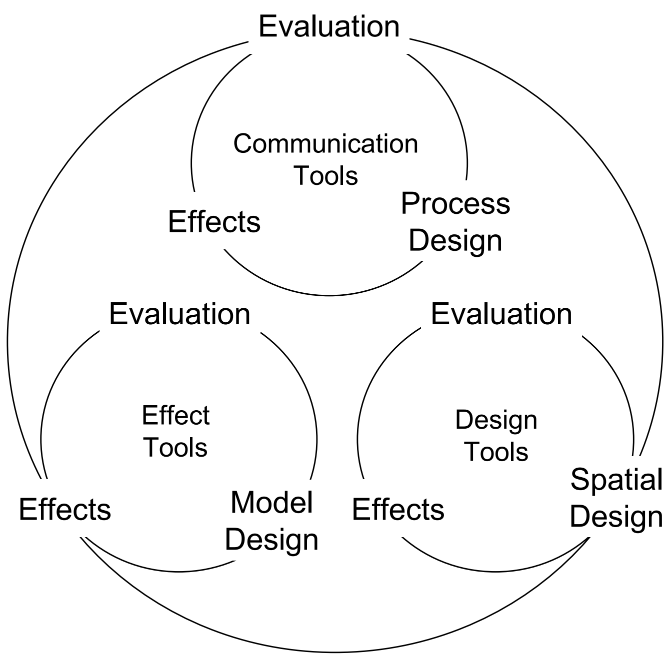


**Figure 1. Transdisciplinary learning cycles. Outer circle: design of the built environment. Inner circles: development of appropriate tools to support the design process.**

Tools in this sense can be very diverse which makes it difficult to give a generic description. In the "Comparison of Effect Tools" – and also in Section 9.2 – a pragmatic approach was chosen. From the viewpoint of the user, an effect tool has an *input,* which means that variables (observations, measurements or prognoses) pertaining to the system are the starting point. In this way, an effect tool is related to an existing or expected reality. An effect tool has an *output*, consisting of one or some aggregated variables, expressing environmental quality or properties (materials, pollution, energy, livability). It is implied that a *procedure* exists to transform the input information into the output information; there are no requirements for the procedure itself. The *input* gives two types of information: on the specific field where the tool can be used, and on the type (rough or detailed; which variables) and amount of data needed**.** Roughly, a larger amount of input data implies a more complex type of tool. The description of the input should be the answer to the question "what type of information and how much data is needed?" The *output* represents the calculation results. The output therefore answers the question "what do I get from the tool?" Each tool is specialized to answer some specific questions, and is therefore limited in its range of application. The *benefit* of the tool is the specific range of its application, answering the question "where can I apply the tool and what is its scope?"

In Chapter 3.5 the requirements for tools are addressed, based on this general description, which is used again in Section 9.2 in the review of the tools.

As the set of subjects of DIOC shows, reducing the environmental burden does not mean that the functional quality of the built environment may be neglected. On the contrary, optimising the livability of the city is a goal too. At least the environmental aspects of the built environment should be balanced against the functional quality and the livability or quality of life. No attempt will be made to give an exact definition of these notions; however, among the environmental aspects of livability *noise* is certainly an important dissatisfier in and around dwellings.

Environmental noise can be regarded as a pollutant, but differs in some relevant aspects from chemical pollutants in soil, water and air. Chemical agents migrate slowly, can accumulate strongly and are often not perceptible. The propagation of sound is fast, physical accumulation is absent, and humans have a very sensitive specific sense organ: the ear. We have ears, because speech communication is important, and sounds can warn us for danger. For the same reasons, the acoustical science is well developed. Extensive scientific and engineering information is available about sound emission, transmission, properties of the ear and hearing, et cetera.

The exposure of people to airborne pollutants (including sound) at a certain position depends on the strength of the source of emission, and the dilution of the agent. Both sound and matter are "diluted" as the distance to the source increases. Therefore keeping distance is a fundamental way to reduce sound levels and concentrations of harmful gaseous or particulate matter. Although the effectiveness is undisputed, the amount of land that is sacrificed by keeping distance is a serious drawback, especially in urban areas, that conflicts with one of the principles of sustainable building: "*do not waste scarce items, in casu land*". The land in these urban noise impact zones can be regarded as a kind of *brown fields:* former industrial areas – often lightly polluted – or more generally, areas that were previously developed. This notion is used as an antonym of *green fields*.

Hence, sustainable development in urban areas points in the direction of redeveloping brown fields. In the present study this means investigating the possibilities of reclaiming land in urban noise impact zones that have been or would be sacrificed to noise control through the principle of distance-keeping. Of course, the livability in these areas is not to be compromised.

In Figure 2 the framework of the study is shown roughly. Environmental impact zones can be found between roads (and railroads) and residential, tertiary or other districts. To reclaim land, and reduce the size of these zones, the "pollution" should be reduced. Here the emphasis is on noise reduction. Descending in the figure, the focus narrows: from global sustainability to the concept of an urban canyon (see Section 3.3), and the requirements of the residential buildings constituting the canyon. The elements include:

- Shielding, dimensions of building masses
- Sound reduction of noise exposed façades
- Application of atria (noise reduction), and its consequences (control of group vocal output)
- (Auditive) privacy in exterior rooms
- Speech intelligibility in public and communal exterior spaces

Traffic noise pollution is a problem in urban areas all over the world. This study is therefore not restricted to The Netherlands, although the local peculiarities will be notable in some places. If a context must be chosen for practical reasons, it is the context of the European Union. As said before, the time horizon lies in the intermediate future: neither next year, nor next century, but in between, around 2040.

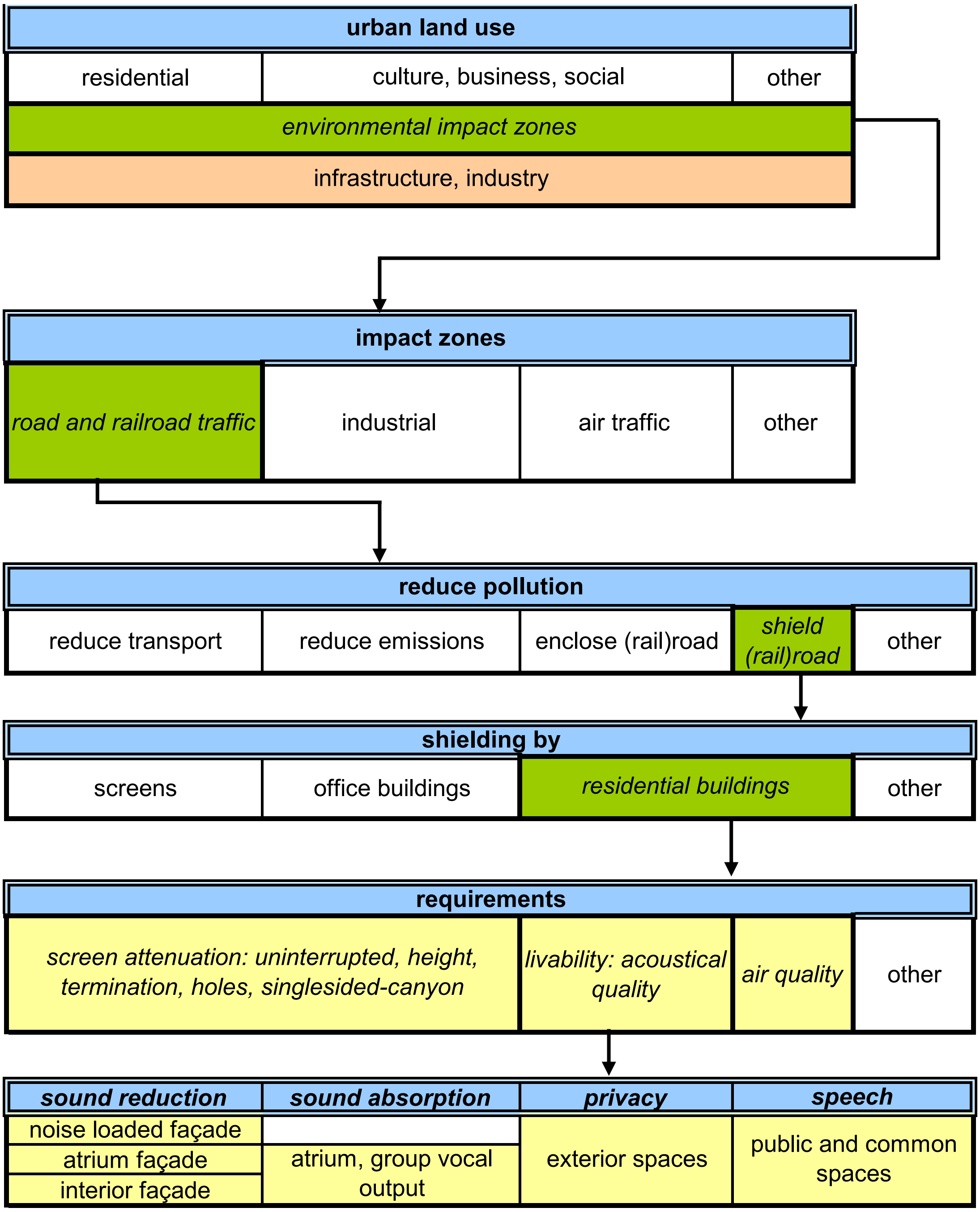


**Figure 2. Framework of traffic noise control and the approach of this study.**

Environmental impact zones along roads and railroads are the domain of this study. In general the zones are situated between the roads and areas with a residential or other function. Zones around industry or airports are excluded, although some aspects of this study may apply to those as well. The pollution in the impact zones can be reduced by several means, like reduction of traffic or of specific emissions. In this study however, the focus is on shielding, especially of noise. Barriers can block noise, but buildings have a greater shielding potential, if they are continuous. Residential buildings are chosen for universality: if dwellings can be realised, other functions will fit even more easily. Several requirements of the shielding residential buildings are discussed, based on different points of acoustical interest.

### *1.2. Outline of this dissertation*

This dissertation has a hybrid character. On the one hand there is the field of urban planning and architecture, from which the problem statement arises, and to where the solutions must be directed. On the other hand, the problem of environmental (noise) impact zones requires the application of methods and techniques from acoustical sciences. A major difference between these two fields is the level of abstraction. Urban planning is usually very concrete, strongly related to its context. Acoustics, as a branch of classical physics is almost free of context and very abstract. Most of the subjects in this dissertation are treated context-free; some case studies may compensate this.

Chapters 1 to 3 focus on traffic noise as a societal problem. Chapter 2 states the problem of the use of the limited amount of land in cities, particularly in noise impact zones; and briefly describes the principles of the Dutch Noise Abatement Law. In Chapter 3 the usual technical solutions, like quietening vehicles and pavement are reviewed, ending however with the intermediate conclusion that solutions in the field of urbanism are indispensable: shielding by residential buildings as a solution deserves more attention. If a street is sandwiched between shielding buildings an urban canyon is the result.

The implementation of this solution relies on urbanism and architectural design in the first place. Tools are required to enable these designers to make the necessary first steps in their plans. In Chapter 4 the types of tools are described and the properties they should have.

In Chapters 5 to 7 the respective tools are treated. In Chapter 5 the assessment of noise annoyance in the vicinity of roads is in focus. The *PAI*-tool is useful in comparing siting alternatives for roads and residential areas. In Chapter 6 the tools are addressed that are concerned with building masses in their capacity of shielding objects, and related side effects such as apertures and termination of the buildings. In Chapter 7 the tools are discussed that can be used in designing the canyon buildings: properties of façades, atria and exterior spaces.

In Chapter 8 examples and applications are given and in Chapter 9 a review of the tools. In Chapters 10 some additional aspects of a non-acoustical nature are discussed. Chapter 11 concludes this dissertation with conclusions and recommendations.

Annex A is a *quick reference guide* into the design conditions of canyon buildings. Although reading of the main text is recommended to provide the necessary background information, the step by step approach in Annex A should enable designers to apply the tools correctly.

The Annexes B and C contain basic information on acoustical notions, which however hardly could suffice as an acoustic primer on its own. For basic reading Beranek (1971) is recommended.

The use of formulae is indispensable in acoustics, but in this dissertation they are present only in Sections 5.2, 6.3, 7.1.1, 7.1.3, 7.4.1, 7.4.2, 7.5.1 and in the Annexes B and C. These can be discarded by non-acousticians.

This research was not intended to refine upon calculation methods of traffic noise or sound reduction of façades; nor was attempted to improve the noise response functions. On the other hand, it used existing methods, sometimes coarsened, to improve their applicability in early stages of urban design, in particular of urban canyons, as a means of noise control.

# 2. Urban land use

## *2.1. Introduction*

The foundation of research projects regarding sustainable development is the limited capacity of planet Earth: a global, very comprehensive problem. DIOC-DGO was focused on sustainable building: the ecological or sustainable city. On a global scale, land may not seem to be scarce, but this does not apply to usable land in suburban and urban areas at present, and even less in the future. In general a choice exists: finding appropriate building sites within the existing city or sacrificing natural areas. In many cases however there is no explicit consideration of the alternative options, and natural areas are destroyed without second thoughts. Sustainable building requires efficient land use, in particular within the city limits, to keep cities as compact as possible.

An urban area is defined by Eisner et al. (1993) as "*a location where there is opportunity for a diversified living environment and diverse life styles. People live, work, and enjoy themselves in social and cultural relationships provided by the proximities of an urban area. Urban areas can be simple or complex. (…) Cities have circulation systems that unite the different areas (…). In large cities, several kinds of transportation and transit are often available*". In this way the context and the properties are regarded from the viewpoint of people. The physical reality is, that buildings, open spaces, infrastructure, in short: the built – visible and invisible – environment is needed to allow urban life. "Urban life" is a very comprehensive notion, which reflects on the many aspects of urban planning and design, as quoted above.

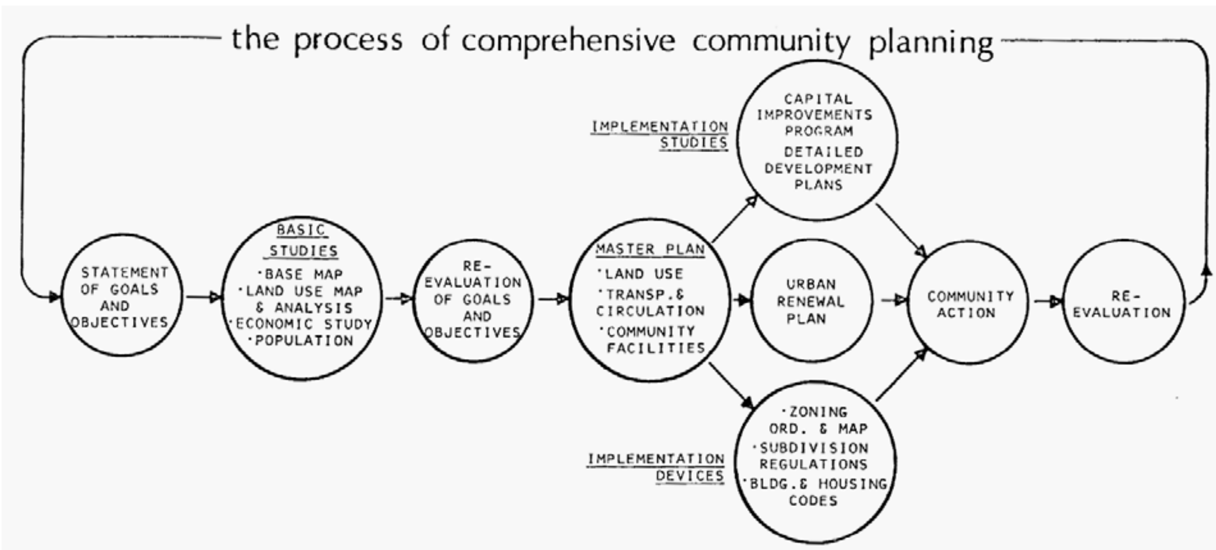


**Figure 3. Planning, shown as a cyclic (learning) process.**

Urban planning, development and design are concerned with urban areas in order to provide healthy and safe living conditions, efficient transport and communication, adequate public facilities, and aesthetic surroundings. Many disciplines are involved in developing urban plans. Urban planning, development and design itself must be regarded as a multidisciplinary complex. One of the many possible descriptions of the complicated process of urban planning is given by DeChiara et al. (1975), see Figure 3; the physical aspects of urban planning seem to be stressed whereas the social and cultural aspects are implicit.

A closer look at the structure of this process by the way shows resemblance with the pattern of the outer learning cycle of Figure 1 (the loop of Figure 3 contains the outer loop of Figure 1 three times).

Goals and objectives of urban planning are usually stated in numbers of inhabitants, density of dwellings, areas available/necessary for specified functions, building heights, and a qualitative description of the characteristics of the neighbourhood. Indicators or numerical tools to express the – present or future – satisfaction of urbanites with their towns are not usual.

The design of urban plans is not a purely technical procedure; many individuals, companies and authorities are stakeholders, and have different views and interests. Urban development plans are instruments of policy at local and regional levels. The plans are usually made under authority of local governments and in democratic systems, public inquiry procedures are included. Ideally, in this way all interests and aspects are taken into account, including such effects of traffic as noise, vibration, air pollution and safety.

In a densely populated country like The Netherlands, there is no wilderness, no wasteland and hardly a spot without a function. Expansion of cities almost inevitably violates the uncultivated or agricultural land worth preserving. Therefore cities must be built compactly. Moreover this keeps distances between destinations (living, working, recreation) short, thus reducing the demand for transport; the population density of the compact city enables efficient ways of public transport. As a side effect, the use of materials and energy for transport and the emission of pollutants can decrease. Building more compactly – intensifying urban areas – however, will not be sufficient, Williams (2000) concludes from several case studies in the 1990's in UK. Traffic volumes and the consequential impacts did not decrease, whereas complaints of noise from domestic sources did increase.

Existing cities need to search for non-residential land within the city boundaries that can be reclaimed for valuable destinations, especially residential. If such a low-grade zone can be made appropriate for residences, other related functions like shops and offices will fit as well, and schools, medical care etc. can be accommodated without much difficulty, from the viewpoint of noise control. The task is therefore to find such zones and explore the possibilities to upgrade them to residential quality. In most cities, large areas bordering main roads and railroads qualify for this. Of course, noise control is a necessary, but not a sufficient condition for livable neighbourhoods; those other environmental, urbanistic, and architectural aspects will remain under-exposed here.

### *2.2. Land use in urban areas*

Many urban areas are hardly used, or used only by offices and low-grade functions because of excessive noise caused by road and rail traffic, or air pollution caused by road traffic. In a growing number of instances, there are even legal obstacles – e.g. the Noise Abatement Act in the Netherlands – for building residences in those zones. In the first place research is needed into possible reductions of noise, polluting gases and particulate matter, and safety problems. Such research is already being conducted. Although interesting results have been achieved on the scale of individual vehicles and special road surfaces, it is not to be expected that the overall emission of road and rail traffic will decrease dramatically. According to Kihlman (2001) the noise emission of cars has been reduced by 1 to 2 dB during the last 25 years, and at the present rate a sufficient reduction will take at least a century.

Covering the present roads or railroads or transferring them into tunnels is a measure that could be very effective in controlling emissions of noise and chemical pollution, but will only be feasible in special cases. If safety problems can be solved, busy railroads are the most likely candidates for this; from the viewpoint of safety and perception of the urban environment, tunnels cannot be regarded as a generally applicable solution. On the other hand, in the case of tunnels the sound emission would hardly justify more research in the field of urban traffic noise control. Therefore the subject of this thesis is “open” road traffic flows of vehicles that are not substantially less noisy than the present ones.

Many countries have legislation aimed at traffic noise control. The main legal instruments are:

- Selective admission of motor vehicles: noisy vehicles are not allowed on the public roads
- Urban planning and design: traffic flows, distances from dwellings to roads, barriers, impact zones etc.
- Building regulations: sound reduction of façades

Roo (2000), in describing the urban conflict, remarks: "*Within a compact city concept, keeping a safe distance – a functional-rational solution – might be too simple a strategy to cope with all the concerns related to urban environmental conflicts"* and presents "complexity dependent decision making" as a solution.

The diversity of implementation of legal rules in countries all over the world is one of the reasons to refrain from discussing them, with the exception of Section 2.3. Another reason stems from the time horizon of this study: it is not known how the rules will be some decades from now. The foundation for the rules however will be the health and comfort of the people exposed to traffic noise, in the open space around their homes (gardens, balconies), and inside. On the one hand, the rules will depend on generic, invariable properties of human physiology, while on the other hand cultural aspects – changing over place and time – will also play a role.

For practical reasons, it is assumed that the rules of the European Union in 2003 are representative as a starting point.

### *2.3. The Dutch Noise abatement act*

In the Dutch situation, many problems of serious noise pollution from traffic and industry have shown a common denominator: lack of distance between the noise source and dwellings. In those cases, measures like noise barriers often are not feasible, for lack of space…
Not too astounding in a densely populated country like The Netherlands.

Regional and urban planning constitute powerful instruments in preventing those problems. From that notion the Noise abatement act originates. In 1968 the Dutch government asked the national Health Council to advice on measures to abate noise, in the interest of public health. The highlights of the report (1971) of the council were:

- Noise abatement starts at the source: establish legal limits for the sound production of specific noise sources

- Noise sources should be kept at an adequate distance from dwellings and other sensitive functions; local and regional planning are appropriate instruments to this end
- The conception of a comprehensive law was proposed regarding noise abatement

This law (Noise abatement law) was passed in 1979. It came into force in the years 1982- 1987. Keeping distance is one of its major elements. To that end impact zones are defined around industrial areas, and along roads and railroads. Roughly, these zones embrace the areas being potentially exposed to noise loads over 50 dB(A) – here the Dutch 24h-value for noise load is used, $L_{den}$-values are 1-2 dB(A) lower . This value is regarded as a reasonable noise limit for dwellings and equally sensitive buildings like schools and hospitals. The noise impact zones are to be considered as zones with potential noise problems. Land use plans and city plans involving noise impact zones require acoustical investigation, first to locate residences actually being exposed – or expected to be exposed – to noise levels in excess of 50 dB(A). If those areas are present the inquiry is continued to determine whether mitigating measures (e.g. increasing distance or inserting noise barriers) can eliminate the noise excess. Only if such measures are not feasible, the proper authorities may grant a dispensation i.e. a raised noise limit. The law itself sets strict upper limits however, for instance 55 dB(A) along highways, freeways and rural roads; 65 dB(A) for streets in built up areas. If a raised noise limit is granted, the façades of the dwellings, schools or hospitals to be built are required to meet an equally raised sound reduction.

A program was set up to clean up the many existing situations of dwellings being exposed to (very) high noise loads; a period of 25 years proved almost sufficient to finish the process. The most frequently applied measures are noise barriers in rural areas, quiet pavement and improvement of façade sound reduction in urban areas.

Noise loads are calculated from prognoses of traffic data (hourly intensities in day time and night time, categories of vehicles, speeds), road data (pavement) and ambient data (buildings, barriers, soil, topography). The calculation methods are prescribed; traffic data must cover the development over the ten years after the time of investigation.

The traffic noise zones are defined by law; their sizes only depend on the type of road and the number of lanes. Every road has a noise impact zone, with the exception of very minor roads. Urban streets have noise impact zones at least 200 m wide on both sides of the street; highway impact zones (six or more lanes) extend to 600 m on either side. It is the spirit of the law to keep the noise impact zones – or at least a large part of them – void of dwellings, destining them primarily for green belts or insensitive functions.

In practice, the restrictions this law poses on urban design have in many instances been experienced as oppressive by designers and municipalities. From the viewpoint of sustainable development, this way of keeping distance must be deemed a luxury we cannot afford much longer.

### *2.4. Land depreciation by noise load*

The Hedonic Pricing Method, as known from economic literature, compares the value of houses that are identical in all aspects other than the one being valued. The difference in the total value would then equal the value of the attribute. The influence of noise for example, is then expressed in the difference in price of otherwise comparable houses. Noise is a major dissatisfier, and therefore a prominent role of the noise load as a factor influencing the price of dwellings is expected. The Scottish Executive Development Department (SEDD) had a study carried out (Bateman et al., 2001) regarding ways to handle claims of real estate owners for loss of value because of the construction of new roads. They conclude that from a number of valuation techniques hedonic pricing is preferred; this means expression of the impact of an environmental factor in financial terms: loss of value, preparedness to pay for improvement etc. In their report an NSDI is defined: *Noise Sensitivity Deprivation Index*, the relative depreciation in house price per unit increase of noise load, in % per dB(A); a linear proportionality between the relative depreciation and the noise load is implied. From several studies in USA, Australia, Canada and Europe an average depreciation is extracted yielding NSDI = 0,55% per dB(A); the extremes are 0,08 and 2,22%. Data from the SEDD-study in Scotland (Glasgow) were processed in four models, with increasing complexity. The values of NSDI for these models were between 0,2% and 0,8% per dB(A).

Verhoef (1994) reports a decrease of residential property value typically about 0,5% per dB(A), for noise loads in excess of 50 dB(A). A survey in Kobe, Japan (Morioka et al. 1996) showed decreases in land prices for noise loads between 51 and 66 dB(A) of 1-2% per dB(A). For comparison: Anderson and Cordell (1988) estimated the positive value of residential landscaping trees to a community at 3,5-4% of the sales prices of single properties in Georgia, U.S.A.

According to Dunayevsky (2002) research on the Moscow real estate market demonstrates a non-linear relationship as shown in Figure 4.

A closer look at the relationship in Figure 4 and the response functions as used in *PAI* (see Section 5.2.1) shows that both have an important quadratic term. If the quotient of the percentage of highly annoyed people and the relative depreciation (percentage of value decrease) – both dependent on noise load – is taken, the value appears to be almost constant (about 1,57) in the range of noise loads from 55 to 75 dB(A). This means a close relationship indeed exists between the models expressed in these functions for annoyance and prices of dwellings.

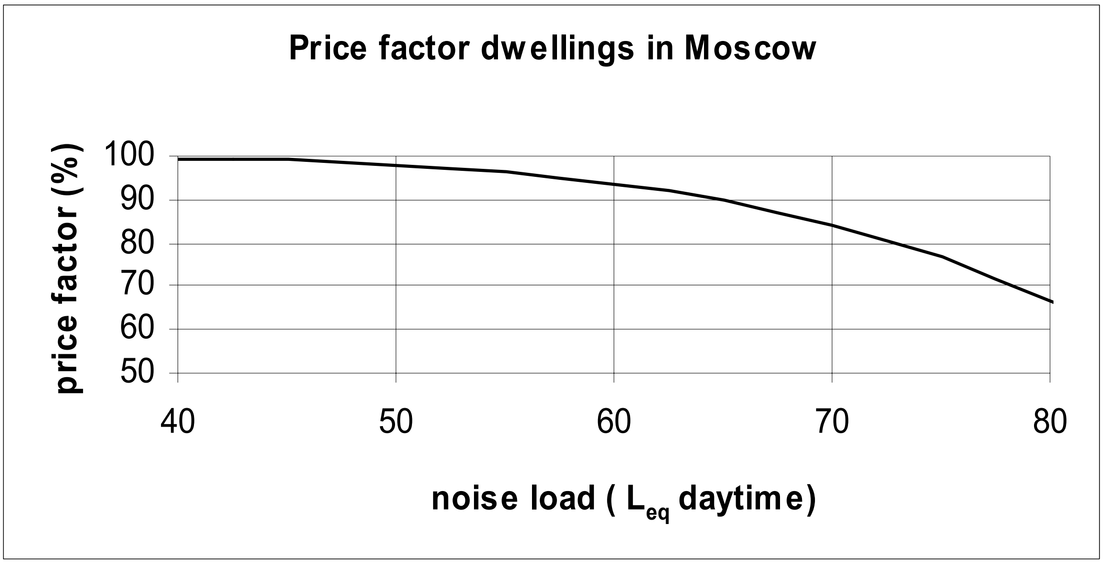


**Figure 4. Noise load reduces the value of dwellings; the price factor of dwellings in Moscow dependent on the noise load.**

Section 8.9 contains an example of hedonic pricing of traffic noise, applied to the effect of several alternative noise barriers on the building capacity of a fictitious building site.

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# 3. Possible solutions for urban noise control

## *3.1. Assessment of noise loads*

A large amount of literature exists in the field of traffic noise and its control. Garcia (2001) gives a recent overview. Thanks to the fact that traffic noise is a problem in large parts of the world, extensive research into many elements has been conducted. Onuu (2000) addresses road traffic noise in Nigeria, where higher noise levels are measured than expected, probably caused by "the reckless use of horns".

Often, and also here it is convenient to distinguish in sound emission, sound transmission and sound immission:

- Emission: noise generation by engines, exhausts, tyres; aerodynamic noise; type of pavement; special quiet road surfaces; dependence on speed – horns are usually negligible
- Transmission: noise reduction by distance, screens, moulds, vegetation, buildings; meteorological influences; reflections of buildings and ground
- Immission: sound reduction of façades, façade elements, ventilation, and structure of façades

**Figure 5. Keeping distance: empty zones along roads…**

**Figure 6. … and railroads.**

It is remarkable, that reliable prognoses can be made of the sound emission of roads without detailed knowledge of each passing vehicle (type of engine, cubic capacity, age etc.). Several calculation models exist, that are satisfied with flows (vehicles per hour), speed, for specified classes (light, medium and heavy vehicles), gradient (if applicable, positive slope only) and type of road surface as input such as the French model NMPB-Routes-96 (1996), and the Dutch RMW (2002); see also the review by Steele (2001). The composition of the traffic differs between countries, and so does the emission of the vehicles; the coefficients in the models reflect this.

The transmission of sound can be modelled satisfactorily for most cases. Distance, simple barriers, annually averaged meteorological conditions, reflections by buildings and even ground reflections can be taken into account. There is some doubt regarding the reliability of the models in case of urban canyons, where multiple reflections take place, shielding objects are complex, and meteorological conditions differ from those in less built-up areas. Yet, in the context of this thesis the priority is given to simplicity.

Compared to measurements, the advantages of the utilisation of an adequate calculation model – if available – are clear. Future situations can be assessed as easily as existing ones. The effects of changes in traffic flows, speed, road surface or the insertion of barriers in existing situations etc. can be predicted. With measurements it is always difficult to decide whether the circumstances are representative, regarding traffic flow (numbers, speeds) and atmospheric conditions.

The immission of sound can be controlled by architectural means, and appropriate ventilation devices; this subject is addressed in Section 7.1.

### *3.2. Review of possibilities for noise control*

Noise control can be effectuated in many ways. Distinguished by discipline, they can be summarized as follows:

- Urban planning, regional planning, including public transport: the motor traffic flows themselves are greatly influenced by the situation of residential areas, business areas, industrial areas, shopping centres et cetera and the quality of walkways, bike tracks, and public transport
- Traffic governance: speed reduction, variant itineraries for trucks etcetra
- Mobility technology: Public transport (underground, light rail, quiet and clean buses) can be enhanced to reduce the number of private cars and their use. Goods transport by rail can be stimulated to reduce truck movements. Even variant modalities of transport can be considered: goods transports through pipes (especially liquids) or by ship, if waterways are available; electronic highways enabling teleconferencing and exchange of documents in digital form, reduce the number of necessary movements of people and goods
- Mechanical engineering: fundamental means, like reducing emission of vehicles
- Civil engineering: special types of (porous) road surface that reduce tyre noise (Sandberg, 2001)
- Urbanism: additional measures like noise screens or moulds (Samuels and Ancich, 2002; Ivanov and Tyurina, 2000)

N.B. Measures to increase the sound reduction of façades are not included here, because these only apply at indoor spaces. Outdoor sound levels (balconies, garden, communal or public circulation spaces) should not be neglected. Only if the feasibility of reducing outdoor sound levels is insufficient, these measures are to be taken, to insure an agreeable indoor environment at least.

Despite all these possibilities, and the positive efforts made, experience over the past decades leads to the expectation that busy, noisy roads will not be eliminated in the next decades.

The application of tunnels – underground or level – can be very effective in reducing noise and chemical pollution. Yet, it is not considered in this study for several reasons, see also Section 2.2; it is too complicated and drastic to be regarded as a general urban solution or as an instrument of noise control only.

Emissions of particulate matter ($PM_{10}$) and polluting gases from combustion motors can be reduced if other types of energy supply (electric, hydrogen) become feasible, but in the near future major effects are not to be expected.

**Figure 7. Noise barrier in Delft, curved to reduce reflections to opposite side.**

In other words, reduction of emissions alone is not enough for reclaiming land from noise impact zones; other means are indispensable.

Sometimes *anti-noise* is mentioned as a means that can cure all kinds of noise problems. In fact anti-noise has shown to be successful in a limited field of applications only, and cannot be expected to play a major role in control of road traffic noise (Scheuren, 1987; Berg, 1999; Aarts et al. 1999).

In suburban or rural areas the *alignment* of new roads or the siting of new residential areas can be optimised in order to reduce the noise annoyance, caused by the road traffic. A problem that is frequently encountered in this matter is the lack of a significant, yet simple metric that can function as a target variable. In practice, often the number of people exposed to a noise load exceeding a certain value (e.g. $L_{den}$ = 60 dB(A)) is used. In this way however, exposition to 61 dB(A) is taken to be equivalent to exposition to 70 dB(A) or even more. In Section 5.2 a better, yet simple tool for this optimisation (*PAI*) is proposed. In environments however, where housing in high density is present or intended, a more sophisticated tool may be required.

**Figure 8. Effective noise reduction requires high, uninterrupted noise barriers (Rotterdam).**

**Figure 9. High noise barrier (Amstelveen).**

**Figure 10. Extreme noise barrier (Zeist).**

The well-known use of noise barriers cannot be discarded, but it is useful to take a second look. From theory it is clear that a sufficient reduction of noise requires high, uninterrupted barriers; see Figure 7 through Figure 9. These closed barriers offer possibilities for control of air quality as well, at least for the non-exposed façades; see Section 10.1. Yet, one could ask if there are no alternative solutions, more appropriate in an urban or suburban environment than those shown in Figure 7 through Figure 9.

### *3.3. Shielding the hinterland from traffic noise*

To realise a sufficient noise reduction, noise barriers have to be high, which make them expensive and potentially less aesthetic or even ugly, in the eyes of residents and road-users; see Figure 10. It is not new to mention buildings as alternative barriers; in fact, office buildings were suggested often in the past. While the maximum height of a barrier is about 8 m, office buildings can easily be designed to be 20 m high or higher. Apart from that, the looks of an office building as seen from the road are much more agreeable and appropriate in an urban environment than a high barrier, even if it were decorated, or made partially transparent etc. Moreover, the cost of high noise barriers is eliminated if their function is taken over by buildings. Yet, until now the utilisation of office buildings as noise barriers has not become successful. The main reason seems to be that the most important property of an office building is its location; it would be a coincidence if the location as a noise barrier would be right from the viewpoint of real estate siting. Further, most of the recent office buildings are standing apart and thus not very effective noise barriers; see Figure 11.

Since shielding residential areas is intended, adding a barrier that consists of dwellings is a natural choice. Erecting long uninterrupted rows of residential buildings can be a solution if an agreeable ambience can be offered to the occupants. For that process the term *canyonisation* is used; *canyonisation* will be the main subject of this thesis. If an ambience can be realised that is suitable for living, such an ambience can easily accommodate other functions as well, like schools, retail shops, offices etc. Integration of these functions in the buildings can certainly enhance their livability. In Figure 12 the notion of *canyonisation* is sketched in several steps, from a standard suburban road to an urban canyon.


**Figure 11. Non-continuous (detached) office buildings offer minor shielding.**

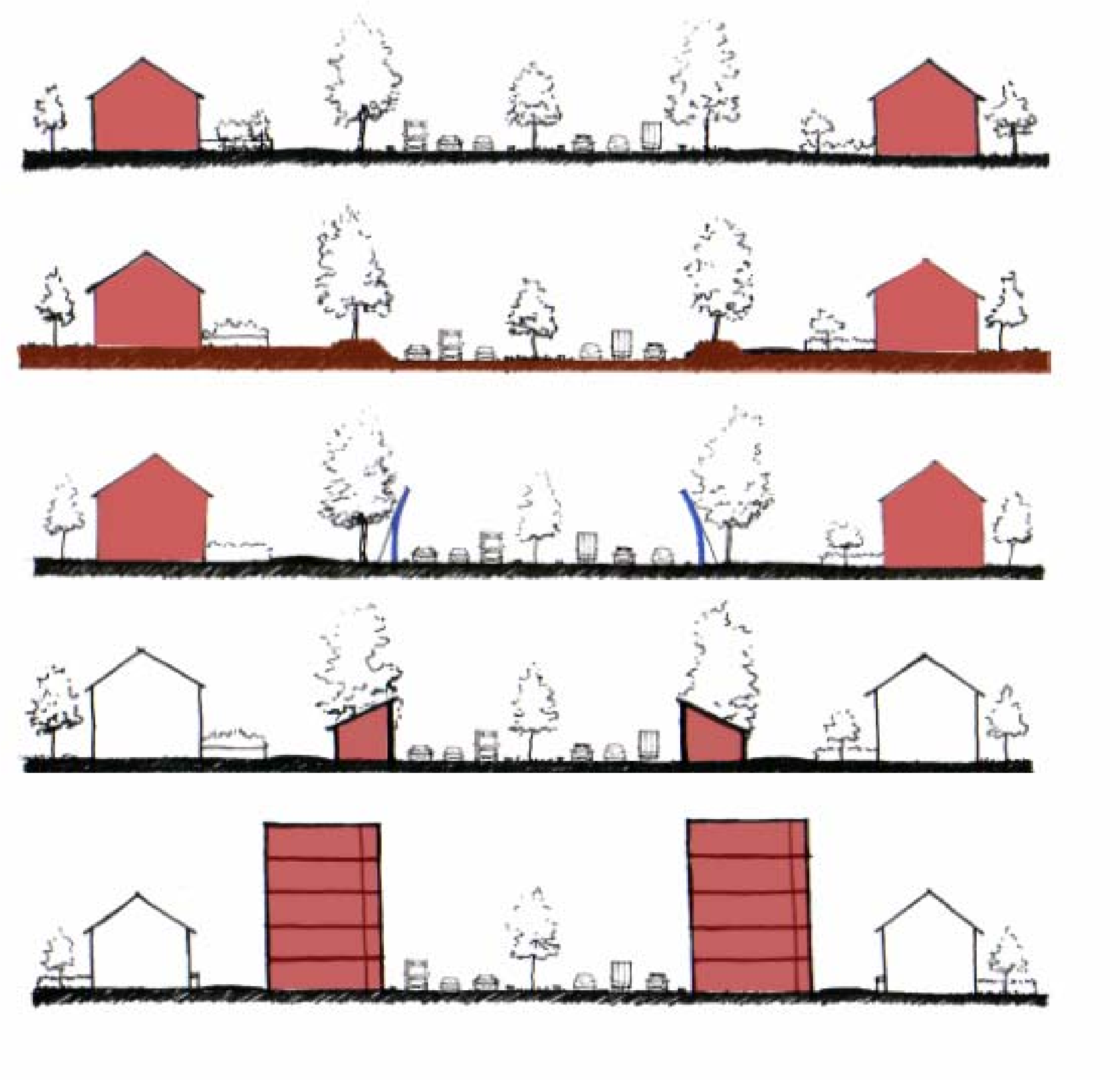

**Figure 12. Notional development of an acoustical urban canyon. Noise can be reduced by several ways of shielding** *(from top to bottom)***: nil, depression, noise barriers, low-grade buildings (sheds, garages) and – most effectively – by creating a canyon.**

While a canyon on a map shows as a line, a network of canyons can create "acoustical polders", quiet areas, indeed reclaimed from the noise impact zones; see Figure 13.

The canyonisation as introduced here implies a new or existing road bordered with wide, scarcely built up zones. Canyonisation offers a way to reclaim these zones for residential purposes. Situations where both the road and noise loaded residential areas are present require a dedicated approach.

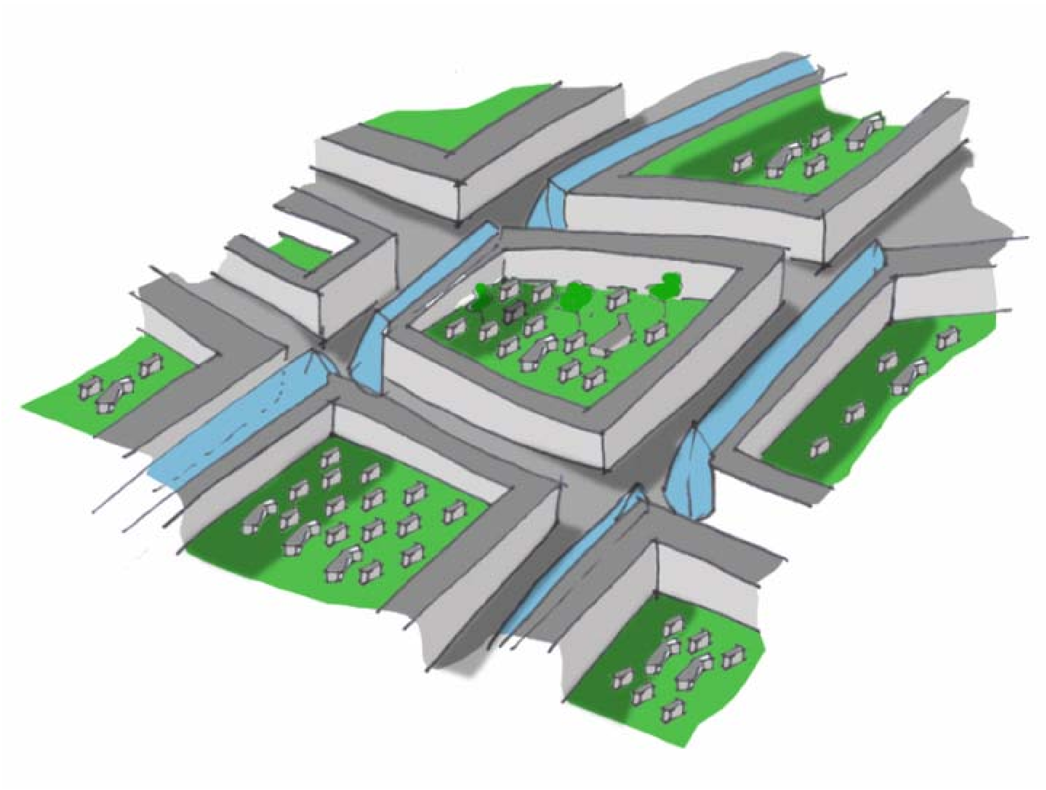

**Figure 13. Crossing urban canyons form "acoustical polders"; quiet neighbourhoods protected from traffic noise by "dike"-buildings.**

### *3.4. Existing situations*

In situations where both the road and noise loaded residential areas are present, two cases may be distinguished:

- Canyon buildings can be inserted between the road and the residential areas, possibly absorbing some existing buildings into the canyon building
- Canyon buildings can not be inserted between the road and the residential areas, not even by incorporating existing buildings into the canyon building

The first case is technically equal to the case of new situations. The second case is beyond the scope of this dissertation, although some of the tools developed, or elements thereof may be useful.

### *3.5. The conceptual phase*

Decisions regarding this approach to urban traffic noise control are taken in early stages of urban design, when planners, urbanists and architects are "playing" with ideas and (polystyrene foam) models; see for example Figure 12 and Figure 13. Many ideas, visions, requirements, do's and don'ts have to be integrated in the outlines of a plan. Detailed information on sizes of blocks, distances of roads and traffic flows is not yet available at that time. Yet, it is in this phase that fundamental decisions are taken, about the plan and its impact on livability and land use. Existing methods to assess the environmental impact – noise in particular – do not fit in this setting. There is a mismatch between the preliminary, fuzzy nature of the urban design and the detailed information required for traffic noise calculations.

It is therefore difficult to apply or even consider the urban canyon as a means of efficient land use and inherent noise control. Tools might be a solution, if they have the right level of abstraction to be applied in the conceptual phase of urban design. The development of appropriate tools is discussed in the next chapter.

# 4. Development of appropriate tools

## *4.1. Tools needed in the conceptual phase*

Several tools were developed, aimed at application in a conceptual phase of the design. In the next chapters the fields will be discussed in which existing methods are difficult to use, or methods are not available at all. This lack of useful methods can cause ill-founded fear with designers for the adoption of the canyon concept, and bring daredevil designers to incorrect or risky applications.

The need for tools was felt in the following areas:

- Comparing the effect of different measures (noise barriers, changing road alignment etc.) in urban design requires expression of the extent of noise annoyance, preferably in a single number. Otherwise the comparison can easily seem ambiguous; for example: the number of highly exposed dwellings (60-65 dB(A)) in option **A** is lower than in option **B**, but for the number of dwellings in the 55-60 dB(A)-class it is the other way around. Which option is preferable? See for example Section 8.1
- The shielding effect of the canyon is a complicated phenomenon. How high must the canyon buildings be? At what distance behind the first-line buildings can a sufficiently low sound level be expected? There are no specific data (urban design, traffic) available as required for a detailed analysis with calculation models. A tool is required, that gives an indication of the feasibility of a canyon design
- The first-line buildings are exposed to high noise levels. *What does this imply for the design of the façade?*, architects wonder. Is it necessary to design concrete façades 300 mm thick? Do we have to limit the sizes of the windows to portholes? Here a tool is desired, that gives a rough outline of the façade design related to the noise load
- Between the first-line building and the street a buffer space can be created, by adding a façade at a distance of 5-10 m of the building, or even more. For convenience the intermediate room is called "atrium". It can accommodate several functions apart from reduction of traffic noise, such as a pedestrian street, shops, and balconies of dwellings. The main attributes of the atrium are the sound reduction index of the glazing, and the amount of sound absorption; they determine the properties of the atrium with respect to sound transmission, and the sound levels caused by the occupants (shoppers, passers-by, residents on their balconies). How to choose the right values for these main variables? Tools are required to provide the designer with information that enables him to decide whether or not an atrium is an appropriate design option

- At least in moderate climate areas balconies are a customary addition to apartments. The first-line building can only have useful balconies at the rear of the building, a relatively quiet area; the noise-exposed façade is considered to be too noisy and may have poor air quality. The presence and serviceability of these balconies is more important here than in the case of apartment buildings without noise load. The quality of these balconies depends on several factors like size, sunny side, view, that are not difficult to assess. The aspect of privacy is no more complicated if conceived as visual privacy. Acoustical privacy however is usually neglected, although there are indications that it plays a serious part in neighbour nuisance. The most probable reasons for this omission are the absence of a criterion and the way of registration of complaints; in The Netherlands, and probably elsewhere too, no distinction is made between neighbour nuisance in the home and in exterior spaces. Therefore a tool is desired that allows judgment of the properties of balconies and other exterior spaces regarding acoustical privacy

## *4.2. Requirements of the tools*

### *4.2.1. General requirements*

Regarding tools as daily utensils, the elements *Output*, *Benefit* and *Input* (see Sections 1.1 and 9.2) can be used to define the desired qualities of the tools. *Output* is mentioned first, to allow the user to examine if it is useful; potential users are urban planners and architects. *Benefit* answers the question: "What can I do with the results?" The *Input* gives an indication of the effort it takes to "operate" the tool: how many data, are they available, do they need preprocessing, et cetera?

- The *output* should be simple to interpret, unambiguous, preferably a single number
- The *benefit* must be clear, related to goals in urban planning, design and architecture, in particular control of noise nuisance
- The *input* should be limited to data that are easily available in the design stage it is to be used in, i.e. in early design stages. If accurate traffic data are required as input data, a major problem arises. See Section 4.3

From these starting points the tools were developed. A side effect of this basis is that a certain limitation of reliability, accuracy and subtlety, (see Section 9.3.) must be accepted in advance.

*4.2.2. Tools to develop*

The following tools were chosen to be developed:

- The Population Annoyance Index, for comparing the effects of different measures; see Section 5.2
- The Canyon Shield Tool, including the effects of apertures, to estimate the shielding effect of an urban canyon; see Section 6.3
- The Façade Glass Tool, to estimate the type of glass required in the noise loaded façade, see Section 7.1.2
- The Atrium Façade Tool, to estimate the type of glass required in the atrium façade; see Section 7.1.3
- The Lombard Absorption Tool, to estimate the measures needed for control of the noise levels in atria caused by the occupants; see Section 7.4.3
- The Required Masking Noise Level, to estimate the auditive privacy between balconies in atria or elsewhere; see Section 7.5.1

### *4.3. Traffic intensity as an input or as a result*

The assessment of traffic noise through calculations always starts with traffic data: how many vehicles of which types pass in a street at which speed? From these and complementary data (pavement, traffic lights, slope) the properties of the sound source are determined. Next the propagation is calculated of sound from the rows of moving vehicles to certain immission points, taking into account all relevant ambient data. The noise load in the immission points can be judged and tested against legal values, if any. Here a target value of $L_{den}$ = 50 dB(A) was used.

In early stages of urban planning and design, in many cases the required traffic data are not available yet. Therefore a reciprocal approach is followed. For an arbitrary traffic intensity the noise load in certain urban configurations is calculated. From the difference between each value and the target value, the traffic intensity that would result in exactly the target value can easily be calculated in each configuration. This traffic intensity then is the maximum allowable intensity in that configuration, related to the target value of $L_{den}$ = 50 dB(A); see  Section 6.3.1. In this way the traffic intensity becomes result of a calculation model. In the tools for canyon shielding, apertures in the canyon wall and elevated canyon building this approach is used.

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# 5. Noise load in urban planning and design

## *5.1. Noise limits*

Urban planning is a complicated process, many parties are involved, the stakes are high, and the decisions have a long lasting impact. For projects exceeding a certain size it is obligatory in The Netherlands to make an Environmental Impact Assessment (EIA). In these studies, and more generally there are alternative options in – for example – the alignment of a new road through an already built up area, or the siting of residential areas near new or existing main roads. EIA requires that relevant data are gathered and presented to ensure that discussions are not held, and decisions are not taken without the availability of sufficient information about the environmental aspects.

Although several other impacts of road and railroad traffic on the environment must not be neglected, it is clear that noise annoyance is a major dissatisfier in residential areas. In many countries, therefore a system of noise limits is in force. First of all the quantity must be defined for expressing the noise load, e.g. the Day-Evening-Night-level $L_{den}$, as defined by the European Union (2002). Subsequently a – preferred – noise limit is established, e.g. $L_{den}$ = 50 dB(A). Usually it will not be possible to comply to this limit without any exception. Some margin is needed, to allow well-considered divergences. The adequate authorities can then decide if sufficient reasons are present to justify a noise load higher than the preferred noise limit. Nevertheless, it is regarded useful to set also a maximum noise limit: local authorities should not be authorised to exceed this limit.

In projects involving residences in the impact zone of main roads – whether EIA is conducted or not – often the problem arises of comparing variants in which at least a part of the residences is exposed to noise loads between the preferred and the maximum noise limit. Of course the maximum limit is to be respected. Comparing is easy if all noise loads in one alternative are lower than in the other, or if in case **B** the number of residences exposed to noise loads of e.g. 55 - 60 dB(A) is higher than in case **A**. Sometimes – e.g. in Dutch legislation – the number of annoyed people is used as the criterion for comparison, the line of demarcation being drawn at e.g. 60 dB(A). All people in dwellings with noise loads over 60 dB(A) are counted then, regardless of the actual sound load, and all other inhabitants are neglected, even if their noise load is 59 dB(A). The resulting number can be regarded as a measure for the “total extent of noise annoyance”. Still, for comparing road alignments or siting and design of residential areas this criterion is too coarse, and this purpose deserves a better method.

### *5.2. Population Annoyance Index (PAI)*

Consider an urban extension area, where residential complexes must be added to an existing structure, and roads have to be upgraded to allow for increased traffic flows. Noise limits have been established in general, but it is clear that no practical solution can be found to comply with the preferred noise limits for all residences. Fortunately, the maximum noise limits are not exceeded. Several options are possible, differing in the allocation of traffic to the roads, the location of dwellings and maybe even the quality of public transport and hence of the traffic flows. If alternative **A** results in lower sound loads everywhere than plan **B**, it is easy to conclude that plan **A** is better from the viewpoint of noise control. In most cases however, the comparison is more complicated. Therefore, a comprehensive metric is needed, an indicator for the total extent of noise annoyance in the neighbourhood, caused by these roads. This indicator will be based on noise response functions, derived by Miedema and Oudshoorn (2001) from a large amount of empirical data.

The noise response functions express the fraction of the people ($p$) being (highly) annoyed by the noise under consideration as a function of the noise load (L): $p = f(L)$. For noise loads below $L_{den}$ = 50 dB(A) this fraction is negligible ($p \approx 0$). If in the area bordering a stretch of road, delimited by the 50 dB(A)-contours, the noise loads are known, the notional number of (highly) annoyed people can be calculated and used as in indicator for the total extent of noise annoyance, caused by this road. The Population Annoyance Index *PAI* is based on Miedema's response function for "Highly Annoyed":

$$p = 0{,}0323\ (L_{den} - 42)^2 \qquad [1]$$

This formula is valid for noise loads over $L_{den}$ = 42 dB(A); for lower noise loads $p = 0$. Noise loads around 50 dB(A) are generally regarded as acceptable; the corresponding number of 2% highly annoyed people is in agreement with this. The absolute value of *PAI* is not relevant, as it depends on the limits of the area considered. In The Netherlands *PAI* has been used in a number of Environmental Impact Assessment studies, including the N248 road considered in Section 8.1.

In Norway an analogous approach is being implemented, by means of the SPI ("støyplageindeks" in Norwegian), developed independently and presented by Gjestland (2003). It is based on an annoyance score *A*:

$$A = 1{,}58 \cdot (L_{den} + k) - 62{,}25 \qquad [2]$$

For road traffic *k* = 0. The A-score correlates strongly with the percentage of Highly Annoyed people, *p* from formula [1] , but is some 15 (%) higher.
The index for the whole of Norway is estimated at 570.000 in 1999; the target of governmental noise reduction programmes is specified as a decrease of this number by 25% in 2010. SPI is also used to monitor the development in the next years. *PAI* has the same potential for setting targets and monitoring the process of noise reduction efforts, on local, regional or higher scales.

In a study by Arnold et al. (1977) a similar procedure is proposed, based on a noise factor ("Lärmfaktor") *LF* defined as a function of the noise load *B*:

$$LF = 2^{(B/10-5,75)} \qquad [3]$$

If the noise load *B* is taken to be expressed in $L_{den}$, the response function [1] is in good agreement with the noise factor [3].

The term "<u>the</u> noise load" suggests that there is only one relevant noise load for each dwelling, which cannot be true in general. Usually noise loads on the façades of dwellings will be different from each other, maybe even for ground floor and higher floors. It seems reasonable to assume that there is at least one quiet façade, and the highest value of the noise loads on façades of rooms is taken as representative. If no quiet façade is present, more annoyance is to be expected, according to Rylander and Björkman (2002) and Kihlman(2001). Within the framework of the *PAI* however, the presence of at least one quiet façade seems a reasonable assumption.

Barbaro et al. (2002) use a comparable approach to establish an optimal sequence of traffic noise abatement measures in Italy at a regional scale. To each noise exposed area they assign a score that depends on the function, the noise load and the number of people involved. In the paper the *PAI* is also described and applied to the same example. The optimal sequence for the measures, calculated through *PAI* is the same as for their "Criterion 2"; Barbaro et al. conclude that *PAI* is at least as useful as the other one.

### *5.2.1. Procedure PAI*

Calculation of the *PAI* requires the noise load on all dwellings in the area of interest to be known, at least the values over 42 dB(A); neglecting sound loads below 50 dB(A) gives only a small error, which is acceptable if done consistently. In many cases it is sufficient to know the contour lines (see Figure 14) and the number of dwellings between each pair of adjacent contours. For each residence the number of inhabitants is assumed to be equal to the mean size of households[2]. Applying the response function [1], the notional "number of highly annoyed inhabitants" can be calculated for each dwelling. The *PAI* is the expected value (in the statistical sense) of the total of number of highly annoyed people in all dwellings in the area of interest. Other noise sensitive buildings like hospitals or houses for the elderly could be included in the calculation by assigning a fictive number of occupants to them, dependent on the type and size of the building.

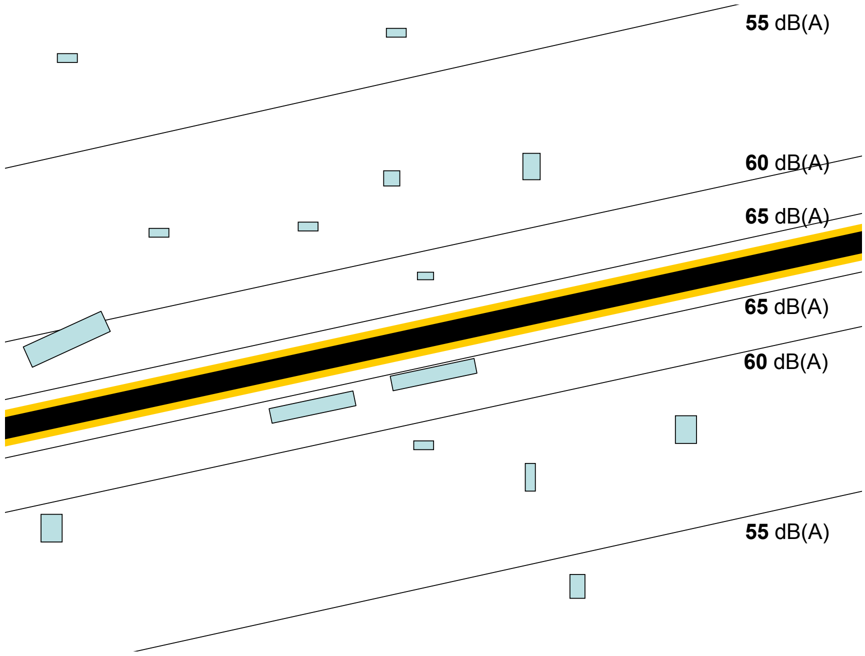



**Figure 14. Simple example of a straight road with noise contours and scattered dwellings. The shielding effect of the dwellings has been neglected.**

If an appropriate GIS (Geographic Information System) is available, it is easy to implement the necessary calculations. In many cases however the acoustical data are presented as noise contours, for example in 5 dB-steps. Then the number of dwellings in each class (45-50; 50-55; etc.) must be counted and assigned the noise load of the mean value of, in this example 47,5; 52,5 dB(A) etc. It can be practical to set a lower limit at 50 dB(A), and neglect all dwellings with a noise load below this limit. The deviation introduced in this way is small and acceptable, provided this is done consistently: the comparison between options is more important than the absolute values. Special circumstances, like dwellings with the most exposed façade noise-insensitive or highly insulated, are neglected, to keep the method simple and practical; loss of accuracy is not relevant, in the light of the (lack of) pretences of the method.

[2] In The Netherlands approximately 2,5 persons per household.

In general it is acceptable to use sound loads at an immission height of 4 m, which is usual in the European Union. The presence of high-rise residences can require an altitude differentiation in the calculation of noise loads.

*5.2.2. Example of calculation*

The noise contours of 50, 55, 60, 65 and 70 dB(A) along a length of road have been determined. There is some scattered building, giving no substantial shielding for the dwellings at larger distances from the road. The residences between the contours were counted. The results and further calculations are shown in Table 1 below.

| Contour area | Midvalue class | Residences | Inhabitants *n* | *p* (%) | *n.p* |
|---|---|---|---|---|---|
| **45..50 dB(A)** | 47,5 dB(A) | 400 | 1000 | 0,98 | 9,8 |
| **50..55** | 52,5 | 250 | 625 | 3,56 | 22,3 |
| **55..60** | 57,5 | 150 | 375 | 7,76 | 29,1 |
| **60..65** | 62,5 | 100 | 250 | 13,57 | 33,9 |
| **65..70** | 67,5 | 6 | 15 | 21,00 | 3,2 |
| | | | | **Sum**: | **98** |

**Table 1. Calculation Population Annoyance Index (*PAI*) case 1.**

The sum of the values in the last column is 98, so *PAI* = 98.

For case 2 a different alignment is chosen, yielding different noise contours. The numbers of dwellings are counted again. Table 2 contains the results.

| Contour area | Midvalue class | Residences | Inhabitants *n* | *p* (%) | *n.p* |
|---|---|---|---|---|---|
| **45..50 dB(A)** | 47,5 dB(A) | 400 | 1000 | 0,98 | 9,8 |
| **50..55** | 52,5 | 294 | 735 | 3,56 | 26,2 |
| **55..60** | 57,5 | 125 | 312 | 7,76 | 24,2 |
| **60..65** | 62,5 | 75 | 188 | 13,57 | 25,5 |
| **65..70** | 67,5 | 12 | 30 | 21,00 | 6,3 |
| | | | | **Sum**: | **92** |

**Table 2. Calculation Population Annoyance Index (*PAI*) case 2.**

The sum of the values in the last column is 92, so *PAI* = 92.

Although the number of residences with high noise load (over 65 dB(A)) is higher in case 2, the total score is better (lower *PAI*). Case 2 should be preferred. Table 2 also shows that the dwellings in the lowest class (45-50 dB(A)) give a minor contribution to the *PAI*, and might have been neglected.

### *5.3. Noise maps.*

If an appropriate grid is defined in an area containing one or more roads, it is possible in many cases, to calculate the sound load for all immission points on this grid. Through interpolation lines of equal noise load (equi-dB(A)-contours) can be constructed and plotted in what is called a noise map; see Figure 15.

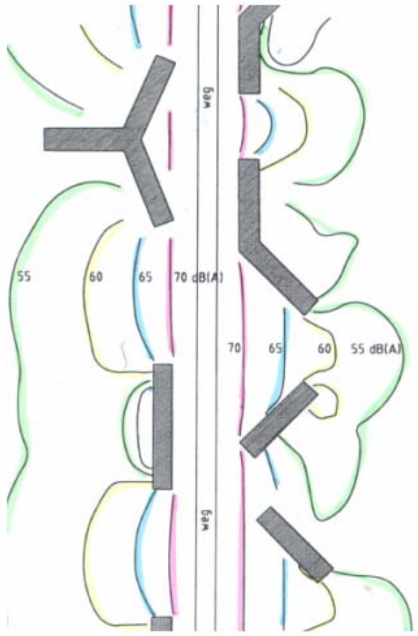



**Figure 15. Example of a noise map, with buildings and calculated noise contours 70; 65; 60 and 55 dB(A).**

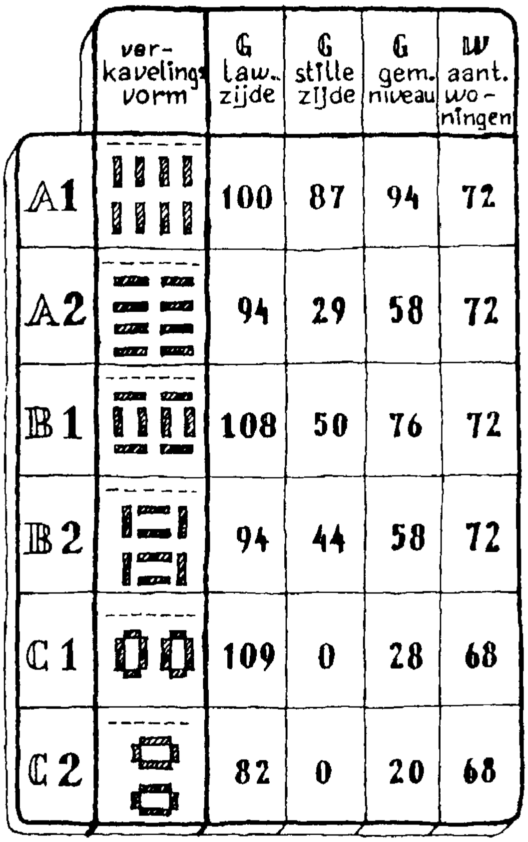
Most of the relevant factors regarding sound emission and transmission can be taken into account, including shielding and reflections by buildings, barriers etc. From the values in the grid-points, contour lines can be determined by interpolation. These contour lines can be drawn on a topographical map, or, more sophisticatedly, by assigning specific ranges different colours of noise load. In Figure 15 an example is given. It must be kept in mind, that these contours or colour coding are valid at one specified height only (usually 5 m); for different immission heights different sound loads will be found.

This way of presenting the results of noise calculations comes into fashion. Kluijver and Stoter (2003) state some of the advantages of GIS (Geographical Information Systems) in this. Maps allow a quick impression of the problematic locations, and the trouble-free areas. In addition, the magnitude of the noise problems can easily be appraised, at least in a rough way. For comparing options however noise maps are less suited, especially if the differences are moderate or varying:

higher noise loads at some locations and lower values elsewhere. An aggregated indicator for the magnitude of the noise annoyance, as mentioned before, would serve better; see chapter 5.2.

### *5.4. Urban development and siting options*

In the 1970's when the Noise Abatement Act was introduced in the Netherlands, extensive research was done into several aspects of traffic noise. Nijs (1978) described one aspect, the influence of variant ways of positioning apartment buildings. Several urban designs with apartment blocks in different orientations (parallel with or perpendicular to the road) were examined; see Figure 16. Comparison of the options is done through a noise annoyance index *G*, related to the noise load, and the number of inhabitants labelled with each specific value of *G*. The method is analogous to the *PAI*; see Section 5.2. The statement that "*traffic noise can be abated by applying a road system with coarse mazes and building extended continuous blocks ('marginal building') along the road*" is illustrated in Figure 16 (C1 and C2 are perimeter blocks) and fits very well in the present study. This approach seems to have met no wide acceptance then, although the plans based on it show good results. Apparently the idea of creating urban canyons did not appeal in the 1970's, and has not been put into practice in The Netherlands.



| | ver-kavelings vorm | G law. zijde | G stille zijde | G gem. niveau | W aant. wo-ningen |
|---|---|---|---|---|---|
| A1 | | 100 | 87 | 94 | 72 |
| A2 | | 94 | 29 | 58 | 72 |
| B1 | | 108 | 50 | 76 | 72 |
| B2 | | 94 | 44 | 58 | 72 |
| C1 | | 109 | 0 | 28 | 68 |
| C2 | | 82 | 0 | 20 | 68 |

**Figure 16. Variant ways of siting apartment buildings; *G* is an indicator for the extent of noise annoyance, analogous to *PAI*.**

In a study for the Dutch Ministry of Health and Environmental Protection (Fiebelkorn et al., 1979) the main elements of *keeping distance* and *application of (uninterrupted) noise barriers* are discussed in the context of urban development. Linking dwellings together to form an uninterrupted row is explicitly mentioned as a possible, effective shielding solution. The drawbacks are not neglected: keeping distance is not only a waste of land, but the open zones reduce the recognisability of the neighbourhoods as well; barriers act as separators between neighbourhoods. Remarkable is the demand for acoustical tools as described in Chapter 3.5; simple, easy to use methods instead of extensive calculations of sound loads.

**Figure 17. Example of a (closed) perimeter block.**

Historically, the closed perimeter block (Figure 17) can be regarded as a natural urban form. This results in a relatively noisy street façade and a quiet inner court. In a guide to the UK Planning Policy Guide Note 3 (DTLR + CABE, 2001) this is recognized also in the context of sustainability and the quality of living environments. Lindemann (1999) shows the street patterns in many cities can be traced back to Greek origin. Hippodamos is regarded as the inventor, or at least the codifier of the system of orthogonal streets. Lindemann argues it is the best, if not the only way to realise adaptable cities. The street pattern often remains the same for centuries, while buildings are replaced by others. The concept of urban canyons does not automatically imply perimeter blocks, but certainly the two concepts agree very well. In fact, a hippodamian street pattern can be regarded a composition of urban canyons.


**Figure 18. Narrow street in Naples.**

The Congrès Internationaux d'Architecture Moderne (CIAM) opposed strongly against the closed perimeter blocks and the associated narrow (canyon like; see Figure 18) streets. Exponent Le Corbusier wrote in 1929, as cited in Mumford (2000):

*"The definition of the street which has held good up to the present day is "a roadway that is usually bordered by pavements, narrow or wide as the case may be". Rising straight up from it are walls of houses, which when seen against the sky-line present a grotesquely jagged silhouette of gables, attics, and zinc chimneys. At the very bottom of this scenic railway lies the street, plunged in eternal twilight. The sky is a remote hope far, far above it. The street is no more than a trench, a deep cleft, a narrow passage. And although we have been accustomed to it for more than a thousand years, our hearts are always oppressed by the constriction of its enclosing walls. . . . It is the well trodden path of the eternal pedestrian, a relic of the centuries, a dislocated organ that can no longer function. The street wears us out. And when all is said and done we have to admit it disgusts us. Then why does it still exist?"*

For the CIAM-movement it was clear that open spaces, and buildings with ample daylight, sun and fresh air were the answer to many urban problems. At that time, traffic noise was not the serious problem it has become nowadays. Apparently, no distinction was made between main streets with much traffic, and the narrow residential streets the quotation above seems to refer to. The same openness that works out so healthy for the residential streets has a major drawback. It releases traffic noise from its natural bonds of the buildings bordering the street. It would have been better practice, not to apply the CIAM-ideas to the main roads, but only to the quiet areas behind the continuous buildings along the main roads. In this way the roads system with coarse mazes, as Nijs (op. cit.) mentioned, emanates. The areas within the mazes can be filled in without regard to traffic noise; see Figure 19.

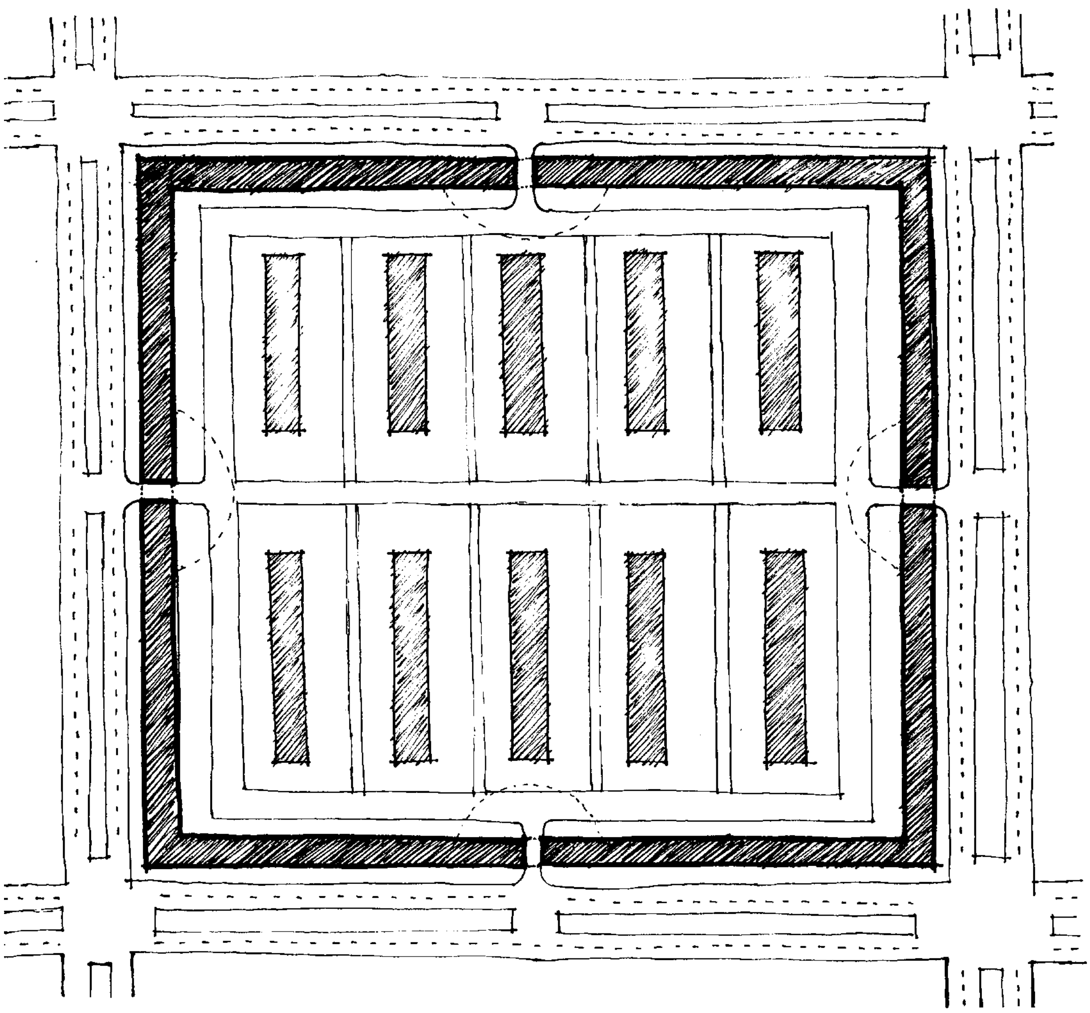


**Figure 19. Perimeter block of large dimensions, enclosing a quiet residential area.**

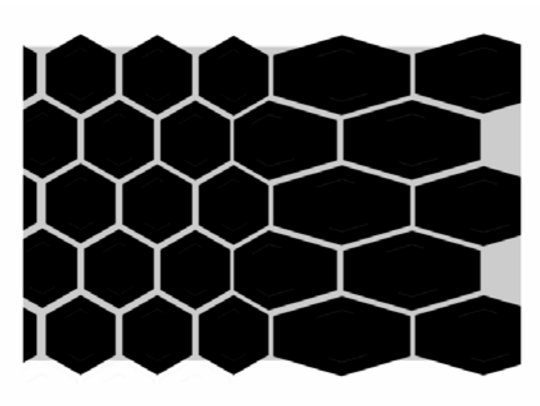


**Figure 20. Hexagonal road system; the right hand side is a stretched variant.**

A road system can also be based on a coarse hexagonal grid (Figure 20). This shape is advocated by Ben-Joseph and Gordon (2000). They claim efficient land-use, because hexagons can be arranged contiguously (without leaving open space). Traffic will be safer because of the three-legged intersections, with better lines of sight, and fewer potential collision points. The absence of long straight roads in the hexagonal grid has the same effect of reducing speed as the roundabouts now widely used in Europe; it is remarkable that the same property may reduce the sense of direction in road users, leading to a greater risk of losing the way, but again reducing speed as well….
The effects can be dosed by choosing an elongated hexagon as basic shape (shown in the right hand part of Figure 20 ): the roads become straighter in one direction, but more zigzag in the perpendicular direction.

(blank)

# 6. Buildings as barriers

## *6.1. Outline of the buildings*

Buildings can be very effective noise barriers. The main reason normal buildings do not always comply, is that they stand detached, or there are too many “openings” between them, as shown in Figure 21. Starting point for an effective urban instrument for shielding is therefore a continuous building of sufficient length: the road is completely shielded. The road can be compared in this case to a river, tamed by dykes that, of course, should not be weakened by holes. Calculations of the shielding effect or the noise loads in the shadow zone of the building can be made to a satisfactory degree of accuracy. The main variables at play are:

- Distance to the road
- Height and width of the building
- Single sided (L-shape) or “urban canyon” (U-shaped cross section)

**Figure 21. Scattered buildings near a road, offer minor shielding of traffic noise.**

In early stages of design however, often a lack of data is noticed, concerning traffic intensity, exact position of roads and buildings etc. In such cases simple estimates, based on the available information are more valuable. For the development of a tool in this conceptual stage, simple starting points are chosen. The building has an unlimited length. The influence of termination and eventual passages through the building – holes from an acoustical point of view – is addressed in Sections 6.3.2 and 6.3.3. Standard values were chosen for traffic and pavement; see Section 6.2.

### *6.2. Standard traffic data*

Sound transmission from a road to the environment is a complex phenomenon, especially if the effect of noise barriers or buildings acting as such is to be taken into account. It requires detailed information including the flow of traffic (numbers of vehicles per hour in day, evening and night period, specified in light, medium and heavy vehicles), average velocities, the road surface type, the positions of all objects causing reflection or shielding, the condition of the soil (reflecting or absorptive). In early stages of design, this information is usually not available. Yet it is in these stages that the possibilities of realising efficient (high density) land use should be explored.

Therefore, a different approach was chosen, as described in Section 4.3. For any daily traffic intensity, the distribution over the types of vehicles and the times of the day standard values are taken.

Fixed variables embrace:

- Velocities of all types of vehicles 70 km/h.
- Standard asphalt road surface.
- Distribution of the vehicle types:

| | |
|---|---|
| light vehicles: | 85% |
| medium weight vehicles: | 8% |
| heavy vehicles: | 7% |

- Temporal distribution of vehicle flow:

| | |
|---|---|
| average hour day time (7.00-19.00h) | 6,7% |
| average hour evening time (19.00-23.00h) | 3% |
| average hour night time (23.00-7.00h) | 1% |

In this way the daily traffic intensity is the single variable describing the sound *emission* completely. The urban context (distance from road to immission point, shielding, reflections, etc.) determines the *transmission* of sound and the noise load (*immission*) is the resulting value. If however, as described in Section 4.3, the immission is fixed (target $L_{den}$ = 50 dB(A)), a certain urban context gives a maximum allowable traffic intensity as a result. This approach is applied in the next sections.

## *6.3. Assessment of attenuation by buildings*

### *6.3.1. Uninterrupted canyon*

Starting point is the cross section of an urban canyon as shown in Figure 22. The main variable describing the canyon is the height of the buildings. A second important input variable is the position of the buildings in the lee area ("hinterland") nearest to the canyon. From the viewpoint of an urban planner, it would be useful to get an indication of the feasibility of this concept. If standard values are chosen for the other variables, the admissible daily traffic flow (vehicles per 24 h) can be determined. In Figure 23 this information is shown graphically. It is based on calculations with the Dutch calculation scheme SRM2 ("*Standard Calculation Model 2*") as defined in RMW(2002).

With these data – representative for the Dutch situation and probably the West-European situation is alike – the equivalent sound levels in day time will equal the DEN-level; in evening (19.00-23.00h) and night time (23.00-7.00h) the sound levels will be 3 and 8 dB(A) less, respectively. The "old Dutch 24h-value" will be 2 dB(A) more than $L_{den}$.

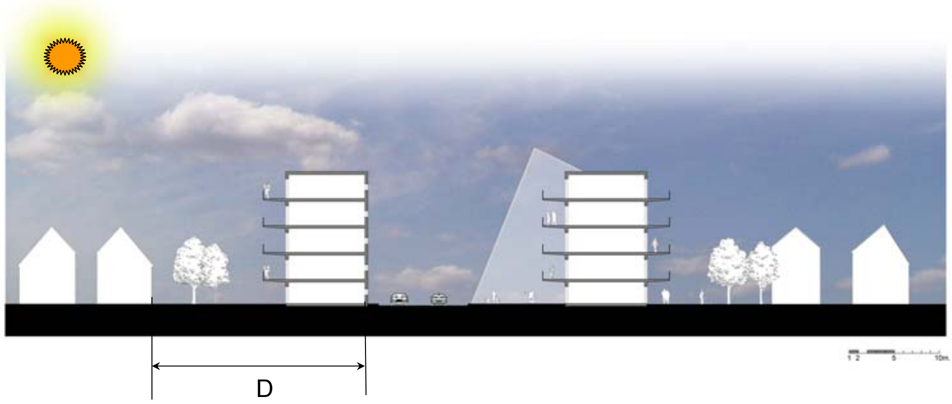



**Figure 22. Cross section of an urban canyon and "hinterland".**

For a standard emission pattern, as given above, the sound levels in the lee area behind the shielding buildings have been calculated, for several values of the horizontal distance to the road axis and of the height of the shielding buildings. The calculation method used, was the sound transmission model SRM2 as prescribed in the Dutch legislation, RMW (2002). In general the agreement between this method and measurements is good; see Section 9.3 . In the case of urban canyons there are some doubts if for instance the multiple reflections and the meteorological influences are taken into account in a correct way. The meteorological conditions (wind profile, temperature profile) in an urban canyon can be different from those in less built-up areas; this would make specific correction factors necessary. Other current models have the same limitation. Still, in the framework of this research it is acceptable to use SRM2, because not the utmost accuracy is demanded, and there are no clear alternative options. Even scale models might not be appropriate with regard to meteorological aspects.

The default value of the traffic flow was 10.000 vehicles per day. If the calculated sound load then exceeds the limit value of 50 dB(A), the traffic flow should be less than 10.000; if on the other hand the calculated sound load is lower, more traffic is acceptable. This can be expressed in the formula:

$$F = F_{ref}.10^{(50-L_{calc})/10} \quad [4]$$

where

$F$ = traffic intensity (flow)
$F_{ref}$ = reference traffic intensity = $10^4$ vehicles per 24 h.
$L_{calc}$ = calculated sound load ($L_{den}$)

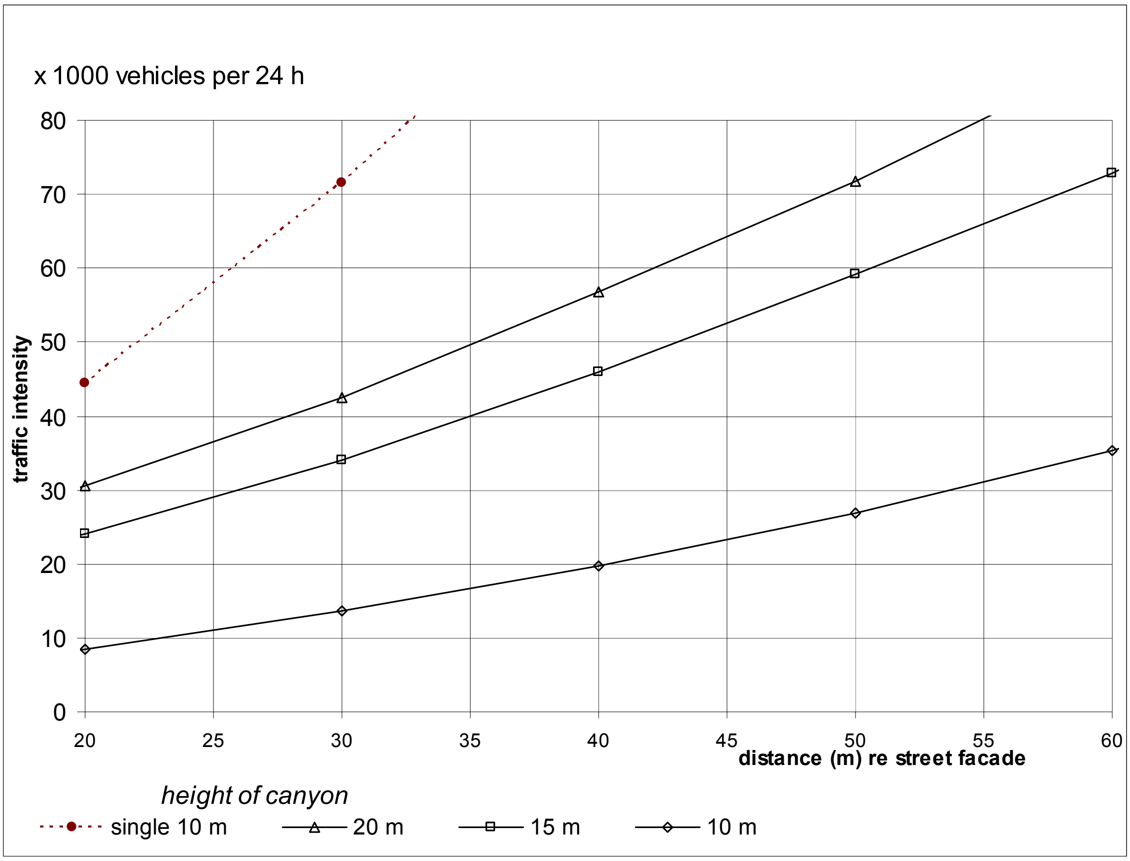



**Figure 23. Admissible daily traffic flow in a canyon. Target is a noise load of $L_{den}$ = 50 dB(A) at a given distance from the street façade; parameter is the height of the canyon buildings.**

The calculated sound loads were transformed into admissible daily traffic flows, and are presented in Figure 23. From these results, simple conclusions for the choice of buildings with a screening function can be drawn. Starting from a desired distance *D* from the reference point (façade; see Figure 22) the maximum daily intensity can be found for different values of the height of the canyon. The viability of the concept can now be judged by comparing this intensity with the real prognosis or estimate. For an uninterrupted urban canyon 10 m high or higher the sound attenuation is at least 15 dB(A) in the area behind the building – the hinterland; see Figure 24 – at 10 m height. Multiple reflections between the buildings reduce the attenuation. Without the second building the reduction would be some 5 dB(A) higher. The figure also shows that as regards the shielding effect, a 10 m high single sided row of buildings ("half canyon") is comparable to a 30 m high canyon.

The canyon façades are assumed to be sound reflecting as usual. The effect of multiple reflections could be reduced by a partially sound absorbing or diffusing covering or shape. The shielding effect may be enhanced by covering the roof with a sound absorbing construction; as suggested by the research by Ishizuka and Fujiwara (2004). These refinements however do not belong to the realm of first surveys (see Section 2.1) in urban planning, but can certainly play a role in a later stage of design.

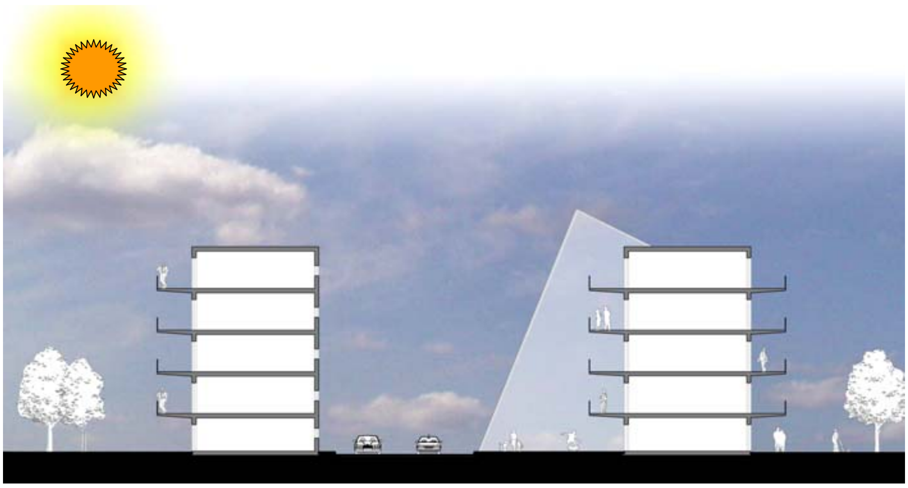


**Figure 24. Cross section of an urban canyon; the left building shows a façade that is adapted to the high noise load. The right building has a second façade, and consequently an atrium.**

### *6.3.2. Termination of barrier-edifice*

If the view on a road from a certain immission point is obstructed by the presence of a building, the sound level at this point is reduced, compared to the case without the building. Sound can reach the immission point through several possible paths:

a) directly from the parts of the road that are not obscured, unshielded
b) diffraction at the sides of the building
c) diffraction over the top of the building
d) through the building

Ad a). As a first approximation, the resulting sound level is directly proportional to the sight angle, if the building is high enough
Ad b). Can be neglected, compared to a)
Ad c). This is the most important transmission path if the building is wide enough (leaves no parts of the road in view), and is the most complicated to calculate
Ad d). Negligible, for the usual case of non-perforated buildings

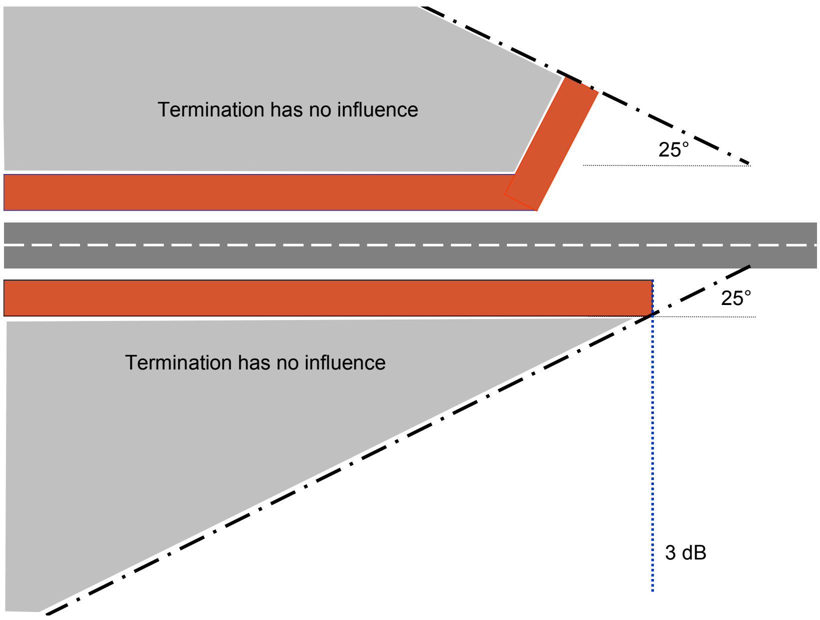



**Figure 25. Termination of a canyon building; the areas where shielding is influenced are roughly indicated. In the upper part the effect of bending the end of a building is shown.**

For the grey-coloured areas in Figure 25, the sight angle is less than 25° of the full angle of 180° and the influence of the termination is negligible. As the reduction values nearer the termination of the building are rather low, it is useful to "bend" the last part of the building, as shown in the upper part of Figure 25. The indicated angle of 25° leads to an optimum bend angle of 90+25 = 115°. The length of the bended part, and the exact angle to choose depend on the intended building area and the noise loads expected, or – equivalent – the admissible traffic intensity; the termination tool does not include a suitable method for this choice.

At the edge line through the termination of the building (see Figure 25, lower part), perpendicular to the road, half of the road is shielded by the building; the other half is not attenuated. Therefore, the sound energy is reduced by 50%, and the resulting reduction in noise load is 3 dB. For other positions where more than 50% of the road is visible – right of the 3 dB-line – the reduction varies between 0 and 3 dB. In many cases a larger noise reduction than 3 dB is required, which makes the indicated areas less favourable. The admissible traffic intensity can be estimated by regarding the road as unshielded (see Section 6.4); for positions on or near the 3 dB-line and the result may be multiplied by 2.

Where less than 50% of the road is visible – left of the 3 dB-line –, the reduction varies between 3 and 15 dB. The reduction *T* can be estimated from formula [32] in Annex B.6.

*6.3.3. Apertures*

As stated in 6.1 the concept of noise control through a street canyon implies uninterrupted, impermeable buildings. Passageways through the buildings (Figure 26) however, can be necessary for vehicles, pedestrians or cyclists. Rough calculations show that even for small apertures (5 - 10 $m^2$) the sound level in the lee area is increased by at least 1 dB, and more than 3 dB(A) in the case of higher canyon buildings (20 m or higher). Applying sound absorbing finishing to ceiling or walls of the passageway can mitigate this effect; consequently sound transmission through the passageway can be reduced by some 3-5 dB(A).

**Figure 26. A passageway acts as a noise leak; hence as a secondary noise source.**

Passageways – especially if permanently open – should be minimised, in number and dimensions. The influence of unavoidable apertures can be estimated as follows. In the street canyon a direct field from the line source (vehicles) exists, and a more or less diffuse sound field. The "open sky" represents the major sound "absorption" in the street. The sound intensity in this field can be expressed relative to the sound pressure level at a certain distance – e.g. 1 m, $L_{p,1m}$ – from the line that represents the noise source, without the influence of reflections other than the ground reflection by the pavement. The sound power $L_{w,ap}$ incident on the aperture is then given by the formula:

$$L_{w,ap} = L_{p,1m} + 10\lg\left(\frac{S_{ap}}{w}\right) + k \qquad [5]$$

where

$S_{ap}$ = front area of the aperture [m²]
$w$ = width of canyon [m]
$k$ = constant, expresses the type of sound field

In a diffuse sound field between 100% reflecting façades, a value of $k$ = 5 would result. Depending on the sound absorption of the façades (10- 20%), calculation with multiple discrete reflections yields values for $k$ between 2 and 4. Hence $k$ = 3 is taken as a central value.

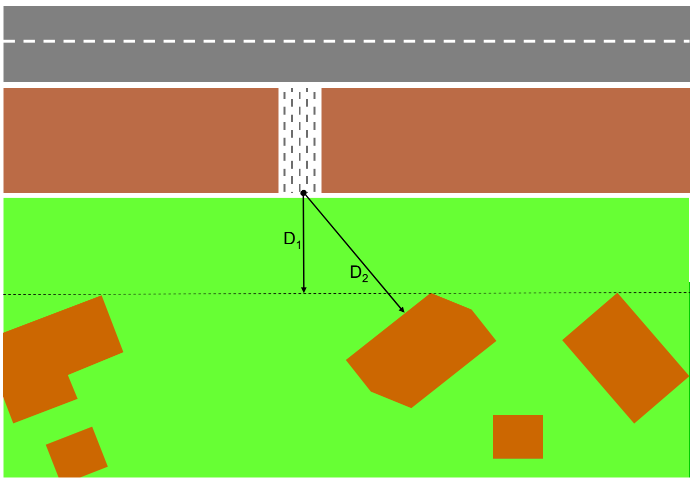



**Figure 27. Distance from aperture to building line ($D_1$) or nearest dwelling ($D_2$).**

Initially no attenuation in the passageway is assumed, so $L_{w,ap}$ also equals the sound power level at the rear end. The sound emission from this source is calculated as from a point source, radiating in a quarter sphere, hence $Q$ = 4. For a road having the characteristics as used in Section 6.2, for several widths of the canyon the sound level at several distances from the point source were calculated. The area of the opening was arbitrarily set at 20 $m^2$. The result is shown in Figure 28.

The characteristic distance or from the rear side of the aperture to the nearest immission point (façade of a dwelling; see Figure 27) is $D_2$; in many cases $D_1$ – distance to building line – can be used. By taking $D_1$ or $D_2$ and the canyon width into account, the admissible traffic intensity can be read from the graph. This graph only applies to a 20 $m^2$ large aperture; for an aperture twice as large, the admissible traffic intensity must be halved to compensate for this.

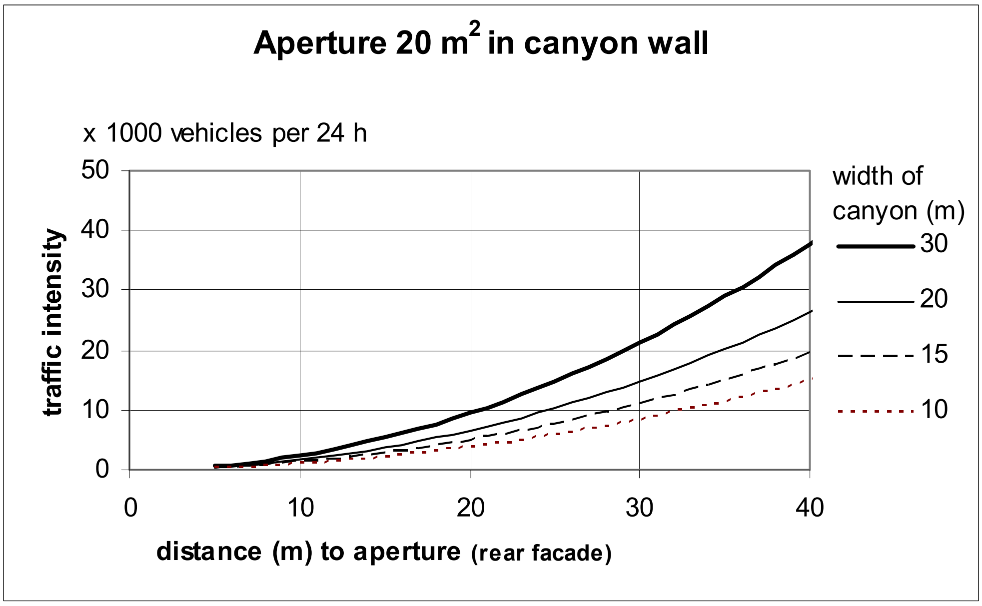



**Figure 28. Maximum admissible traffic intensity for an aperture of 20 m² cross section in a canyon building, leading to $L_{den}$ = 50 dB(A) at a given distance from the aperture; the width of the canyon is the parameter.**

A more generic approach is possible. As the sound power of the secondary point source, through the primary source (the road), depends linearly on both the traffic intensity *F*, and the area of the aperture *S*, the product of both (*F.S*) can be used as the characteristic variable. In the calculations the value of $F.S = 5.\ 10^4$ $m^2$.veh/24h. In the same way as used in Section 6.3.1, these results were transformed into maximum allowable values of *F.S*. The final results are presented in Figure 29. It shows, for example, that if a dwelling is put at 30 m distance from the opening in the canyon building, and the canyon is 20 m wide, the value of *F.S* must not exceed 0,35. $10^6$ $m^2$.veh/24h. This implies that an opening of 7 $m^2$ is not acceptable for traffic flows over 50.000 veh/24h. Just the same, for a traffic flow of 17.500 veh/24h the maximum allowable opening is 20 $m^2$. It should be emphasised that only the sound transmission through the opening is regarded here. This is acceptable if the contribution of sound diffraction over the top of the building may be neglected;

this will be true if the corresponding admissible traffic intensity $F_{top}$(from Figure 23) is more than three times as high as $F_{open}$, the admissible traffic intensity resulting from the presence of the aperture. If the allowable traffic flows $F_{top}$ and $F_{open}$ are roughly equal, both must be reduced by 50% to keep the cumulated sound load at 50 dB(A). See further Section 6.3.5.

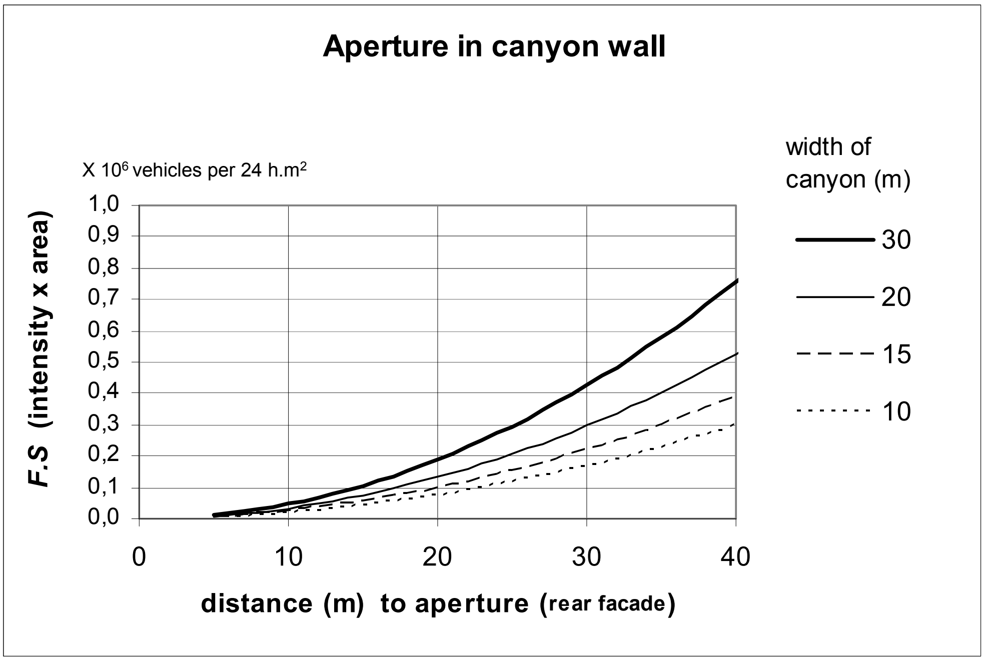



**Figure 29. Maximum allowable (product of) traffic flow and the area of an aperture in a canyon building, leading to $L_{den}$ = 50 dB(A) at a given distance from the aperture; the width of the canyon is the parameter.**

### *6.3.4. Elevated canyon building*

A canyon building can be elevated, resting mainly on an open structure of columns, to create a view for the road users into the hinterland, and for the residents onto the road. In this case the sound transmission through the open space under the building might destroy the canyon concept. The application of sound absorption as mentioned in Section 6.3.2 before, is essential, but requires an increase of the absorption length; see Figure 30. A deck extension behind the building can offer the required length. For an elevation of about 3 m, calculations were made. The sound field in the canyon is supposed to be more or less diffuse, as discussed in the previous section. The sound energy entering the space under the building will not decrease by means of “dilution”, but by means of absorption in the absorbent finishing of the ceiling; further, some diffusing elements (“obstacles”) are assumed, to reduce direct sight lines that would reduce sound attenuation. From standard acoustical theory an attenuation $T$ is calculated of:

$$T = \frac{y}{h} \cdot \alpha^{1,4} + 10\,\lg \frac{h+w}{h} - 3 \quad [dB] \qquad [6]$$

where

*y* = length of deck [m]
*h* = height of space under canyon building [m]
*a* = sound absorption coefficient [-]
*w* = width of canyon[m]

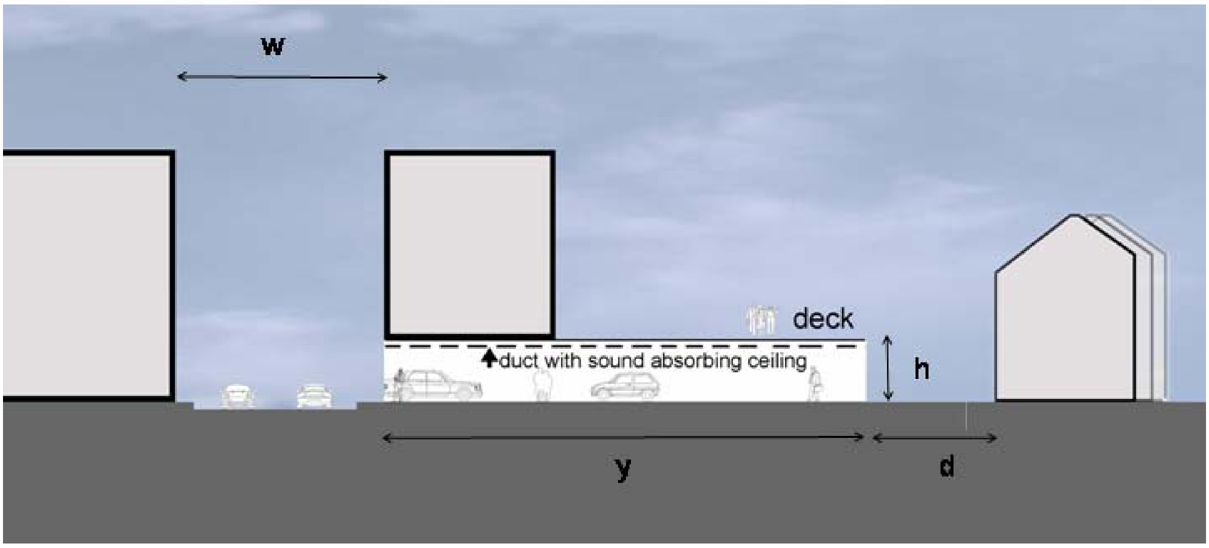



**Figure 30. Section of an elevated canyon building with an extended deck.**

The mouth of the covered space – the termination of the deck – acts as a secondary noise source, a line source, just as the original road. Its acoustical power is attenuated by the mechanism mentioned above. In the same way as in Section 6.1 the noise load in the hinterland was calculated for a standard road, for several widths of the canyon, several distances from the mouth and several lengths of the extended deck. A ceiling finishing with a sound absorption coefficient of 70% was assumed. For a 30 m wide canyon the results are shown in Figure 31.

Starting with the chosen distance from the mouth to the immission point (façades of dwellings) and taking the absorption length into account, the admissible traffic intensity can be read from the graph. For a narrower canyon – less non-reflecting open sky – the traffic intensity must be proportionally less to compensate for this. A canyon 15 m wide can accommodate only half of the traffic, within the same noise limits in the shielded area.

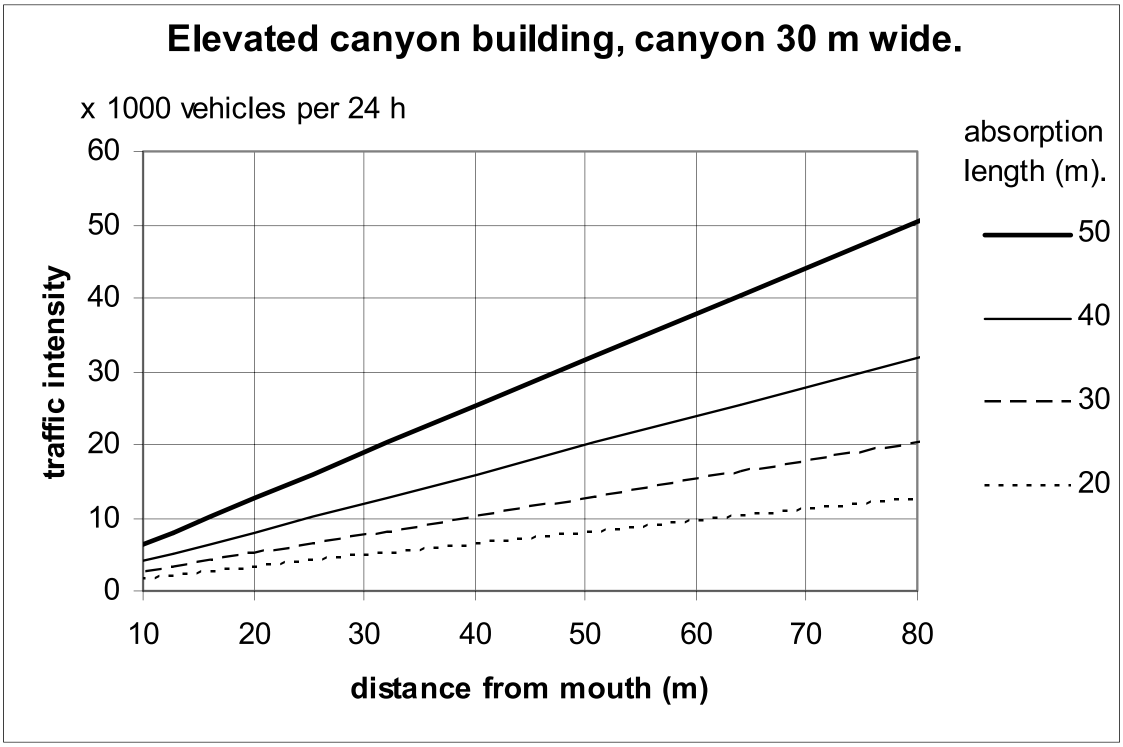



**Figure 31. Admissible traffic intensity for an elevated canyon building, leading to $L_{den}$ = 50 dB(A) at a given distance from the mouth; the absorption length is the parameter.**

It is possible to give a more generic approach. The noise load is a function of the daily intensity (*F*) and the width of the canyon (*w*), and appears to be a function of the ratio $F/w$ too. The canyon width is assumed to be between 10 and 30 m. Therefore the values of $F/w$ (admissible traffic intensity divided by width of the canyon) were calculated yielding a sound load of $L_{den}$ = 50 dB(A), in dependence of the distance from the mouth, and the length of the deck. The results are shown in Figure 32.

It is clear that in this case of an elevated canyon building, the shielding effect is almost lost. Compared to Figure 23 the admissible daily traffic intensities are now much lower; moreover, the (virtual) sound source is much closer to the hinterland.

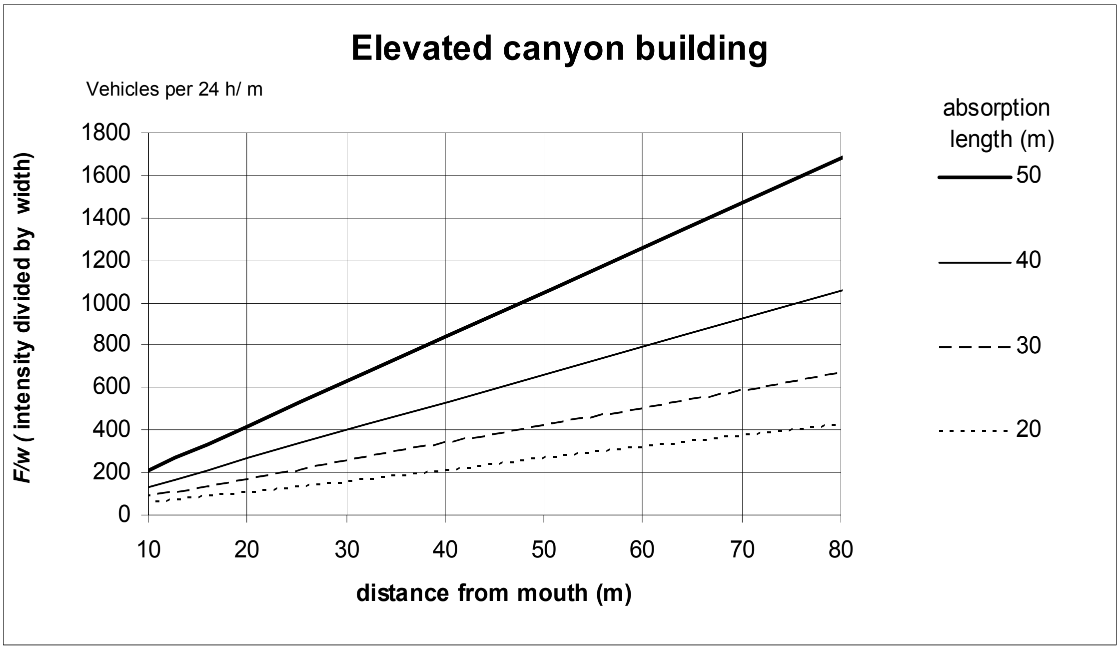



**Figure 32. Admissible traffic intensity for an elevated canyon building. The *F/w* value on the vertical axis must be multiplied by the width of the canyon in meters to find the admissible traffic intensity per 24 hours.**

*6.3.5. Combinations*

The shielding effect of canyons, and the influences of small apertures and very long openings – an elevated building – have all been expressed in maximum allowable traffic intensities; see Figure 23, Figure 29 and Figure 32, without cumulation of the noise loads: each item was treated separately. If two items play together, the resulting noise load will be between $L_{den}$ = 50 and 53 dB(A). To reduce the resulting noise load to $L_{den}$ = 50 dB(A) when the maximum traffic intensities are $F_1$ and $F_2$ the combined traffic intensity must be reduced to:

$$F_{comb} = \frac{F_1 \cdot F_2}{F_1 + F_2} \qquad [7]$$

If $F_1$ is much smaller than $F_2$, the resulting $F_{comb}$ is roughly equal to $F_1$, and vice versa. If $F_1$ and $F_2$ are nearly equal, the resulting $F_{comb}$ is roughly equal to $F_2/2$.

## 6.4. *Very quiet roads*

The sound emission of very quiet roads can be low enough to permit dwellings at rather short distances from the road. The canyon concept is not suitable then. It can even be accepted, that the first line of (detached) dwellings is exposed to an increased noise load, if only the noise load on the second line of dwellings does not exceed $L_{den}$ = 50 or 55 dB(A). But how quiet is a quiet road?

Calculations were made to determine the free field contour lines in a similar way as was done in Section 6.3.1; the parameters were chosen in accordance with the character of "very quiet roads":

- Average speed 50 km/h
- No heavy vehicles
- Partially (50%) garden-like, non-metalled soil

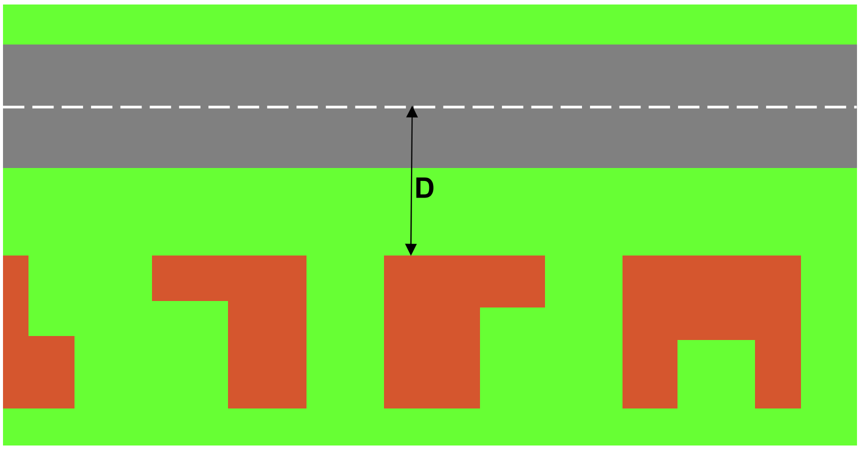



**Figure 33. Distance *D* from road axis to façades of dwellings.**

From these data the daily traffic intensities were calculated at certain distances *D* from the axis of the road, admissible to comply with a maximum noise load of $L_{den}$ = 50 or 55 dB(A). The results are shown in Figure 34.

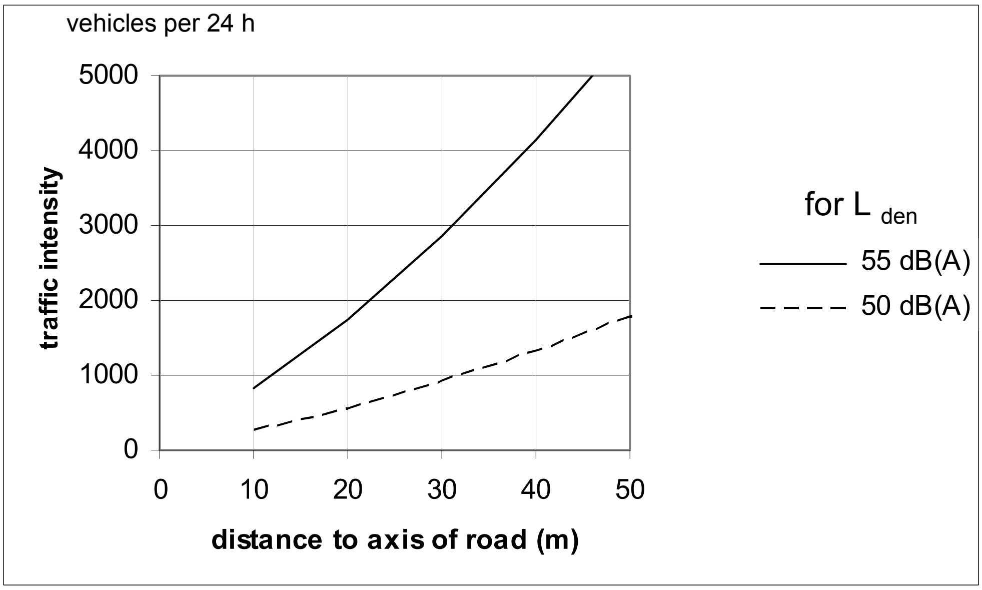



**Figure 34. Admissible traffic intensities without barriers. Target values $L_{den}$ = 50 or 55 dB(A) at a given distance from the axis of the street.**

Of course, this applies to the roads within large closed perimeter blocks ("acoustical polders") as well: these roads must be "very quiet roads", otherwise the canyon concept is violated.

### *6.5. Functions of the buildings*

For the shielding effect, the function of the buildings is not relevant. It seems logical to choose functions that are not very sensitive to noise, such as factories, storehouses, or offices. From the viewpoint of urban design however, this would be a severe restriction. If the goal is to reclaim land for residential purposes, the building itself should be inhabitable too. Moreover, in that case less or equally sensitive functions like kindergartens, schools, hotels and shops can be integrated in the building. Starting point is therefore that the building, or at least most of it, should offer an agreeable acoustical ambience for residential functions.

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# 7. Requirements of buildings

## *7.1. Livable buildings*

The livability of buildings could be described as the quality of offering healthy, comfortable housing for people and the accompanying functions. Livability is clearly a comprehensive idea. A small but important aspect of livability is noise nuisance. Many countries have legislation concerning admissible sound levels caused by road traffic, incident on the façades of buildings and inside buildings. Extensive research has been carried out in preparation of the rules. The international standard ISO 1996-1 (1984) and -2 (1987)[3] and the directive of the European Union (2002) relating to the assessment of environmental noise must be mentioned as fundamental documents. Some essential notions are:

- Use of decibel(A) or dB(A) (A-weighting; see Annex B.8)
- Use of the equivalent sound level ($L_{eq}$) as the method to account for the fluctuation of the actual sound level; see Annex C.3
- Evening and night-time are more sensitive periods, therefore a "penalty" is added, for example of 5 dB(A) in the evening and 10 dB(A) in the night-time. These corrections are part of the day-evening-night level DNEL or $L_{den}$; see Annex C.3
- Specific limits for the external sound load on buildings, depending on the type of area and the function of the building. As such these limits have a limited meaning: the façade itself is not noise-sensitive. Strongly connected with the external limits however are the noise loads on external spaces like balconies and gardens, and the acceptability of open windows: excessive noise loads would prohibit the comfortable use of the external spaces and windows
- Specific limits for intruding sound, depending on the function of the building (residential, education, health care, office, etc.)

Fixing limits is sensible only if there are means to achieve the goal, or in other words, to eliminate an excess of the limits. External limits at fixed positions require shielding or reduction of noise emission (less or quieter vehicles). Internal limits (intruding sound) can be met by constructing a façade with sufficient sound reduction.

Privacy too is an element of livability; with several aspects, regarding several senses (sight, hearing, smell). The best-known acoustical aspect is "speech privacy"; see Section 7.5.

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[3] and its predecessor ISO/R 1996 (1971)

In Annex C some elements of noise annoyance are addressed.

*7.1.1. Sound reduction by façades*

The sound energy incident on a façade gives rise to a certain sound level in the room behind the façade. The internal sound level depends on:

- The sound level incident on the façade
- The sound reduction of the façade
- The dimensions and amount of sound absorption in the room

A comprehensive calculation model for the sound reduction of the façade is given in the European Standard EN 12354-3:2000, *Building acoustics – Estimation of acoustic performance of buildings from the performance of elements – part 3: Airborne sound insulation against outdoor sound.*

The calculation model is straightforward, but may seem complicated because it should take into account several influences that are not always present, like special shapes of the façade. The difference between the sound level on the façade ($L_{1;\,2m}$; it is measured at a distance of 2 m in front of the façade) and the resulting sound level in the room ($L_2$) is called the *standardised sound level difference* $D_{2m,nT}$. It is calculated from the formula

$$D_{2m,nT} = R' + \Delta L_{fs} + 10 \lg \frac{V}{6T_0 S} \quad dB \qquad [8]$$

where

$R'$ = apparent sound reduction index of façade [dB]
$\Delta L_{fs}$ = level difference due to façade shape [dB]
$V$ = volume of the receiving room [$m^3$]
$S$ = total area of the façade as seen from inside (sum of the area of all façade elements) [$m^2$]
$T_0$ = reference reverberation time (0,5 s)

For a simple, plane façade, consisting of opaque parts (e.g. concrete, brick, or sandwich panel) and glazing the calculation model is simple. A rectangular room behind the façade will be assumed, with depth 3 m ($V/S$ = 3 m) and a reverberation time of $T$ = 0,5 s. The term $\Delta L_{fs} = 0$ for a plane façade. In this special case the *standardised sound level difference* $D_{2m,nT}$ equals R*', the apparent sound reduction index* of the façade.

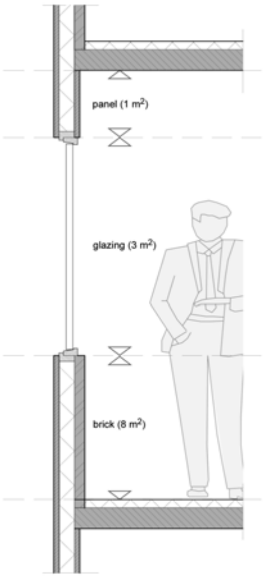


**Figure 35. Cross section of the façade of the example below.**

Just the way the façade is constructed from several parts (concrete, window frames, glazing, sealed joints), the quantity $R'_i$ for the façade of a room is calculated from the *partial sound reduction index* values $R_{pi}$, taking their areas $S_i$ into account, relative to the total façade area $S$.

$$R_{pi} = R'_i - 10\ \lg\left(\frac{S_i}{S}\right) \qquad [9]$$

$$R' = -10\ \lg \sum_i 10^{-\frac{R_{pi}}{10}} \qquad [10]$$

An example may clarify the procedure, see the table below.

| Item | $S_i$ (m²) | $R'_i$ (dB) | $R_{pi}$ (dB) |
|---|---|---|---|
| glazing | 3 | 30 | 36,0 |
| panel | 1 | 28 | 38,8 |
| brick | 8 | 50 | 51,8 |
| **RESULT** | **12** | | **34** |

As the last column shows, the partial sound reduction index expresses the influence of that particular element on the value of the façade in total; the lowest partial values are the weightiest.

Some elements like joints do not have a well-defined area. In the European Standard EN 12354-3: 2000 methods are given to handle this type of elements. In this study, they are not needed.

*7.1.2. Tool for noise exposed façade*

In an early stage of design, when only the outline of the façade of the building is known, information on the consequences of the noise load for the construction of the façade is useful. Therefore a tool was devised, to produce this information. A few assumptions are made, aimed at a sufficiently high sound reduction; see Figure 36:

- The external noise load and the internal noise limit are expressed in day-evening-night level DNEL or $L_{den}$
- The façade is closed and carefully sealed; ventilation is provided through rear façade or via air ducts
- The façade consists mainly of brick or concrete cavity wall (600 kg/m$^2$, $R_{A,tr}$ = 54 dB(A)[4]), and a glazed part.
- The noise limit in the room is 35 dB(A); of course, if no noise sensitive rooms would be situated behind the noise exposed façade, this noise limit would not apply, and the required sound reduction would be much lower and could be disregarded in this stage of design.

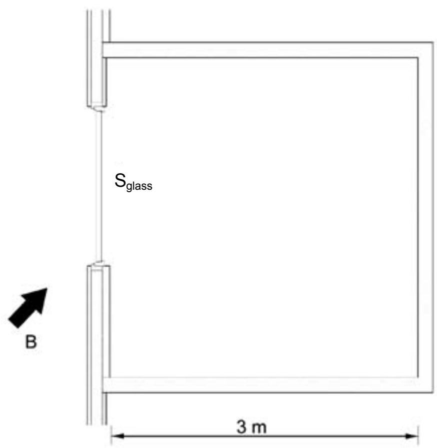


**Figure 36. Simplified cross section of a room with a noise exposed façade.**

The given noise load incident on the façade is *B*. The required sound level difference for living rooms and bedrooms is then $D_{2m,nT} = B + 3 - 35$. For the glazing many options exist. For this tool typical examples were chosen for the most important types as shown below.

[4] In a later stage, calculations will show if a lighter construction is acceptable.

| Type | **Typical dimensions** [glass-air gap-glass in mm] [* means laminated pane] | $R_{A,tr}$ [ A-weighted sound reduction relative to the standard spectrum of traffic noise] |
|---|---|---|
| Standard double glazing | 6-12-4 | **29** dB(A) |
| Large air gap glazing | 8-24-12 | **34** dB(A) |
| Laminated glazing with large air gap | 12*-24-12* | **39** dB(A) |
| Double frame (very large air gap) | 8*-120-14* | **43** dB(A) |

**Table 3. Representative types of glazing.**

For these types of glazing, the admissible noise load $B_{max}$ is given as a function of the percentage of the glazed parts in the façade in Figure 37. The value of $R_{A,tr}$ is used as a parameter. The glass types "29, 34, 39 dB(A)" can be applied in normal (although wider and/or heavier) frames. The glass type 43 dB(A) implies a special design of the façade, to allow for the double frame.

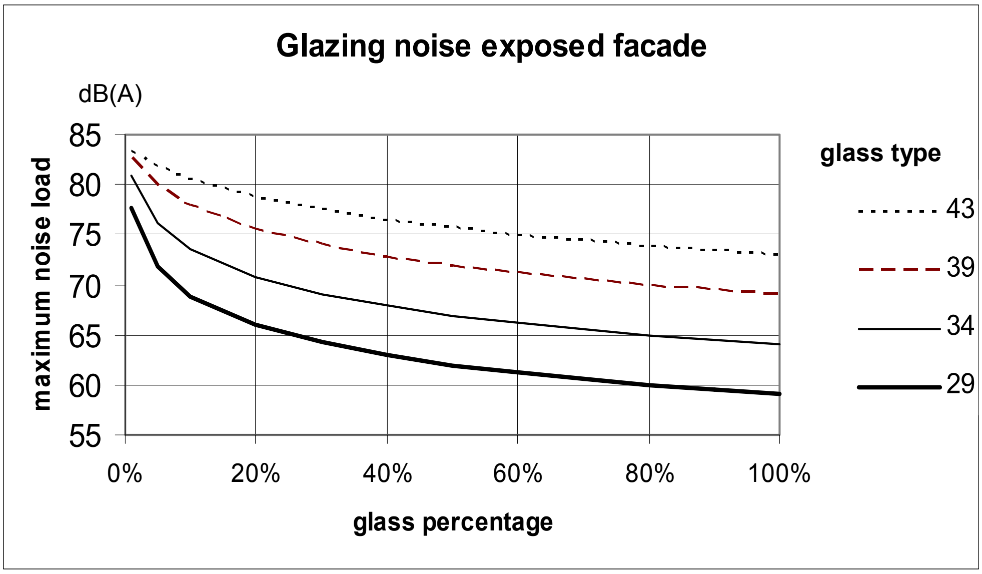


**Figure 37. Admissible noise load as a function of the percentage of glass area in the façade; target value is an interior noise level of $L_{den}$ = 35 dB(A). The glass type is parameter; see Table 3.**

The graph shows that for noise loads of 60 dB(A) and below, the designer has a wide choice, and even 100% glass is possible. On the other hand, for noise loads over 70 dB(A) serious limitations are faced. In the intermediate domain, practical solutions are not too difficult to find.

In the same way as in Section 4.3 and 6.1 the noise loads can be "translated" into admissible traffic intensities. The noise load on the canyon façades appears to be dependant on the quotient of the daily intensity and the width of the canyon $F/w$. In Figure 38 the results are shown. The canyon width is assumed to be between 10 and 30 m.

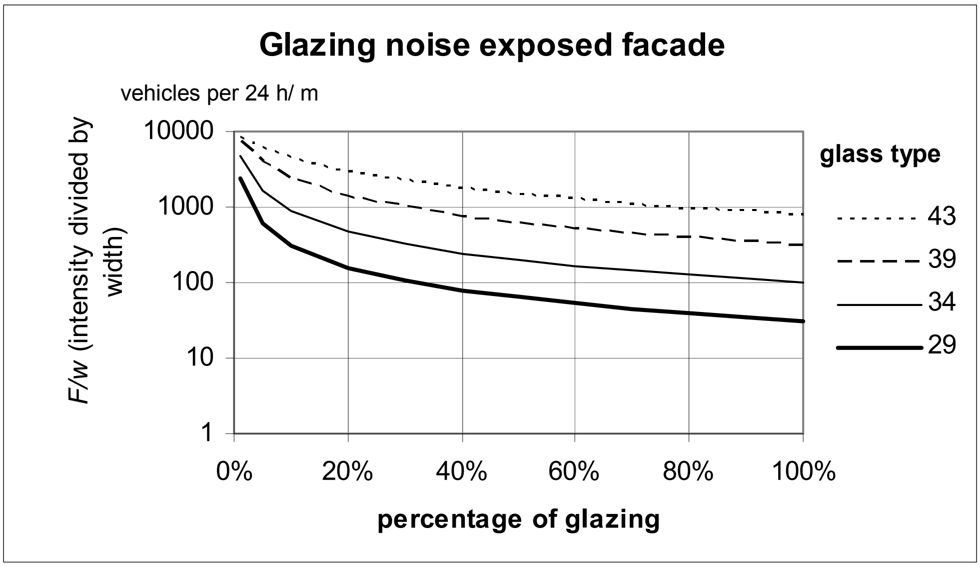


**Figure 38. Admissible traffic intensity as a function of the glass percentage in the façade. The *F/w* value on the vertical axis must be multiplied by the width of the canyon in meters to find the admissible traffic intensity per 24 hours. The glass type is parameter; see Table 3.**

The application of these graphs could be extended as an approximation of façades containing lightweight panels, by taking the area of panels + glazing instead of the glazing alone.

### *7.1.3. Extra façade (atrium)*

The insertion of a second façade makes the calculation of sound transmission from outside to the interior of the building more complex. Instead of a single step from outside noise to interior, a buffer room is introduced that makes a second step in calculations necessary. The extra sound reduction of the second façade $D_{extra}$ can be estimated as

$$D_{extra} = R'_{extra} - 10\lg\frac{S}{A} \qquad [11]$$

where

$R'_{extra}$ = apparent sound reduction of extra façade

$S$ = area of extra façade [m$^2$]

$A$ = absorption in atrium [m$^2$]

For single glazing $R'_{extra}$ will be at least 26 dB(A). For reasons of internal noise control (Group Vocal Output; see Section 7.4) a certain amount of sound absorption is required. As a first estimate, sound absorptive treatment of 50% of the building façade is assumed, with an effective sound absorption coefficient of 50%. Because the building façade and the extra façade have roughly the same area, $S/A \approx 4$. With these values, $D_{extra} \approx 20$ dB(A).

In the same way as used in Section 7.1.2 the admissible traffic intensity can be calculated. Again the criterion is a noise load in the interior of the apartments of 35 dB(A). A standard (interior) dwelling façade is assumed, typically having a sound reduction of 20 dB(A). Because here too the noise load depends on the quotient of traffic intensity and width of the canyon, this ratio was chosen as the dependent variable. In Figure 39 it is shown as a function of the amount of sound absorption in the atrium, relative to the area of the atrium façade ($A/S$). The glass type is parameter; the number stands for the A-weighted sound reduction in dB(A), relative to the spectrum of standard traffic noise. In Table 4 the values of $R'_{A,\ extra}$ for some glass types are given. Recently special acoustical interlayers were introduced instead of resin; glass panes with these interlayers are equivalent to resin laminated panes.

| **Type** | $R'_{A,\ extra}$ [ approximate A-weighted extra sound reduction] |
|---|---|
| 10 mm | **28** dB(A) |
| 14 mm, PVB laminated | **30** dB(A) |
| 16 mm, resin laminated | **32** dB(A) |

**Table 4. Representative types of single glazing and extra sound reduction values.**

If the atrium is open at the top, as can be useful in the summer season, sound transmission through this opening will have to be considered. A rough calculation yields a sound transmission into the reverberant field of the atrium of the same magnitude as through the simple glazing, if the opening is a well-situated (facing the hinterland) slit of some 250 mm height. If the slit is replaced by a kind of sound absorbent duct, or provided with splitter silencers with a sound reduction of 5 dB in the 125 and 250 Hz octave bands, the contribution of the slit can be neglected. For larger openings the required sound reduction is larger, openings smaller than 100 mm are acceptable without additional measures. Application of mechanical ventilation allows even smaller openings. The sound production of the fans themselves can and must be controlled by the provisions, known in the field of HVAC (Heating, Ventilation and Air Conditioning). If one of the better glass types from Table 4 is chosen, sound-reducing measures in the ventilation openings must be applied accordingly.

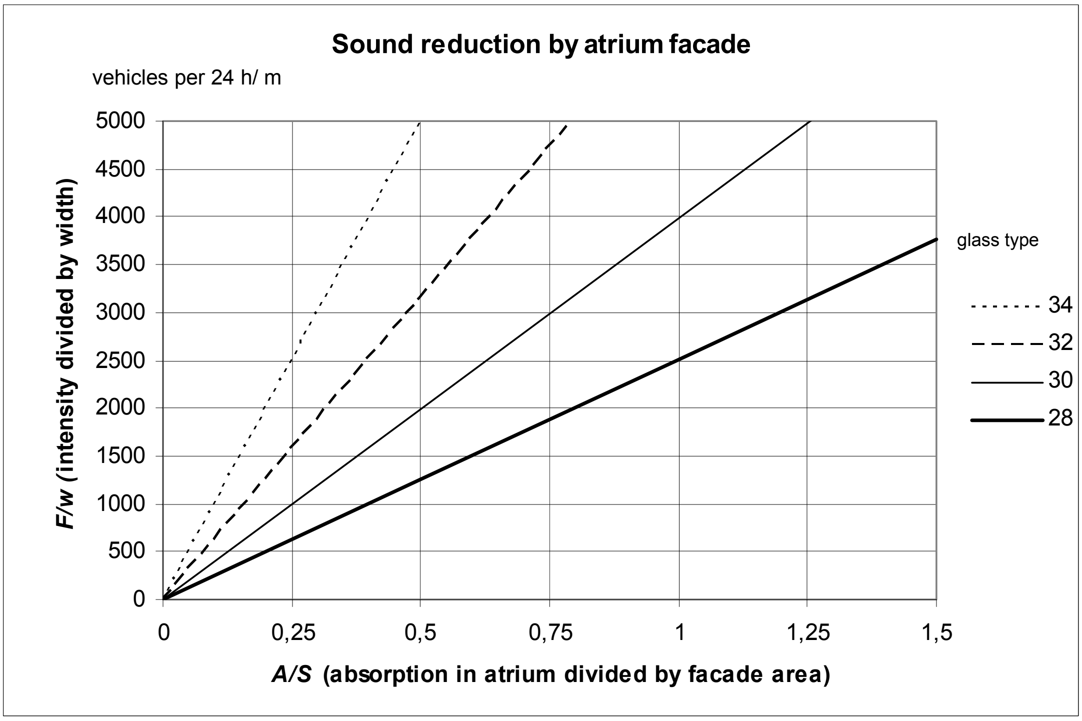


**Figure 39. Admissible traffic intensity as a function of the amount of sound absorption in the atrium, relative to the area of the atrium façade. The *F/w* value on the vertical axis is to be multiplied by the width of the canyon in meters to find the admissible traffic intensity per 24 hours. The glass type is parameter; see Table 4.**

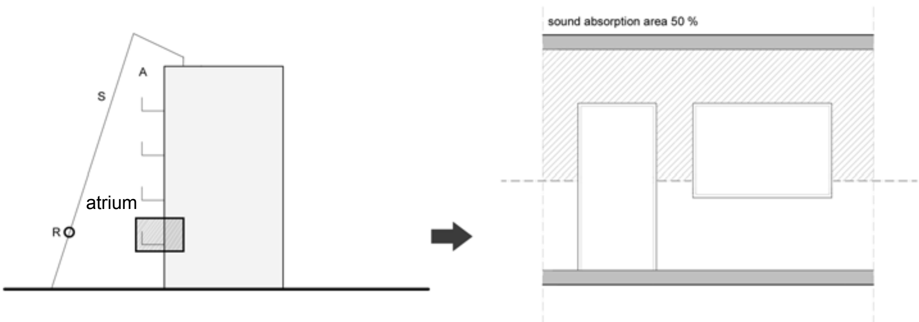


**Figure 40. Cross section of an atrium and location of a sound absorptive area in the façade.**

## *7.2. Public spaces*

It is not usual to set noise limits in communal or public spaces. If ambient noise impedes social conversation in communal spaces or in pedestrian areas and cycle-tracks, there is reason to set limits nevertheless. The limits can be based on the Speech Interference Level SIL; see Annex C.2. A functional criterion might be, that normal conversation should be possible between pedestrians or cyclists, walking or riding at 0,5 m to 1 m from each other.

## *7.3. Atria as serviceable rooms*

### *7.3.1. General*

A second glass façade in front of the building, at such a distance that a serviceable room is created, is very interesting from the point of view of noise control. This room is called atrium; see Figure 40. On the one hand the load of noise from the road on the original façade can be reduced to preferable levels of around 50 dB(A), allowing agreeable sojourn in "exterior spaces " (balconies, loggia's of apartments) in the atrium. Some more public space could be added for circulation, but also for small shops, or the entrance of a hotel. Bach and Pressmann (1992) pose that for cities to be made more livable *"a greater protection from undesirable climate must occur if 'greener' living is to be achieved";* atria can provide this protection from climatic impacts, including noise.

On the other hand, noise caused by the occupants in the atrium can reach levels that are much higher and annoying than the reduced environmental noise. The second façade can act as an acoustical reflector, and aggravate the problem of insufficient speech privacy in the "exterior spaces" (Section 7.5). These aspects too need attention.

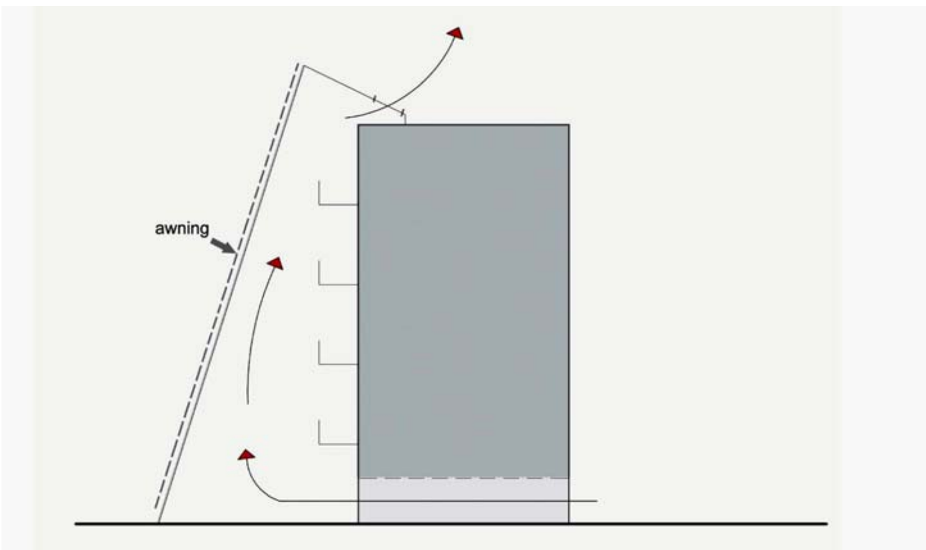


**Figure 41. Cross section of an atrium, natural air flow indicated.**

Ventilation of the atrium is necessary; in summer, large flows may be needed to control the ambient temperature in the atrium. The preferred system will be natural ventilation, air inlet from the rear of the canyon building at low level; the exhaust openings will be at roof level, facing the hinterland, as shown in Figure 41. In this way better air quality in the atrium is expected too. Ventilation in summer could be enhanced by a (partially) movable roof.

*7.3.2. Sound reduction*

The sound level in the atrium will consist of contributions from exterior traffic, internal equipment and occupants (people walking, talking etc.). The last will be addressed in the next section. Control of noise from technical installations must be considered at the appropriate time. Here we are concerned with the aspect traffic noise, and the sound reduction of the atrium façade. For reasonable comfort and privacy (see Section 7.5) an equivalent sound level of 55 dB(A) is chosen.

The sound level in the atrium is given by the formula[5]:

$$L_{p,atrium} = L_{p,canyon} - R' + 10\lg\frac{S}{A} \qquad [12]$$

where

*R'* = sound reduction index of the façade
*S* = area of façade [m$^2$]
*A* = amount of sound absorption in atrium [m$^2$]

The same variables as in the previous section determine the traffic intensity which is admissible within the noise limit of 55 dB(A) in the atrium. Not by accident, Figure 39 is applicable here too. Some examples of single glazing with their sound reduction indices are given in Table 5. Because of the sound spectra involved, these values are higher than those in Table 4. This also implies that the requirements of Section 7.1.3 are dominant, unless, of course, the starting points are changed.

| **Type** | **$R'_{A,tr}$** [ A-weighted sound reduction relative to the standard spectrum of traffic noise] |
|---|---|
| 10 mm | **30** dB(A) |
| 14 mm, PVB laminated | **32** dB(A) |
| 16 mm, resin laminated | **34** dB(A) |

**Table 5. Representative types of single glazing and their sound reduction values**

[5] The influence of the type of sound field in the canyon is discussed in Section 6.3.3.

In Figure 42 an example is shown of an office building, provided with several atria for reasons of the control of external (traffic) noise, the Ministry of Housing, Planning and Environment. It was not designed to have a function in shielding other buildings from traffic noise.

**Figure 42. Office building with atria for noise control (Ministry in The Hague; scale model).**

## *7.4. Internal noise control in atria*

### *7.4.1. Group vocal output*

It is a common experience that the noise level caused by the conversation of groups increases with the number of people; proportionally at first, when not many people are present yet, but even stronger if certain limits (noise level or number of people) are exceeded. At social events like cocktail parties, this phenomenon can often be regarded. This raises the question if the sound level caused by the people in a room can be predicted or estimated in some way. At least as important is the question to what extent the acoustical properties of the room determine the sound levels, and can be manipulated accordingly.

The mean sound power level for a speaker in a normal environment (not too noisy) is about 65 dB(A) re 1 pW. From the number of speakers ($n$) in a room, and the amount of sound absorption ($A$ [$m^2$]) the resulting sound level in the reverberant field can be calculated:

$$L_{p,rev} = 65 + 10\ \lg\left(\frac{4.n}{A}\right) \qquad [13]$$

The validity of this formula is limited to low ambient sound levels. As stated, sound levels can become (much) higher when the number of people increases. It is a realistic assumption, that the underlying reason is the intention of people to maintain conversation. Speakers want to make themselves heard; listeners want to understand what is said. A thought experiment can be useful to get a clear picture of the mechanisms involved.

Consider a room where a gathering is held. People arrive one by one; at first forming a circle with only one speaker at a time. The distance between neighbours in the circle will be constant, e.g. 1 m. As the number of people grows, the perimeter and consequently the diameter of the circle do, until conversation becomes less easy, because the distance between the speaker and some of the listeners hinders the speech intelligibility. Then the circle breaks up into two smaller ones. These new circles keep growing with new participants entering, until they break up again. In this way, the number of speakers increases, and so does the sound level in the room. This causes the speakers to raise their voices. Two processes can be observed that are meant to keep conversation possible: the conversation circles become smaller, therefore the number of speakers increases, and the sound power level per speaker increases. Over all an increase in sound level can be noticed related to the number of people by 20 lg $n$. [Internal communication from Peutz consultants]

It also appears that the amount of sound absorption per capita plays an important role. The effects of the number of occupants, trying to maintain or start their conversation, and the amount of sound absorption can be expressed in a model, based on the extensive literature on speech intelligibility, preferred speech levels, etc.

Of course communication comprises more than speech and intelligibility. Saarinen (1976) points at non-verbal communication, behaviour in a wide sense, including proxemics: the use of space by individuals in a group. These aspects are not taken into account. They should be kept in mind in the interpretation of experiments, and explain a part of the variance in the results.

*7.4.2. Conversation circles.*

As the vocal output of persons taking part in a conversation, depends on the background level, but the background level itself is largely determined by the vocal output of the speakers, the phenomena in conversation circles must be regarded as a system with feedback. Under certain assumptions, the process can be calculated, resulting in the sound level in a room as a function of the number of persons present and the amount of sound absorption. This sound level will be called the *Lombard* level, after the French physician who in 1911 first described the phenomenon, that speakers raise their voices when background noise levels increase.

The assumptions include:

- A diffuse reverberant sound field
- The vocal effort of each speaker depends only on the ambient sound level; several relationships are described (Heusden, E. van, et al. (1979); ISO 9921-1 (1996);Webster (1970)), some of them have been used in this study
- The conversation groups form circles; the interpersonal distance between members of a circle is constant (1m), for groups of five or more persons. For smaller groups – four or less – the interpersonal distance is smaller (0,5 to 1 m). The maximum distance *D* between two members of the group is the diameter of the circle. In formula:

$$D = \frac{n.d}{\pi} \qquad [14]$$

where
*n* = number of members
*d* = interpersonal distance

This distance *D* is taken to determine the (worst case) speech intelligibility.

The members of the group are supposed to take part in the conversation. Therefore they strive for understanding the speech of all other members. Only one member speaks at a time. If speech intelligibility is unsatisfactory people will leave the circle, to join some other circle or to form a new one. This process is simulated by assuming first that all persons present form one circle. If speech intelligibility is unsatisfactory, the number of circles is increased by one, and people are spread equally over the circles. For practical reasons the number of members is allowed to be non-integer, as it is only used to calculate the diameter of the circles. This process is repeated until speech intelligibility is satisfactory, or the conversation circles consist of only two persons. In each iteration the ambient noise level is calculated as the sum of the constant background noise level and the vocal output of all other speakers; only the reverberant field has been regarded. The ambient noise level at the end of each iteration process is the Lombard level, a function of two variables: the number of people and the amount of sound absorption. This function is called the Lombard-2 function.

The personal vocal effort (as a function of the ambient sound level) and the criterion for speech intelligibility can differ. For each criterion the whole process can be repeated, yielding a new Lombard-2 function. So each criterion has its own Lombard-2 function; see Figure 45 and Table 6. The process described here was implemented in a number of spreadsheet programs, one for each criterion of speech intelligibility and the connected personal vocal output function. These criteria embrace:

- Implicit criteria of Webster (1970), from his figure 1
- Criterion of Heusden et al.(1979), preferred listening level if conversation circles are large (5 or more persons), required listening level if conversation circles are smaller
- International standard ISO 9921-1 (1996)

| | Amount of sound absorption *A* (m²) | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Number of people** | **100** | **126** | **159** | **200** | **252** | **317** | **400** | **504** | **635** | **800** | **1008** | **1270** | **1600** | **2016** | **2540** | **3200** | **4032** | **5080** | **6400** | **8063** | **10159** |
| **10** | 57 | 56 | 54 | 53 | 52 | 51 | 49 | 48 | 48 | 47 | 46 | 46 | 45 | 45 | 45 | 44 | 44 | 44 | 44 | 44 | 44 |
| **13** | 57 | 56 | 54 | 53 | 52 | 51 | 49 | 48 | 48 | 47 | 46 | 46 | 45 | 45 | 45 | 44 | 44 | 44 | 44 | 44 | 44 |
| **16** | 64 | 60 | 54 | 53 | 52 | 51 | 49 | 48 | 48 | 47 | 46 | 46 | 45 | 45 | 45 | 44 | 44 | 44 | 44 | 44 | 44 |
| **20** | 66 | 65 | 61 | 57 | 52 | 51 | 49 | 48 | 48 | 47 | 46 | 46 | 45 | 45 | 45 | 44 | 44 | 44 | 44 | 44 | 44 |
| **25** | 68 | 66 | 65 | 63 | 58 | 54 | 49 | 48 | 48 | 47 | 46 | 46 | 45 | 45 | 45 | 44 | 44 | 44 | 44 | 44 | 44 |
| **32** | 70 | 68 | 67 | 64 | 63 | 60 | 55 | 52 | 48 | 47 | 46 | 46 | 45 | 45 | 45 | 44 | 44 | 44 | 44 | 44 | 44 |
| **40** | 71 | 70 | 68 | 66 | 65 | 63 | 61 | 57 | 53 | 49 | 46 | 46 | 45 | 45 | 45 | 44 | 44 | 44 | 44 | 44 | 44 |
| **50** | 74 | 72 | 70 | 68 | 67 | 65 | 63 | 61 | 57 | 54 | 50 | 48 | 47 | 46 | 46 | 45 | 45 | 44 | 44 | 44 | 44 |
| **64** | 78 | 74 | 72 | 70 | 68 | 67 | 65 | 63 | 61 | 58 | 55 | 52 | 49 | 47 | 46 | 45 | 45 | 45 | 44 | 44 | 44 |
| **80** | 86 | 78 | 74 | 72 | 70 | 68 | 66 | 65 | 63 | 61 | 58 | 55 | 52 | 49 | 48 | 46 | 45 | 45 | 45 | 45 | 44 |
| **101** | 88 | 86 | 78 | 74 | 72 | 70 | 68 | 67 | 65 | 63 | 62 | 58 | 55 | 52 | 50 | 48 | 46 | 46 | 45 | 45 | 45 |
| **127** | 89 | 88 | 86 | 78 | 75 | 72 | 70 | 68 | 67 | 65 | 63 | 62 | 58 | 55 | 53 | 50 | 48 | 47 | 46 | 45 | 45 |
| **160** | 90 | 89 | 87 | 86 | 78 | 75 | 72 | 70 | 69 | 67 | 65 | 63 | 62 | 59 | 55 | 53 | 50 | 48 | 47 | 46 | 45 |
| **202** | 92 | 91 | 89 | 88 | 86 | 78 | 75 | 72 | 70 | 69 | 67 | 65 | 63 | 62 | 59 | 56 | 53 | 51 | 48 | 47 | 46 |
| **254** | 94 | 92 | 91 | 89 | 88 | 86 | 78 | 75 | 72 | 70 | 69 | 67 | 65 | 63 | 62 | 59 | 56 | 53 | 51 | 48 | 47 |
| **320** | 95 | 94 | 92 | 91 | 89 | 88 | 86 | 78 | 75 | 72 | 70 | 69 | 67 | 65 | 63 | 62 | 59 | 56 | 53 | 51 | 48 |
| **403** | 97 | 95 | 94 | 92 | 91 | 89 | 88 | 86 | 78 | 75 | 72 | 70 | 69 | 67 | 65 | 63 | 62 | 59 | 56 | 53 | 51 |
| **508** | 98 | 97 | 95 | 94 | 92 | 91 | 89 | 88 | 86 | 78 | 75 | 72 | 70 | 69 | 67 | 65 | 63 | 62 | 59 | 56 | 53 |
| **640** | 100 | 98 | 97 | 95 | 94 | 92 | 91 | 89 | 88 | 86 | 78 | 75 | 72 | 70 | 69 | 67 | 65 | 63 | 62 | 59 | 56 |
| **806** | 101 | 100 | 98 | 97 | 95 | 94 | 92 | 91 | 89 | 88 | 86 | 78 | 75 | 72 | 70 | 69 | 67 | 65 | 63 | 62 | 59 |
| **1016** | 103 | 101 | 100 | 98 | 97 | 95 | 94 | 92 | 91 | 89 | 88 | 86 | 78 | 75 | 72 | 70 | 69 | 67 | 65 | 63 | 62 |

**Table 6. Numerical values of the Lombard-2 function (calculated sound levels in dB(A)) for ISO 9921 as a function of the number of people and the amount of sound absorption.**

### *7.4.3. Absorption per capita*

An important step in data reduction could be made, if the Lombard-2 functions were reduced to functions of one variable. Therefore a new independent variable is introduced: $A/n$, the amount of sound absorption per person. The values are given in Table 7. The calculated Lombard levels are plotted against this variable, as shown in Figure 46. Because each value of $A/n$ can be the result of several combinations of $A$ and $n$, many data points can occur with a single $A/n$-value. As the figure shows, the spread is not very large, and there is a clear trend. The trend line can be called a Lombard-1 function: the sound level in a room as a function of the absorption per person ($A/n$).

| | Amount of sound absorption **A** ($m^2$) | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Number of people** | **100** | **126** | **159** | **200** | **252** | **317** | **400** | **504** | **635** | **800** | **1008** | **1270** | **1600** | **2016** | **2540** | **3200** | **4032** | **5080** | **6400** | **8063** | **10159** |
| **10** | 10 | 13 | 16 | 20 | 25 | 32 | 40 | 50 | 63 | 80 | 101 | 127 | 160 | 202 | 254 | 320 | 403 | 508 | 640 | 806 | 1016 |
| **13** | 7,7 | 10 | 12 | 15 | 19 | 24 | 31 | 39 | 49 | 62 | 78 | 98 | 123 | 155 | 195 | 246 | 310 | 391 | 492 | 620 | 781 |
| **16** | 6,3 | 7,9 | 10 | 13 | 16 | 20 | 25 | 31 | 40 | 50 | 63 | 79 | 100 | 126 | 159 | 200 | 252 | 317 | 400 | 504 | 635 |
| **20** | 5,0 | 6,3 | 7,9 | 10 | 13 | 16 | 20 | 25 | 32 | 40 | 50 | 63 | 80 | 101 | 127 | 160 | 202 | 254 | 320 | 403 | 508 |
| **25** | 4,0 | 5,0 | 6,3 | 8,0 | 10 | 13 | 16 | 20 | 25 | 32 | 40 | 51 | 64 | 81 | 102 | 128 | 161 | 203 | 256 | 323 | 406 |
| **32** | 3,1 | 3,9 | 5,0 | 6,3 | 7,9 | 10 | 13 | 16 | 20 | 25 | 31 | 40 | 50 | 63 | 79 | 100 | 126 | 159 | 200 | 252 | 317 |
| **40** | 2,5 | 3,1 | 4,0 | 5,0 | 6,3 | 7,9 | 10 | 13 | 16 | 20 | 25 | 32 | 40 | 50 | 63 | 80 | 101 | 127 | 160 | 202 | 254 |
| **50** | 2,0 | 2,5 | 3,2 | 4,0 | 5,0 | 6,3 | 8,0 | 10 | 13 | 16 | 20 | 25 | 32 | 40 | 51 | 64 | 81 | 102 | 128 | 161 | 203 |
| **64** | 1,6 | 2,0 | 2,5 | 3,1 | 3,9 | 5,0 | 6,3 | 7,9 | 10 | 13 | 16 | 20 | 25 | 31 | 40 | 50 | 63 | 79 | 100 | 126 | 159 |
| **80** | 1,3 | 1,6 | 2,0 | 2,5 | 3,1 | 4,0 | 5,0 | 6,3 | 7,9 | 10 | 13 | 16 | 20 | 25 | 32 | 40 | 50 | 63 | 80 | 101 | 127 |
| **101** | 1,0 | 1,2 | 1,6 | 2,0 | 2,5 | 3,1 | 4,0 | 5,0 | 6,3 | 7,9 | 10 | 13 | 16 | 20 | 25 | 32 | 40 | 50 | 63 | 80 | 101 |
| **127** | 0,8 | 1,0 | 1,2 | 1,6 | 2,0 | 2,5 | 3,1 | 4,0 | 5,0 | 6,3 | 7,9 | 10 | 13 | 16 | 20 | 25 | 32 | 40 | 50 | 63 | 80 |
| **160** | 0,6 | 0,8 | 1,0 | 1,3 | 1,6 | 2,0 | 2,5 | 3,1 | 4,0 | 5,0 | 6,3 | 7,9 | 10 | 13 | 16 | 20 | 25 | 32 | 40 | 50 | 63 |
| **202** | 0,5 | 0,6 | 0,8 | 1,0 | 1,2 | 1,6 | 2,0 | 2,5 | 3,1 | 4,0 | 5,0 | 6,3 | 7,9 | 10 | 13 | 16 | 20 | 25 | 32 | 40 | 50 |
| **254** | 0,4 | 0,5 | 0,6 | 0,8 | 1,0 | 1,2 | 1,6 | 2,0 | 2,5 | 3,1 | 4,0 | 5,0 | 6,3 | 7,9 | 10 | 13 | 16 | 20 | 25 | 32 | 40 |
| **320** | 0,3 | 0,4 | 0,5 | 0,6 | 0,8 | 1,0 | 1,3 | 1,6 | 2,0 | 2,5 | 3,1 | 4,0 | 5,0 | 6,3 | 7,9 | 10 | 13 | 16 | 20 | 25 | 32 |
| **403** | 0,2 | 0,3 | 0,4 | 0,5 | 0,6 | 0,8 | 1,0 | 1,3 | 1,6 | 2,0 | 2,5 | 3,2 | 4,0 | 5,0 | 6,3 | 7,9 | 10 | 13 | 16 | 20 | 25 |
| **508** | 0,2 | 0,2 | 0,3 | 0,4 | 0,5 | 0,6 | 0,8 | 1,0 | 1,2 | 1,6 | 2,0 | 2,5 | 3,1 | 4,0 | 5,0 | 6,3 | 7,9 | 10 | 13 | 16 | 20 |
| **640** | 0,2 | 0,2 | 0,2 | 0,3 | 0,4 | 0,5 | 0,6 | 0,8 | 1,0 | 1,3 | 1,6 | 2,0 | 2,5 | 3,1 | 4,0 | 5,0 | 6,3 | 7,9 | 10 | 13 | 16 |
| **806** | 0,1 | 0,2 | 0,2 | 0,2 | 0,3 | 0,4 | 0,5 | 0,6 | 0,8 | 1,0 | 1,3 | 1,6 | 2,0 | 2,5 | 3,2 | 4,0 | 5,0 | 6,3 | 7,9 | 10 | 13 |
| **1016** | 0,1 | 0,1 | 0,2 | 0,2 | 0,2 | 0,3 | 0,4 | 0,5 | 0,6 | 0,8 | 1,0 | 1,2 | 1,6 | 2,0 | 2,5 | 3,1 | 4,0 | 5,0 | 6,3 | 7,9 | 10 |

**Table 7. Values of the new independent variable *A/n*.**

The Lombard-1 curves all have the same trend, as was expected. As long as there is ample sound absorption per capita, and the sound levels are still low, the agreement between the Lombard-1 functions is large, and the differences might be attributed for an important part to differences in the social context, type of occasion, etc. Different definitions of the speech level, especially the way of determining an equivalent speech sound level may be involved as well, for example ISO 8253-3 (1996).

Basically a slope of – 10 dB/decade is expected; see formula [13]. For values of $A/n < 10$ m$^2$ the curve is steeper, about – 30 dB/decade. The transition point can be estimated at roughly $A/n = 5$ - 10 m$^2$.

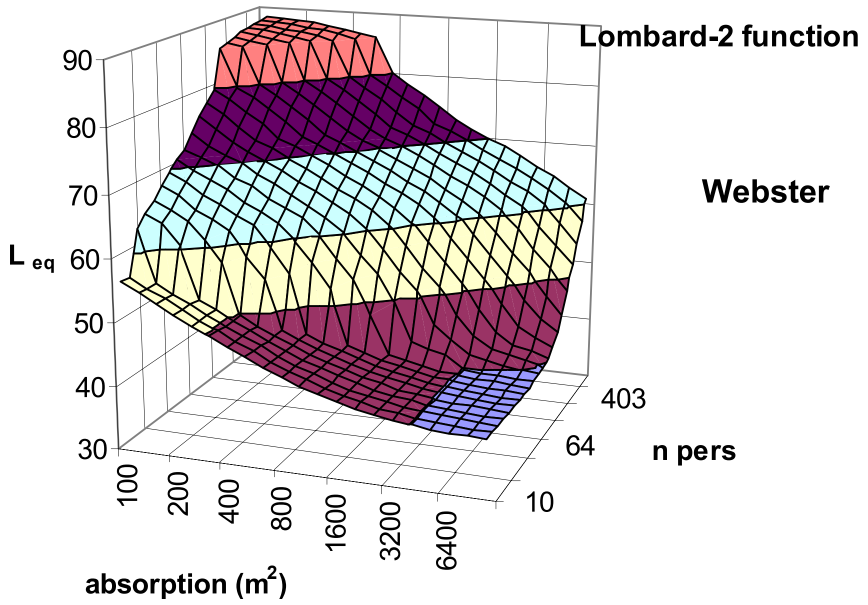


**Figure 43. Equivalent sound level (Group vocal output) as a function of the amount of sound absorption and the number of occupants (Webster).**


**Figure 44. Equivalent sound level (*Group vocal output*) as a function of the amount of sound absorption per capita (Webster).**

More or less arbitrarily a sound level of 60 dB(A) can be regarded as the start of noisiness in public spaces. The different Lombard functions lead to different *A/n*-values for which this limit is reached:

- Webster : $A/n \approx 10$ m$^2$.
- Van Heusden: $A/n \approx 3$ m$^2$.
- ISO 9921: $A/n \approx 7$ m$^2$.

A value of 5- 10 m$^2$ therefore seems a reasonable compromise, as a guideline for the minimum amount of sound absorption per capita in atria.

The model results in relationships as shown in Figure 43. Further the amount of sound absorption per person *A/n* appears to be a good descriptor of the group vocal output; see Figure 44. For values of $A/n$> 10-15 m$^2$, sound levels remain moderate. Smaller values, indicating more people or less absorption, yield sound levels, increasing at a higher rate than 10.lg *n*. For a different criterion of speech intelligibility, according to ISO 9921, the results are shown in Figure 45 and Figure 46; they show the same trends.

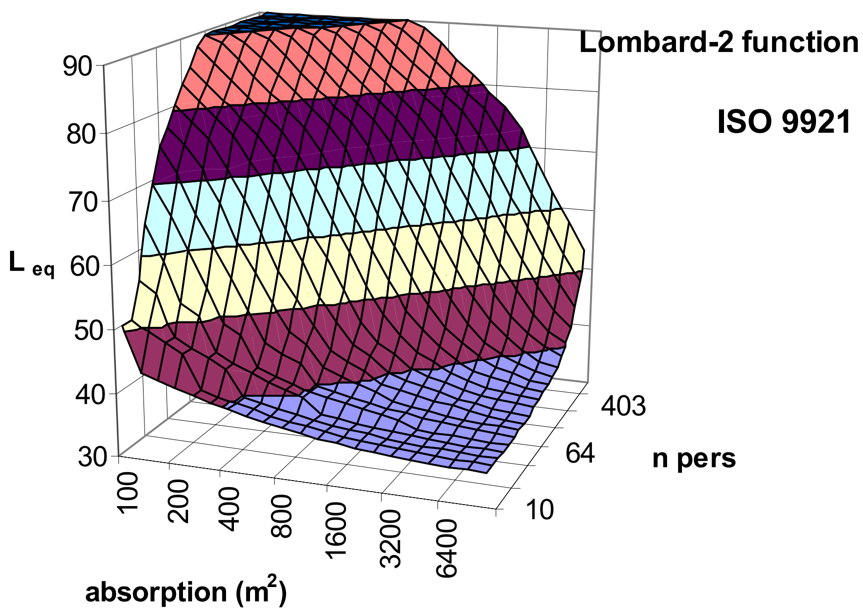


**Figure 45. Equivalent sound level (*Group vocal output*) as a function of the amount of sound absorption and the number of occupants (Lombard-2 function) for ISO 9921.**

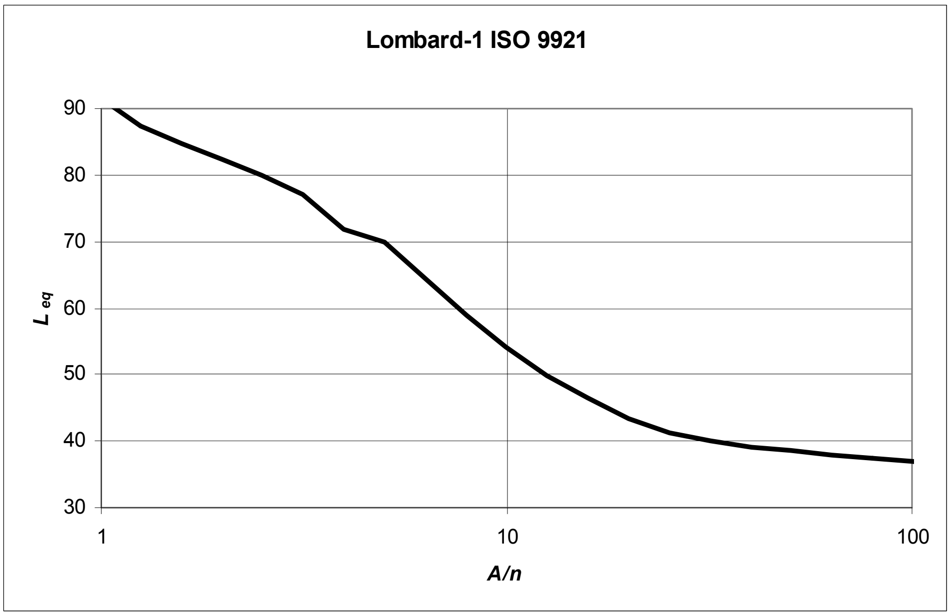


**Figure 46. Equivalent sound level (*Group vocal output*) as a function of the amount of sound absorption per capita (Lombard-1 function) for ISO 9921.**

*7.4.4. Architectural guideline*

This introduction was necessary to arrive at the point: can the sound level of the occupants in a large room like an atrium be controlled, and in which way? The answer is that control is possible within certain limits, of behaviour (fitting within the given formulae) and density of people. Therefore an amount of sound absorption per person of around 5-10 m$^2$ should be adopted as a guideline. Sometimes the (maximum) number of people to be expected is known, and can be used directly. In other cases a density of roughly one person per 5-10 m$^2$ floor area can be assumed; this means an amount of sound absorption roughly equal to the floor area. If this condition is met, one may expect that the sound levels caused by the occupants in the atrium will not rise to extreme values, but remain below 60-65 dB(A). Of course, no guarantee can be given: noisy behaviour or higher density of occupants is ruled out.

Under normal circumstances, the density of occupants in an atrium will be more in the order of one person per 100 m$^2$, resulting in a sound level below 50 dB(A), ceteris paribus.

In short, apart from the intruding exterior noise, sound production by people in the atrium must be considered. The densities of people and of sound absorption are the main variables. The discussion given above leads to the conclusion that in rooms like atria attached to canyon buildings an amount of sound absorption equal to the floor area of the room is a good choice to prevent excessive noise levels. In many cases the boundaries of the atrium will consist mainly of façades, and a glazed roof. The opaque parts of the façade of the apartment building and balconies are the only surfaces available for sound absorption. Nevertheless, in rather high atria these surfaces can be sufficient. If not, sound absorbing elements can be considered, like baffles perpendicular to the glass façade – perpendicular to minimise the reduction of view. These baffles could be designed in such a way, that they can function as fixed or movable sun-shading elements as well.

Where higher densities of people are to be expected, for example at the entrance of a hotel or shops, sound absorbing surfaces or elements near these areas may be necessary, and feasible.

*7.4.5. Examples Group Vocal Output*

For a number of occasions data regarding number of people, amount of sound absorption and resulting equivalent sound level have been compiled; partly from literature i.c. Gardner (1971), others from Peutz' archives. Gardner presented several graphs, stating the group vocal output level as a function of the number of individuals in a particular room. From each of those, the midpoints of two clusters of data points (a low and a high one) were extracted. The rooms embrace a service dining room, conference dining room and an auditorium. From the Peutz archives, a gathering in a school in Leyden (Holland) in 1977 was chosen, where the sound level and the number of individuals were recorded during the first 20 minutes after the arrival of the first participants. A singular point is the sound level recorded at a club night of the Nootdorp Bridge Club (NBC) in a "normal" room – insufficient floor space, insufficient sound absorption– on 200 March 11. While playing cards the equivalent sound levels caused by the 96 players are low, around 55 dB(A); during the halfway intermission 75 dB(A) is measured.

The data points are plotted in Figure 47, where also the range of the values as calculated with the model of conversation circles (Section 7.4) is drawn. The data points fit well in the range of the model; the spread is rather large as can expected for such a complex phenomenon. Measurements in six swimming pools (from the Peutz archives) were excluded: they show much higher sound levels than the occasions with adults in normal conditions. Vermeir (1994) too notices a much higher sound power in swimming pools than in normal speech.

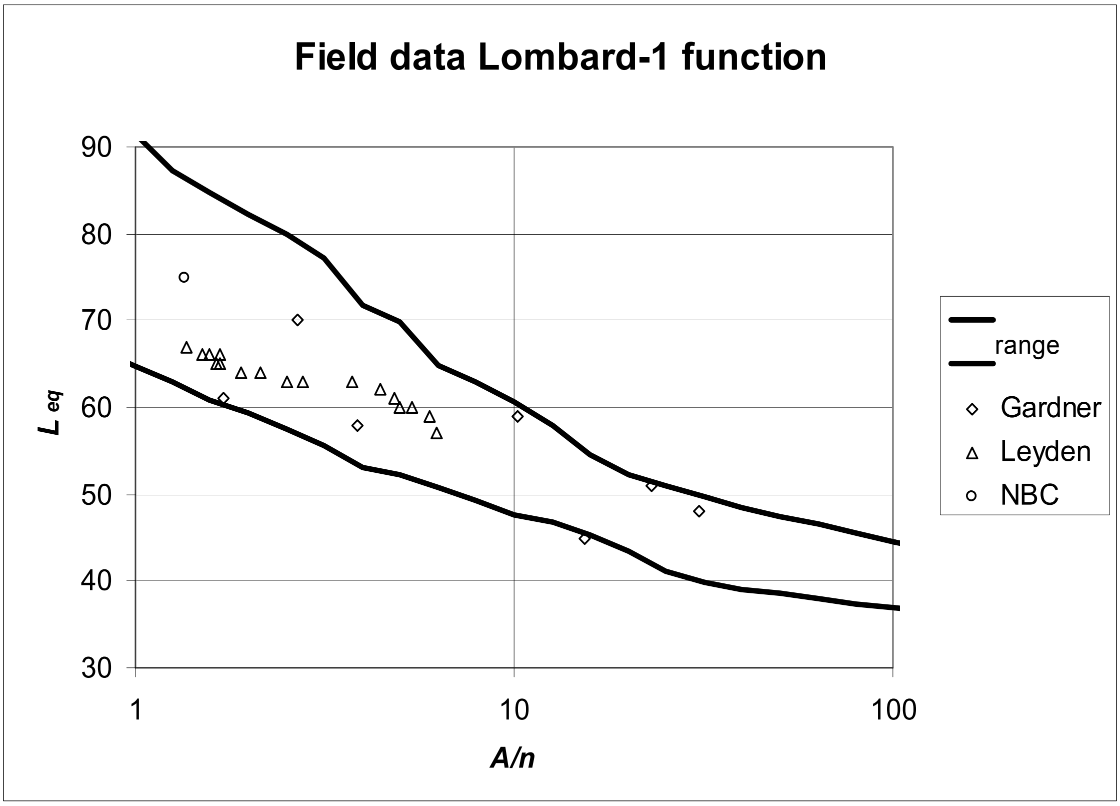


**Figure 47. Equivalent sound level (*Group vocal output*) as a function of the absorption per capita; data points and range of model values indicated.**

### *7.5. Exterior spaces, privacy*

In some countries it is compulsory to have exterior spaces (gardens, balconies, or loggias); in most cases it is desirable to have the opportunity for inhabitants to expose themselves to the open air on their own premises. The dwellings in the frontline have one noise-exposed façade. The exterior spaces will preferably be situated at the non-exposed, lee side of the building. This limitation in choice makes the other aspects of quality more important. These aspects embrace solar orientation (sun or shadow), dimensions, view, privacy (visual, auditive). One important element of this is the possibility to choose, for example between sun and shadow, communication with the neighbours or not.

In common practice, most of these factors, especially the visual ones, can be taken into account by existing design and drawing tools. The well-known architectural encyclopaedia by Neufert (2000) dedicates one page to balconies, and several remarks to (visual) privacy:

*"Corner balconies offer privacy and good shelter and are therefore preferable to open balconies."*

[The German original edition by the way has *Sichtschutz* instead of *privacy*.]

*"Balconies which are offset in their elevation can make façades less severe but it is difficult to provide privacy and protection from the weather and sun".*

*"Balconies which are offset in their plan layout on the other hand offer excellent privacy and shelter."*
[Here *privacy* is the translation of *Schutz gegen Einsicht*.]

Social behaviour as a starting point is described by Altman (1975). Privacy is mentioned by Menzel (1989) as one of the leading principles in the design of the much-discussed high-rise district Bijlmermeer or Amsterdam-South-East; the context shows that attention focuses on the visual and social elements. "*In medium high-rise not everyone has his own garden. (…) For compensation a maximum degree of privacy must be pursued. Maximising the distance between the blocks is tried to achieve this.*" [Du Laing, cited by Menzel]. The aspect of auditive (or speech) privacy has received little attention until now, which can partly be explained by the absence of appropriate tools to assess the degree of speech privacy.

Noise annoyance surveys show high numbers of people annoyed by neighbour noise. Dongen et al. (1998) give (Dutch) noise response functions for neighbour noise. Generally no distinction is made between noise annoyance experienced in the home and in the exterior spaces, and the last element is usually neglected. Consequently only conclusions are drawn regarding the sound reduction between dwellings. There is however reason to assume that noise annoyance in exterior spaces, caused by conversation of neighbours plays a part as well (see the practical example in Section 8.8). The intelligibility of this conversation is perceived as a violation of privacy, and therefore annoying. But privacy has a second, passive component: it concerns *hearing*, but also *being heard*; *seeing* and *being seen*, maybe even *smelling* and *being smelt*. Regarding the acoustical aspect an indicator is proposed, called the *Required Masking Noise Level*, $L_{mn}$, based on the notion of speech privacy.

### *7.5.1. The masking noise level required for speech privacy*

Human speech is a very special kind of sound. If it is received by the persons it was aimed at, communication is realised. Speech hitting ears of non-intended receivers however can be very intruding, and therefore annoying to those receivers in particular if intelligible; secondly, the fact that the message is picked up by a third party violates the intimacy of the conversation. Especially in the last case speech privacy is said to be insufficient. Speech privacy as a notion can be defined as the degree in which conversation (in an adjacent room) cannot be overheard. It is commonly used to derive requirements for the sound insulation of partition walls, in offices, hospitals etc.

The base of this concept is: masking of the speech signal by background noise. This can be expressed in a simple form in the formula:

$$SP = L_m + D - L_s - P \quad [15]$$

where:
*SP* = a measure for speech privacy
$L_s$ = the vocal output of the speaker ($L_p$ at 1m distance, A-weighted)
*D* = the sound attenuation from talker (1 m distance) to listener (ear position)
$L_m$ = the masking sound level at the listener's position (A-weighted)
*P* = a weighting term; see under.

In the weighting term *P* the confidentiality and other non-acoustical influences can be taken into account. In general, the value of *P* ranges from 5 to 10 dB. For positive values of *SP* the speech privacy is said to be sufficient; for negative values complaints are to be expected.

This formula does not reflect the more subtle dependence of masking on the spectra of speech and the background noise. Normal speech, and background noise with normal spectra (like ISO-NR-curves) are assumed. With more sophisticated methods like Articulation Index [ANSI S3.5 (1997)] different spectra could be treated; in this case there is no need for that.

If the masking sound level $L_m$ is not constant, the minimum sound level should be taken (e.g. the 95%-level $L_{95}$, the sound level that is exceeded for 95% of the time) and not the equivalent sound level, because "masking" implies continuity.

**Figure 48. Balconies with sufficient acoustical privacy?**

Consider a multifamily building, each apartment having a balcony. For pairs of source (talker) and receiver (listener) position on balconies next to or above each other the speech privacy SP can be calculated. Assumptions must be made with regard to speech effort (typical level 60 dB(A) at 1 m distance), and the weighting term *P*; here *P* = 10 is taken. The other terms are variables, describing the environment: the background noise and attenuation. In other words, assuming certain standard values for speech volume a relationship should exist between background noise level and the sound attenuation between neighbours. From this, for each instance the background noise level $L_{mn}$ required to mask the speech signal can be calculated. This level $L_{mn}$ can be used as an indicator for (an important aspect of) the quality of the building.

$$L_{mn} = 70 - D \qquad [16]$$

*D* is the sound attenuation from talker (1 m distance) to listener (ear position).

It must be emphasised that $L_{mn}$ is a notional sound level, determined by architectural properties. $L_{mn}$ can be calculated from these architectural data or measured in the field or in a mock-up.

For all pairs of source and receiver positions calculations can be made of the resulting sound attenuation, and so for the required masking noise level $L_{mn}$. For each (receiver) position, only the highest value of $L_{mn}$ is important.

Low values of $L_{mn}$ indicate good speech privacy, e.g. 30 dB(A) or below. This level of background noise is almost always exceeded by the traffic noise in the atrium and natural sounds.

Higher values of $L_{mn}$ are no problem as long as the background noise at the receiver position meets the same levels. In general an equivalent sound level of 50 dB(A) is regarded as (still) acceptable; corresponding $L_{95}$ values will be in the range of 40-45 dB(A). When the required value $L_{mn}$ exceeds 55 dB(A) a dilemma arises: if the masking sound is "sufficient " it will become disturbing itself, otherwise speech privacy is insufficient. This indicates that the design of the balconies and the building should be improved, by increasing distance or shielding, or by reducing reflections.

The values of the required masking noise level can be judged as shown in Table 8.

| Required masking noise level | Assessment |
|---|---|
| 30 dB(A) | Very good |
| 35 | Good |
| 40 | Reasonable |
| 45 | Average |
| 50 | Insufficient |
| 55 | Poor |

**Table 8. Rating of the required masking noise level $L_{mn}$.**

*7.5.2. Use of the Required Masking Noise Level*

It must be emphasised that the *Required Masking Noise Level* is a notional quantity, dependent only on the architectural properties of the exterior spaces and their relationship. As such, it can be used as a target value, e.g.: *"the value of $L_{mn}$ shall not exceed 45 dB(A) in project Y"*. The target value to use will depend on the practical possibilities, and on the ambient sound level present or expected in the area of interest, i.c. on the façades of the dwellings.

The aspects speech privacy and (traffic) noise annoyance each define a noise limit. The limit for noise annoyance is set at $L_{amb}$ = 55 dB(A); the bold horizontal line in Figure 49 should not be exceeded. At the same time, $L_{mn}$ should be smaller than $L_{amb}$, to insure sufficient speech privacy; this is expressed in the inclined line. If both limits are taken together a triangular area in the graph results, designated with a plus sign, where both requirements are met. In the upper part of the graph, ambient noise is annoying; in the lower right hand part (at the right from the inclined line) speech privacy is insufficient, both areas being designated with a minus sign.

Low ambient sound levels are favourable, but demand more attention for speech privacy. In general this can be achieved by increasing the sound attenuation between speaker and listener or more specific: increasing distance, making effective noise barriers between balconies, and reducing the relevant sound reflections.

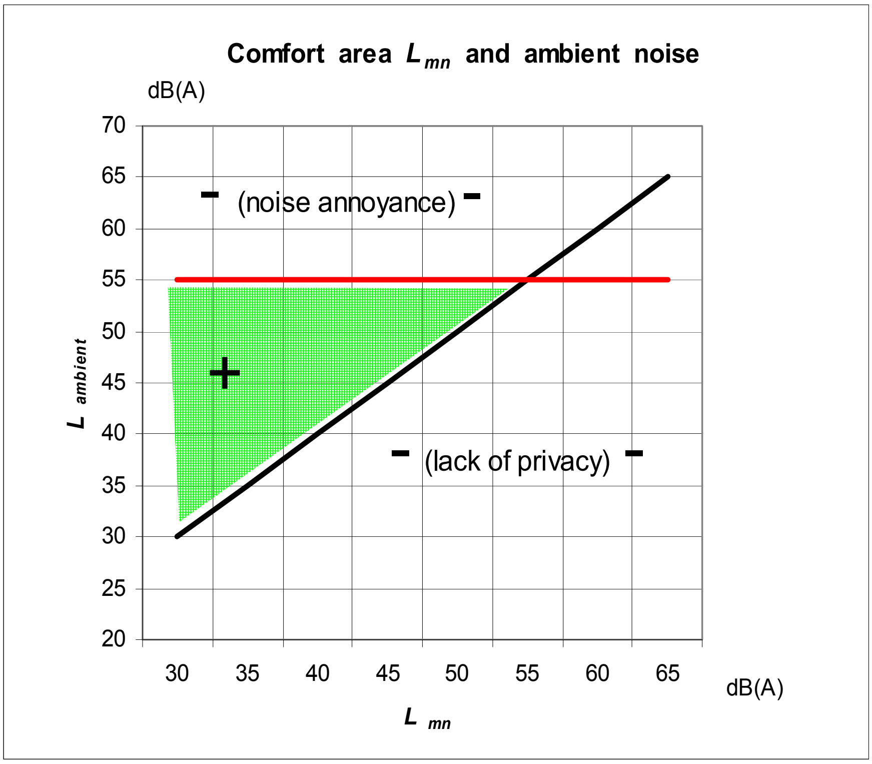


**Figure 49. Comfort area (+) for the combined aspects of noise annoyance (ambient sound level) and speech privacy (required masking noise level).**

Many screens between terraces are of an open type (e.g. woven wood) or bushes; privacy screens between balconies often show an open perimeter, or worse: see Figure 50. This makes them acoustically ineffective. A non-porous screen, sealed at the perimeter is a necessary condition. The mass should be at least 10 kg/m$^2$. Then the sound attenuating effect of the screen depends on the difference in path length; see Annex B.5.

**Figure 50. Balcony screen offering visual privacy only.**

**Figure 51. Open garden fences …..**

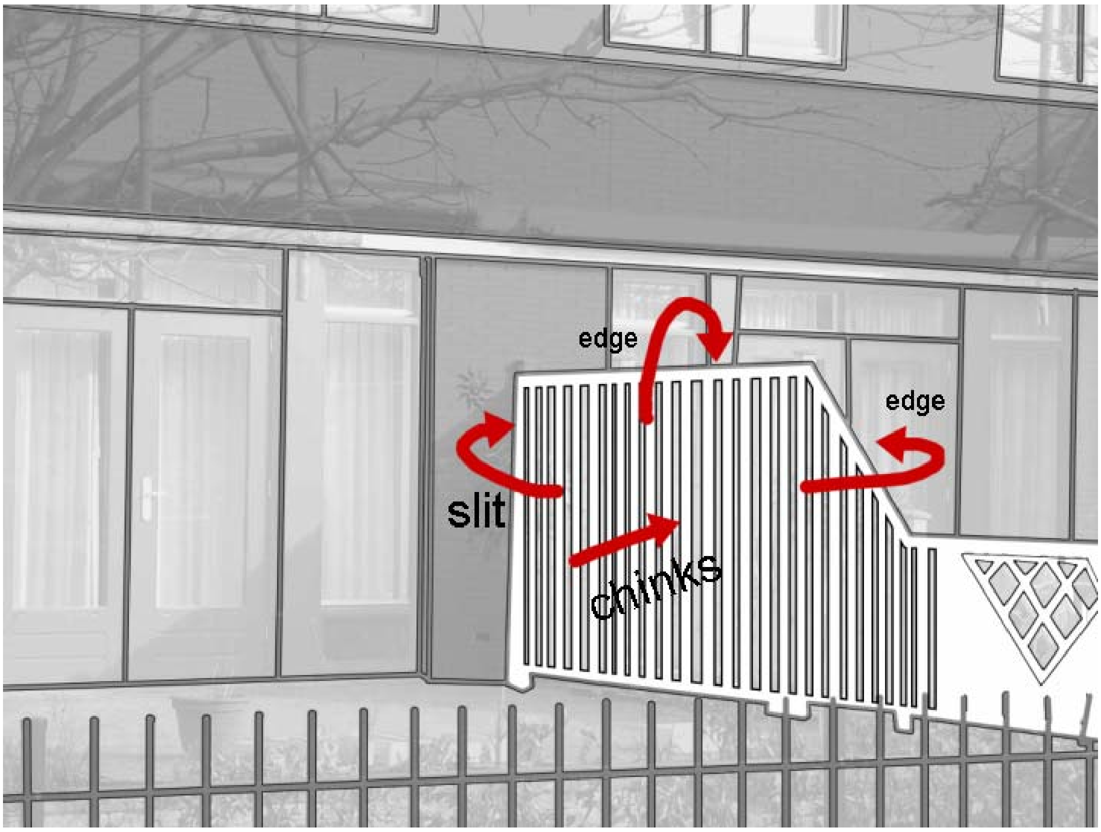


**Figure 52. …. are acoustically ineffective.**

In Section 8.6 an example is given of the application of the required masking noise level $L_{mn}$ in a refurbishing project; possible changes in the building, balconies in particular, are judged and compared to the existing building.

(blank)

# 8. Examples and applications

## *8.1. Application of the Population Annoyance Index in an EIA project*

The provincial road N284 between Reusel and the highway (A67) junction, is – together with the N269 – the main access to the Brabant Kempen area in The Netherlands, and connects several villages: Reusel, Bladel, Hapert, Duizel and Eersel; see Figure 53. In the past, beltways (tight bypasses) were made for all villages, so the village centres are spared. The road sees many accidents, while congestion increases.

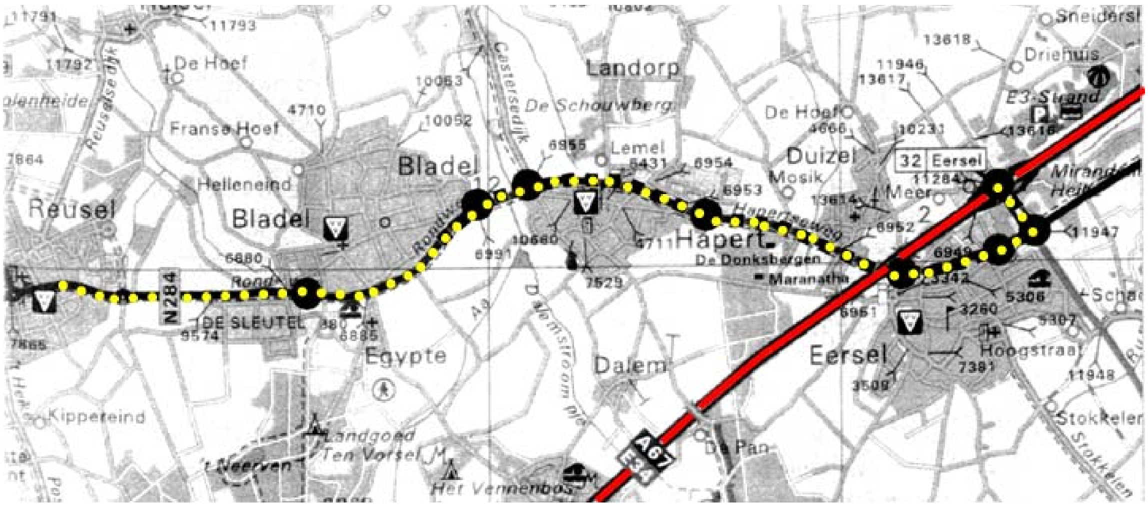


**Figure 53. Road map of provincial road N 284, present state.**

The Provincial Government of Noord-Brabant had an Environmental Impact Assessment [IEA] (OAG et al., 2002) carried out for a number of variant solutions. They can be summarised as follows:

- Nil-option: status quo
- Nil-plus: only minor improvements, including dynamic road management and upgrading of crossings
- Improvement: extra lanes added to the existing road between Hapert and A67-junction
- Duizel-option: northern bypass between Hapert and A67-junction [A; see Figure 54]
- Nature friendly option: improved A67-junction, no new bypasses [B]
- Hapert- option: southern bypass between Hapert and A67-junction [C]
- De Pan- option: longer southern bypass, between Bladel and A67-junction [D]

All new bypasses [A-D] are planned in agricultural rural areas; see Figure 54. The road surface is standard asphalt (fine texture) in all options.

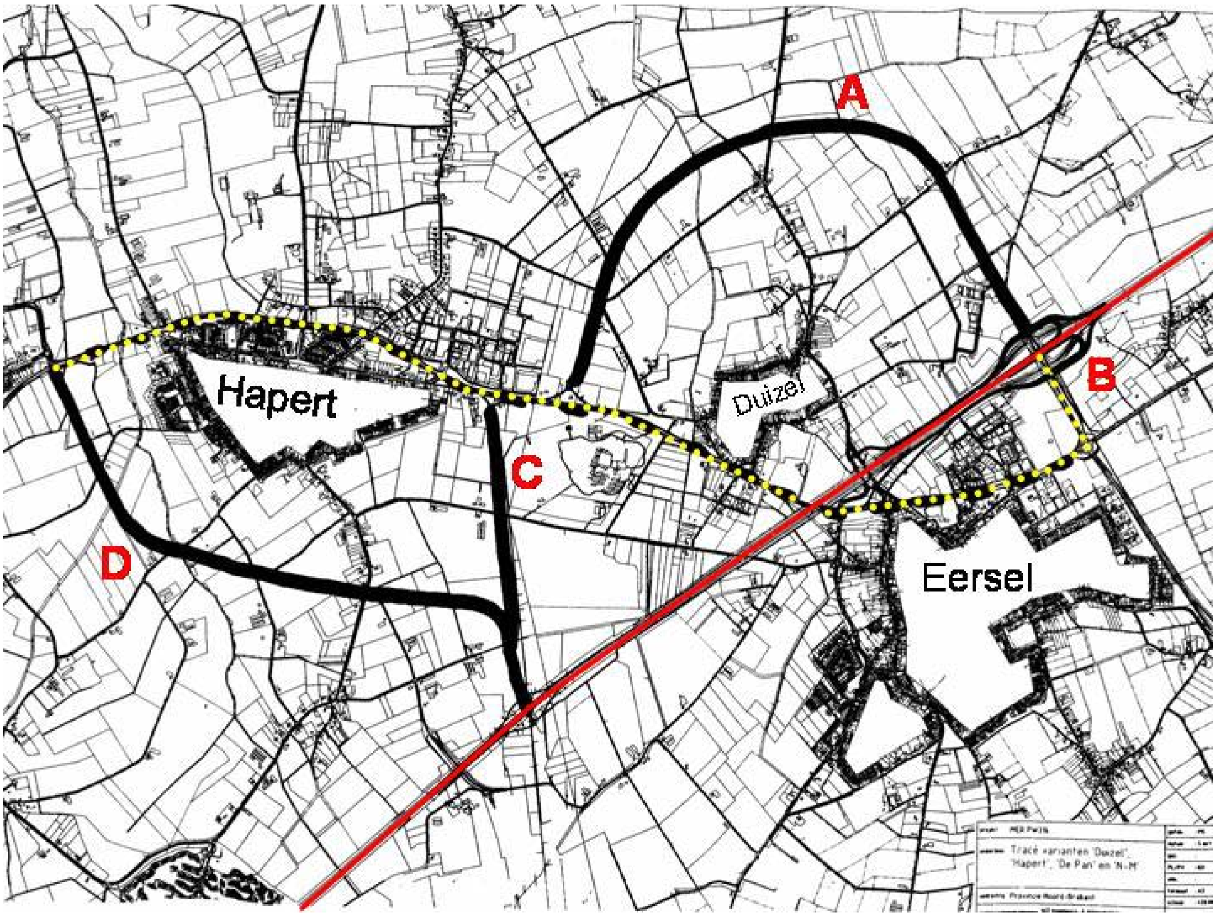


**Figure 54. Road map of N 284 with alternative bypasses, around Hapert and Duizel.**

The acoustical impact of the options was to be calculated and expressed in two aggregated variables: the Population Annoyance Index *PAI* and the extra-urban area (km$^2$) exposed to a noise load over 50 dB(A). The first indicates the "extent of noise annoyance" for the population of the area in study; the second is related to the influence on possible future building sites, recreation fields and fauna. The results for all options, based on prognoses for the traffic in the year 2012 are summed up in Table 9.

| | **Existing alignment** | | | **New alignment** | | | |
|---|---|---|---|---|---|---|---|
| | **Nil** | **Nil-plus** | **Improv-ement** | **Existing junction A67** | | **New junction A67** | |
| | | | | **Nature** | **Duizel** | **Hapert** | **De Pan** |
| ***PAI*** | 166 | 145 | 138 | 133 | 131 | 129 | 110 |
| **Area [km$^2$]** | 5,81 | 4,41 | 4,67 | 5,31 | 6,08 | 4,63 | 5,47 |

**Table 9. Acoustical impact of alternative solutions for N284 Reusel-Eersel.**

The *nil*-option is, as expected, clearly the worst. The *De Pan*-option is the least annoying, thanks to a large bypass; the consequence appears to be a large noise exposed extra-urban territory. This is a common trend in marking out roads: ground plans through rural areas cause large impact on extra-urban areas, but result in low *PAI*-values, while alignment through urban areas results in the opposite.

Application of the *PAI* gives a clear and quick insight of the acoustical impact of the options; by calculating *PAI*-values for specific parts of the road, the "distribution of annoyance" can be shown.

## *8.2. Canyon shielding, aperture and elevated building*

The use of the Canyon Shield graph (Figure 23 on page 46) can be illustrated with an example; see Figure 55. A first draft of a new district contains an urban canyon, 10 m wide, canyon buildings 10 m high, 10 m wide, and a non-residential strip (park, small shops, pavilions) 25 m wide; the second line of dwellings then starts at 35 m from the street façade of the canyon buildings. In the figure the maximum daily traffic intensity can be read as 18.000 motor vehicles; this number applies to a reasonable district road. With simple rules from traffic science, a rough estimate can be made of the daily traffic intensity. If much more than 18.000 motor vehicles per day are expected, the height of the canyon buildings can be increased. A height of 15 m would be sufficient to "accommodate" a daily flow of 40.000 motor vehicles in the canyon, as Figure 55 shows.

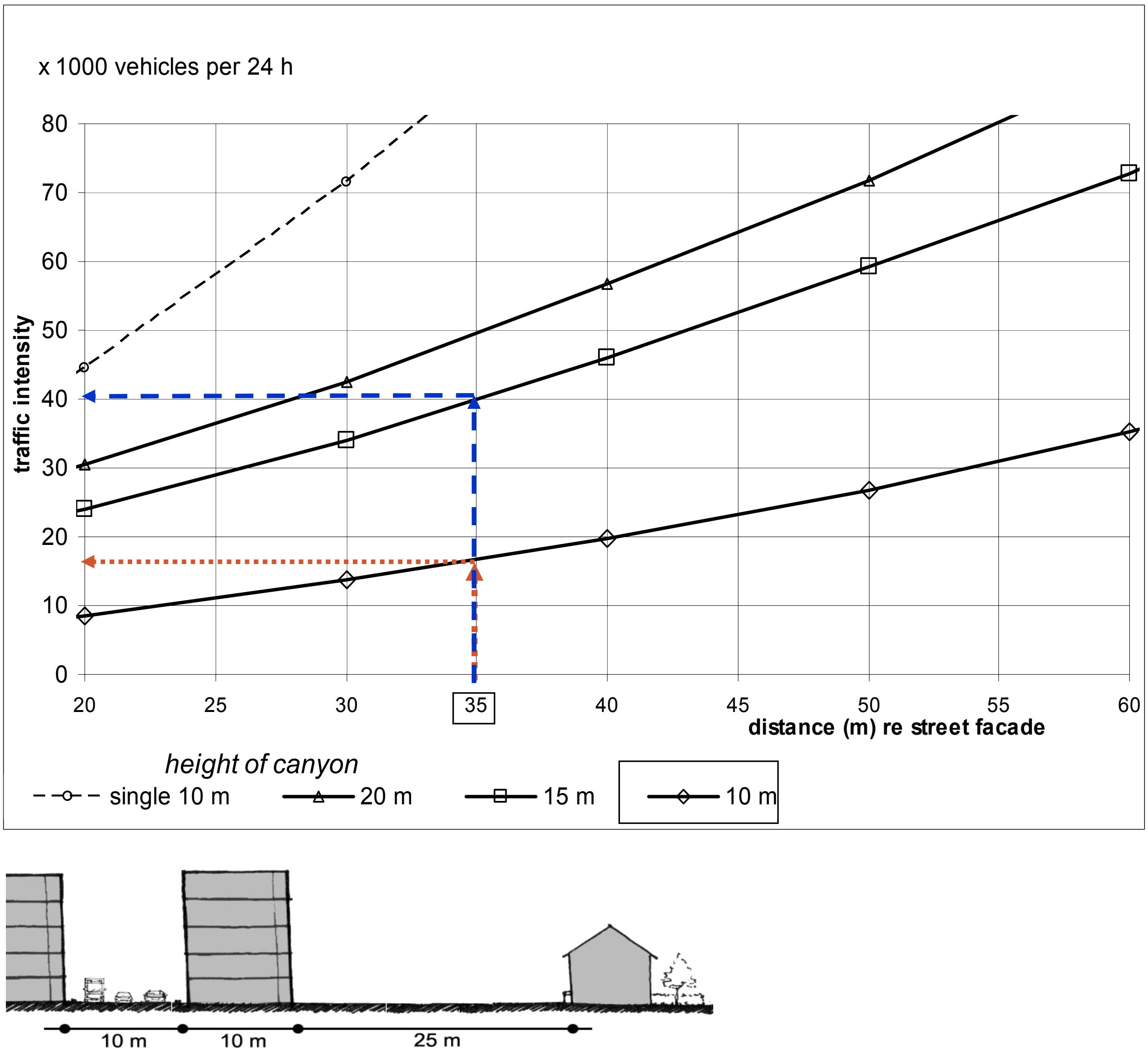


**Figure 55. Example: admissible traffic intensities in urban canyons.**

If a *passageway* (3 x 2,5 m) is made in this canyon building, the consequences can be assessed by means of Figure 56 (copied from Figure 29 on page 52). The distance of the second line of dwellings from the rear façade of the canyon building is 25 m; with the width of the canyon of 10 m, the graph yields a value of *F.S* = 0,12. $10^6$ veh/24h. $m^2$. As the area of the aperture is 7,5 $m^2$, the admissible daily traffic intensity is 16.000 motor vehicles (0,12 . $10^6$/ 7,5). This number is only slightly lower than the 18.000 the canyon itself allows. Therefore formula [7] in Section 6.3.5 must be applied to get the number of vehicles admissible if both effects (sound from the canyon as such, and extra through the aperture) are taken into account. The result is 8.500 motor vehicles.

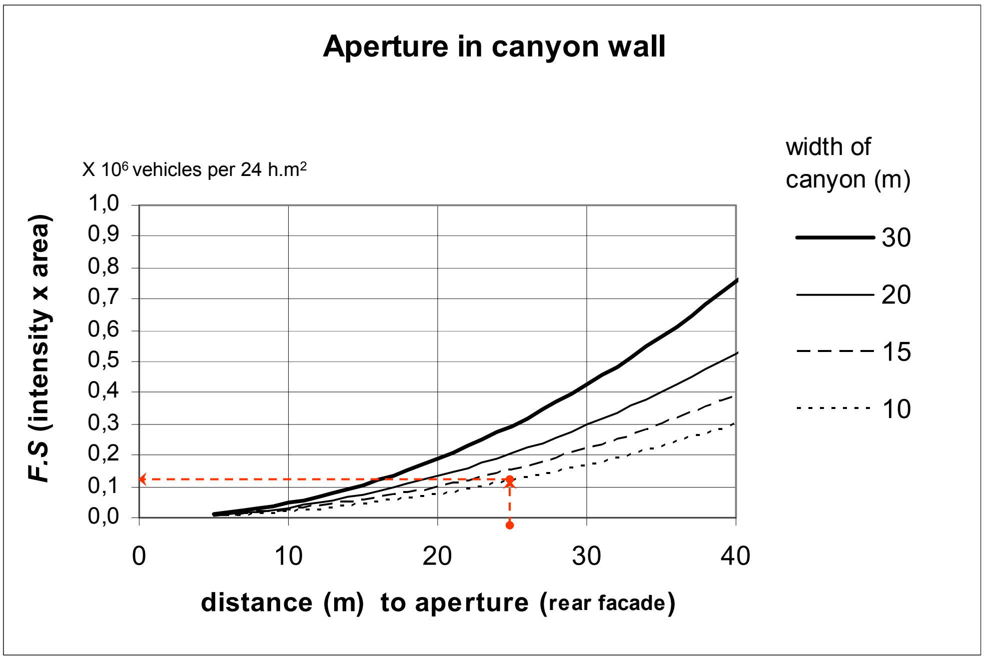


**Figure 56. Example: admissible traffic intensity in the case of a passageway through a canyon building.**

If the whole canyon building is lifted (*elevated*) a much larger aperture results. An extended deck is assumed, 15 m long, so the second line of dwellings is at 10 m from the mouth; the ceiling under the building and the extended deck is sound absorbing, 25 m long. From Figure 57 (copied from Figure 32 on page 55) it can be seen, that less than 1000 motor vehicles would be allowed now, a very small number. This demonstrates the contradictory aspect: a canyon should consist of continuous buildings and apertures should be minimized.

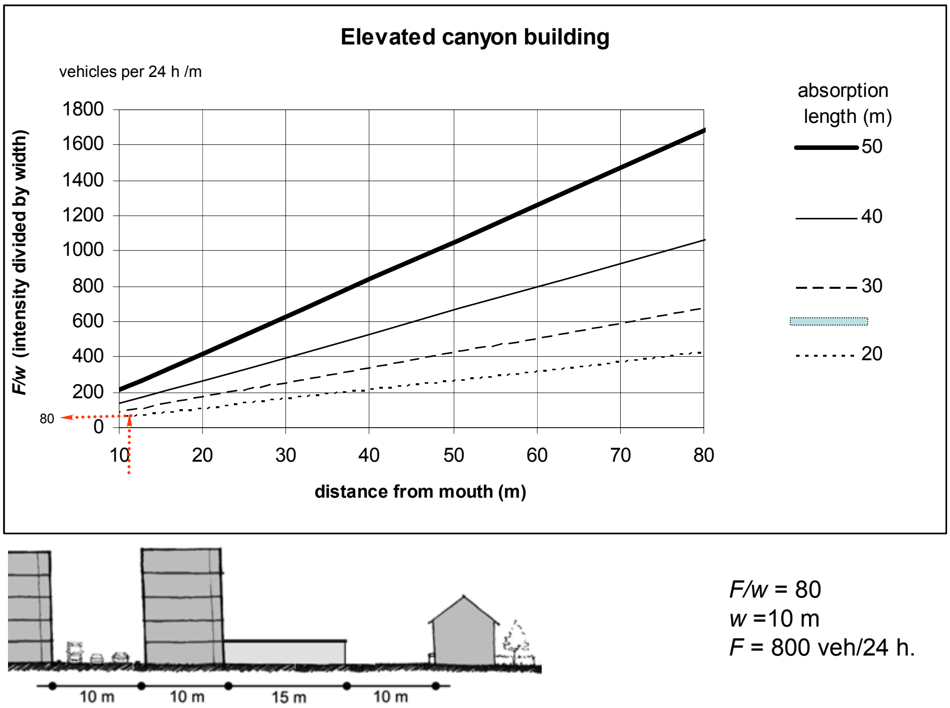


**Figure 57. Example: admissible traffic intensity in the case of an elevated canyon building.**

## *8.3. Noise exposed façade*

The sound level in an urban canyon can be very high. For a sound level of e.g. 77 dB(A), the question can be asked whether a glass percentage of 30 in the façade is acceptable. In Figure 58 (copy of Figure 37) it can be seen, that 30% glass requires $R_{A,tr}$ = 43 dB(A) to yield an acceptable sound load of 77 dB(A). If an even higher sound load is expected, a special façade design is necessary. Other options could be, to keep noise sensitive rooms away from this façade, to insert buffer rooms or to apply a second façade.

In a second example, the noise load is around 65 dB(A). Which glass percentage is acceptable, from the viewpoint of sound reduction? Figure 58 shows that glass with a sound reduction value of $R_{A,tr}$ = 34 dB(A) or more, even allows 80% glass in the façade.

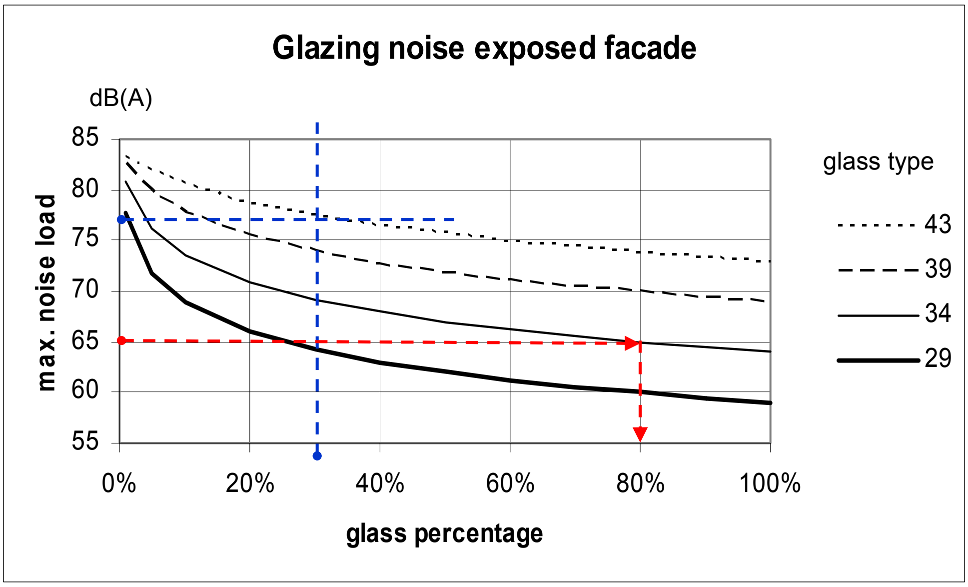


**Figure 58. Example: choice of the glass type in a noise exposed façade; maximum noise load as a function of glass percentage.**

In Figure 59 (a copy of Figure 38 on page 64) comparable information is shown. Now the first question is: is 30% glass in the façade acceptable in the case of a 10 m wide canyon, having a traffic intensity of 10.000 motor vehicles per 24 hours? The *F/w*-value is then 1000, and the graph shows that a glass type **39** dB(A) is required. The second question is: given a traffic intensity of 2000 motor vehicles per 24 hours in a 10 m wide canyon, which glass percentage is acceptable from the viewpoint of noise reduction? Starting with an *F/w*-value of 200 the graph shows that a glass type **34** dB(A) even allows 50% glass in the façade.

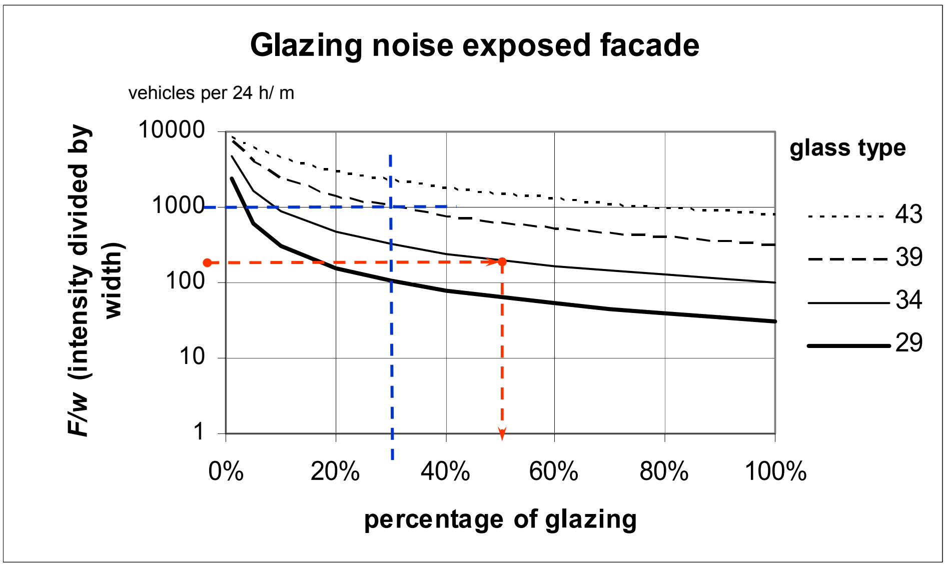


**Figure 59. Example: choice of the glass type in a noise exposed façade; admissible traffic intensity as a function of glass percentage.**

## *8.4. Atrium façade*

The sound reduction index of the atrium façade dominates the traffic sound level in the atrium directly, and the traffic sound level in the apartments indirectly. In Section 7.1.3 it is shown that under the assumptions there and in Section 7.3.2 the latter aspect determines the glass type.

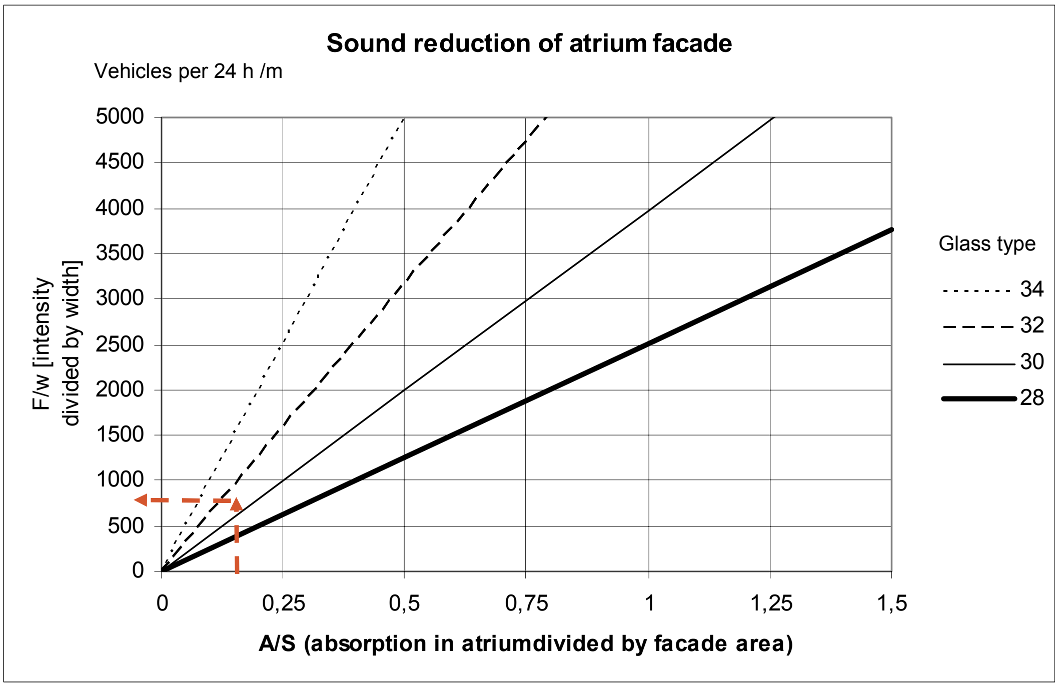


**Figure 60. Example: choice of the glass type in the atrium façade; admissible traffic intensity as a function of the amount of sound absorption in the atrium.**

In an atrium having an amount of sound absorption equal to one fifth of the area of the atrium façade ($A/S$ = 0,2), a glass type **30** dB(A) is sufficient to allow 8000 motor vehicles per 24 hours in a 10 m wide canyon ($F/w$ = 800), as can be read from Figure 60, which is a copy of Figure 39 on page 66. In Table 4 the glass type appears to be 14 mm (PVB-foils).

## *8.5. Comprehensive example canyon*

### *8.5.1. Canyon outline*

In the canyon as shown in Figure 61 the application of the tools for shielding, aperture, façades and atrium will be demonstrated. Roughly it is expected that the traffic intensity in the canyon is less than 10.000 vehicles/24h, but certainly below 15.000.

The canyon buildings are 15 m high. The hinterland residential area starts 30 m from the rear of the canyon buildings. Distances from the street façade are 40 m (P) and 50 m (Q). The normative allowable traffic intensity is then 47.000 (see Figure 23 or Figure 55).

*8.5.2. Building P.*

In building P an aperture is planned, 2,6 m wide, 3 m high; the area is 7,8 $m^2$. The shortest distance to dwellings, measured from the rear of the opening is 30 m. The *F.S*-value is then 170.000 (see Figure 29 or Figure 56); the allowable traffic intensity is 170.000/7,8 = 21.800. The noise contribution of the aperture adds up to the amount already expressed in the number of 47.000 vehicles. The admissible number regarding the limit of $L_{den}$ = 50 dB(A) is calculated with equation [7] and is almost 15.000. This value matches the traffic expectations.

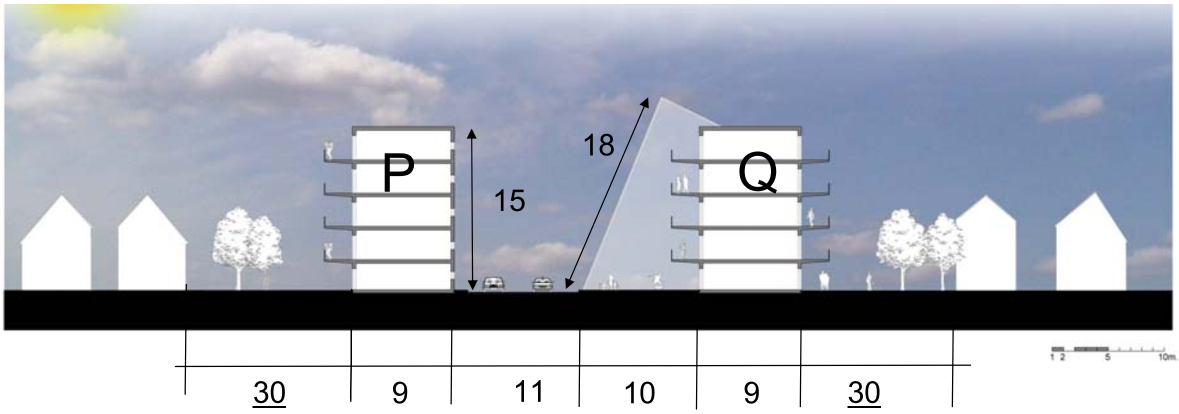


**Figure 61. Example canyon, with dimensions in meters.**

The noise exposed (North) façade of building P is designed to have a glass percentage of 30; laminated glazing with a large air gap, $R_{A,tr}$ = 39 dB(A) (see Table 3 on page 63) is chosen here. In Figure 38 or Figure 59 an *F/w*-value of 1000 is read. Hence, the allowable traffic intensity is 1000 x 11 = 11.000 veh/24h. Of course, if no noise sensitive rooms are situated behind the noise exposed façade, the required sound reduction is much lower, and can be disregarded in this stage of design.

*8.5.3. Building Q*

Half of the (inner) façade of building Q has a sound absorbing finishing, perforated wooden panels with mineral wool; absorption coefficient of 50%. Further this is a standard façade; sound reduction 20 dB(A) relative to the spectrum of standard traffic noise.

The amount of sound absorption [$A_a$], the area of the atrium façade [$S_c$] and the atrium floor area [$F_a$] are all expressed for a section of 1 m building length; the ratios $A_a/ S_c$ and $A_a /F_a$ are dimensionless.

- $A_a$ = 15 x 0,3 = 4,5 m$^2$
- $S_c$ = 18 m$^2$
- $F_a$ = 10 m$^2$

- $A_a/ S_c$ = 0,25
- $A_a /F_a$ = 0,45

In Figure 39 or Figure 60 an $A/S$-value of 0,25 and glass type **30** yield an $F/w$-value of 1000, and a corresponding allowable traffic intensity of 11.000 motor vehicles per 24 h. The glass type can be found in Table 4 on page 65: thickness 14 mm, PVB laminated.

The value of the ratio $A_a /F_a$ = 0,45 is smaller than the target value of around 1, as stated in Section 7.4.4 on page 76. Depending on the type of functions in the atrium, extra sound absorption is advisable to reduce the risk of high internal sound levels caused by the occupants; an additional advantage is that glass with a lower sound reduction index can be chosen.

#### *8.5.4. Conclusion*

The canyon described above can accommodate a traffic flow of 11.000 veh/24h; the building masses as such allow a much larger flow: 47.000 veh/24h.

First the aperture causes a reduction of the admissible traffic flow to 15.000 veh/24h. Moreover, the choice of the type of glazing decreases this value to 11.000 veh/24h.

It is advisable to increase the amount of sound absorption in the atrium, to reduce the chances of high noise levels caused by occupants; at the same time the traffic noise level are reduced.

Apparently a 15 m high canyon is already high enough to give effective noise reduction in the hinterland. Avoiding apertures and choosing highly sound insulating glazing can increase the admissible traffic flow.

### *8.6. Balconies in Poptahof: acoustical privacy*

One of the practical problems studied by DIOC as an integration project was the Delft neighbourhood Poptahof, built in the 1960's and now in need of renovation; see Figure 62. The aspect of speech privacy and the application of the required masking sound level $L_{mn}$

(see Section 7.5.1) were a part of that study, although traffic noise control as such was not an item. Apart from the interior changes, an enlargement of the balconies was considered; see Figure 63 and Figure 64. A second change that might affect the quality of the balconies was the creation of duplex apartments; the odd floors would lose their balconies, thus doubling the vertical distance between the balconies; see Figure 65. A major factor in the sound transmission between balconies in vertical direction is the height of (the closed part of) the parapets. Variants with sound absorbing ceilings (absorption coefficient 75%) were considered as well. In all options the positions for source and receiver were chosen 0,5 m in front of the façade, 1 m high, 4,35 m from the separation in the present situation; where the new balconies are adjacent a distance of 1,9 m from the separation is taken. For the options discussed, the required masking sound level $L_{mn}$ was calculated; the results are given in Table 10.

**Figure 62. Poptahof, rear façade with balconies.**

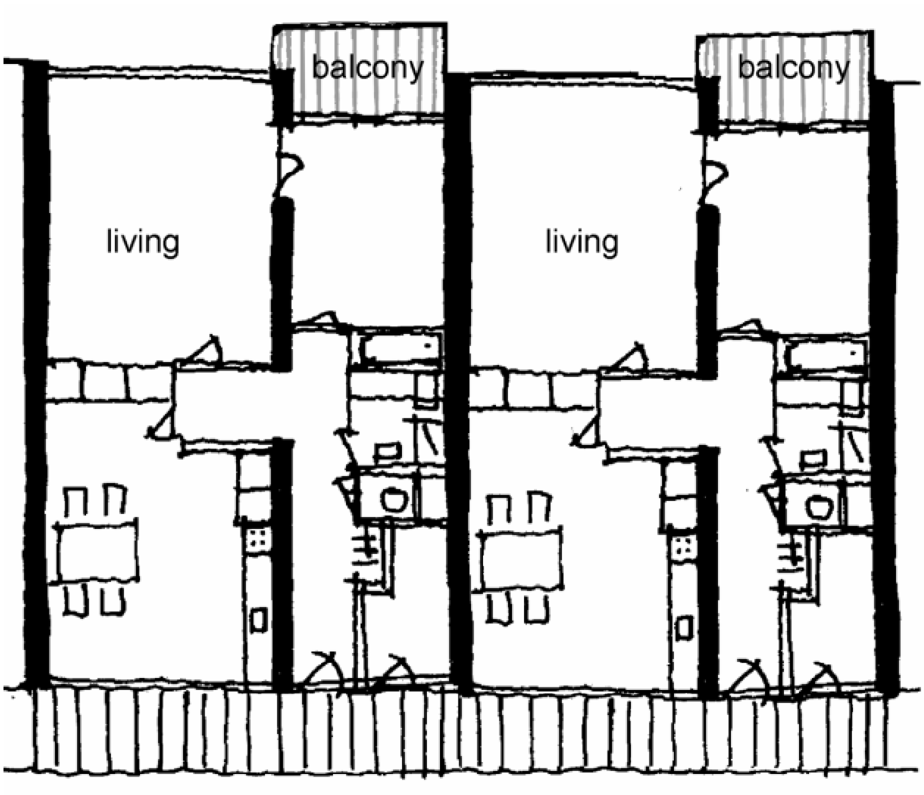


**Figure 63. Present floor plan Poptahof apartments.**

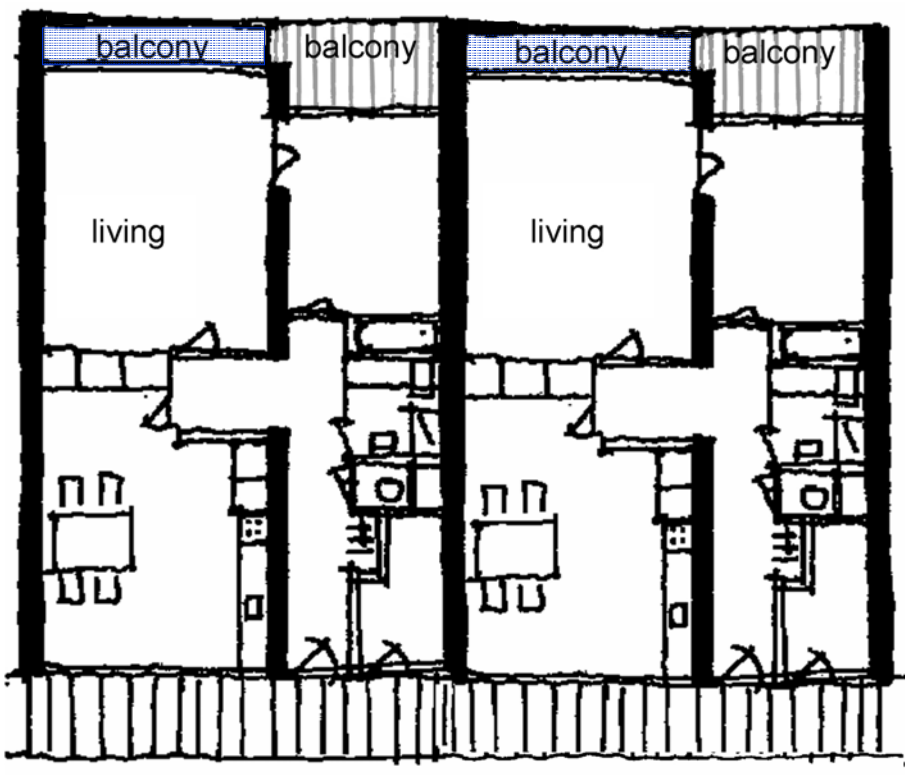


**Figure 64. Floor plan apartment with extended balconies.**

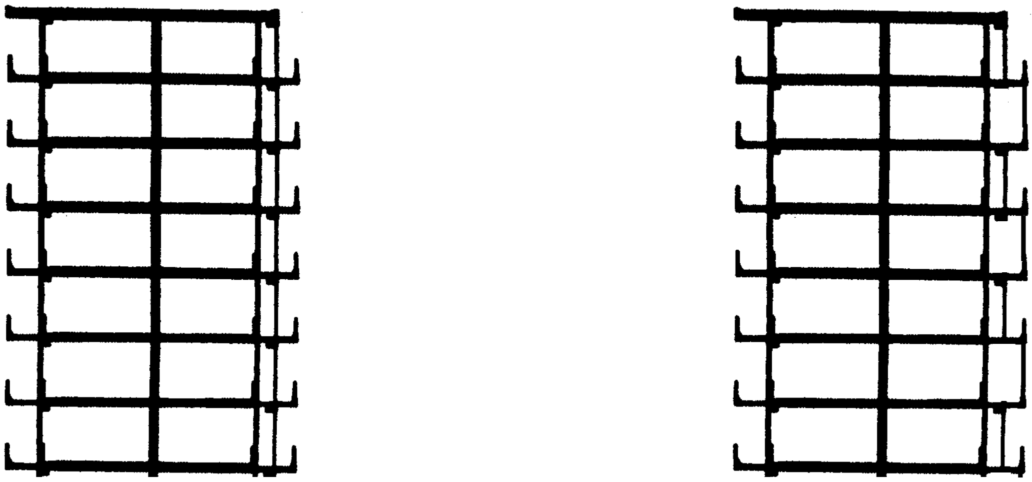

**Figure 65. Present cross section (left) and alternative option.**

| **Description** | $L_{mn}$ |
|---|---|
| Horizontal, present situation | 46 dB(A) |
| Horizontal, type AA, BB | 49 |
| Present, open balustrade | 50 |
| Present, parapet 0,5 m closed | 48 |
| Present, parapet 1,0 m closed | 46 |
| Narrow balcony, open balustrade | 55 |
| Narrow balcony, parapet 0,8 m closed | 52 |
| Narrow balcony, parapet 0,8 m closed, ceiling | 50 |
| Duplex, narrow balcony, open balustrade | 49 |
| Duplex, narrow balcony, parapet 0,8 m closed | 46 |
| Duplex, narrow balcony, parapet 0,8 m closed, ceiling | 44 |

**Table 10. Required masking noise level $L_{mn}$ for several alternative balcony arrangements.**

The first two options concern horizontal relations; they are less critical than the others, which are all vertical relations. At present the speech privacy must be judged as insufficient. The plans with narrow balconies (Figure 64) make the matter worse. Adding a sound absorbing ceiling and changing the balustrades in closed parapets can mitigate this. In the duplex situation distances are larger, and better privacy is feasible; with the measures mentioned, even a significantly better speech privacy than the present situation can be obtained.

## *8.7. "Spoorzicht" dwellings*

The next example was chosen for two reasons: it shows the application of an uninterrupted (front) row of dwellings as a noise barrier for the dwellings behind. Secondly, the noise source in this case is a busy railroad with a large percentage of freight trains, which causes vibrations as well. Therefore vibration reducing measures were found to be necessary.

*Note*. The property developer decided, after completion of the design, to switch to a different type of bungalows, so the project will not be built according to this design, although the principles of noise barrier and vibration reduction remain.

In Elst (The Netherlands), a new residential quarter was planned on a terrain next to the railroad Arnhem-Nijmegen; see Figure 66. This site gave rise to the name: Spoorzicht (Dutch for "Railway view"), and indicated that the trains would be visible from the houses. Calculations of the noise load from passing trains yielded very high values (maximum $L_{den}$ over 75 dB(A)). Therefore a continuous row of dwellings in the front line, nearest to the railroad was given a function of shielding the houses in the hinterland. A height of 6,8 m (see Figure 66) was the a priori established condition for this function.

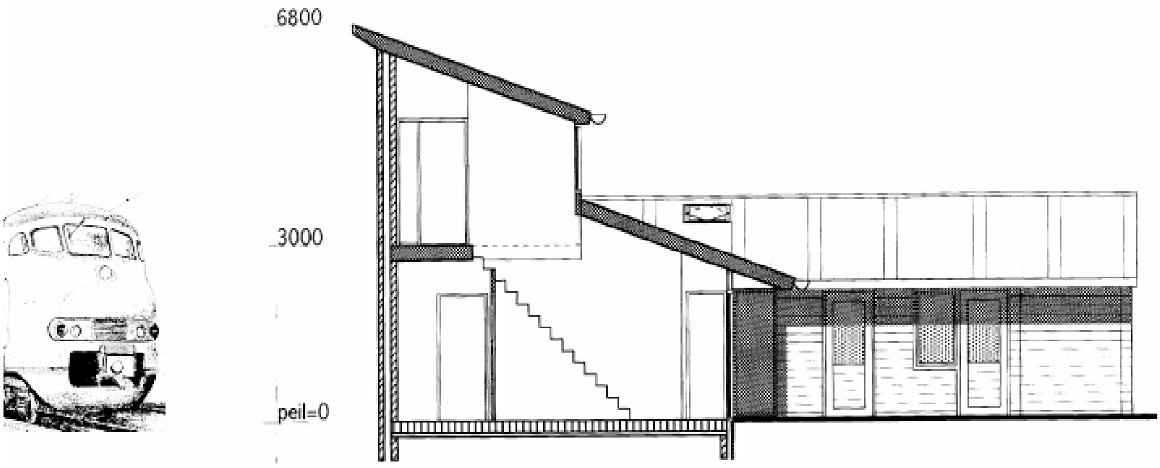


**Figure 66. Section of the "Spoorzicht" dwellings in Elst.**

### *8.7.1. Vibration control*

To gain more information about the risk of annoying vibrations caused by passing trains, measurements were made by Peutz consulting engineers. From these measurements in the field there appeared to be a great risk of annoyance. The measurements of the vibrations caused by passing trains of the relevant types were carried out in January and February 2000, literally in the field, on pins driven into the ground at 15 m and 50 m distance from the axis of the track-system. The time-averaged vibration velocity, frequency-weighted with the KB-filter according to German standard DIN 4150 (1992) were calculated, taking into account the prognosis for 2005/2010 of the numbers of passing trains per type. Maximum values are 0,19 mm/s at 15 m and 0,04 mm/s at 50 m distance.

The transmission of vibrations from the ground to the dwellings is a complicated phenomenon. Roughly the velocities in the dwelling construction are calculated to be 1,5 times those measured in the ground. The resulting values for the front line dwellings at 15 m distance are too high judged by the standard DIN 4150. Therefore measures were advised to reduce the vibration velocities in the dwellings.

Between the foundation piles and the concrete foundation frame, resilient, rubber mountings were to be inserted. A vertical resonant frequency of about 10 Hz of the resulting mass-spring system was calculated to give sufficient attenuation of the ground vibration. The whole house acts as the "mass", resting on the "springs" in the foundation system. The rubber mountings would entail horizontal resonant frequencies much below 10 Hz. In this way the whole house is protected against intruding train vibrations.

#### *8.7.2. Required masking noise level*

The dwellings have gardens, separated by a low-rise extension of the house (garage or study). For several positions of source (speaker) and receiver the required masking noise level (see Section 7.5) was calculated. The resulting values are around $L_{mn}$ = 35 dB(A). This agreeable value arises from the presence of the garages between the gardens. Not only do the garages shield the gardens from each other, also the distances are increased.

### *8.8. Barrier dwellings: traffic noise and acoustical privacy in practice*

In the last few years several special residential projects were built near roads and railroads. The noise-exposed façades of all of these dwellings were designed to be highly sound insulating, or even "deaf" or missing. Their rear façades are quiet. A façade is called "deaf" in the context of the Dutch Noise Abatement Act if it has a high sound reduction index, and is non opening; fixed windows are allowed. Further, a building can be integrated in a sound barrier/mound; in such a case the noise-exposed façade is missing. In all cases an interior sound level of $L_{den}$ = 37 dB(A) is obeyed, and a quiet façade and quiet exterior space are present. The noise control objectives are obviously met.

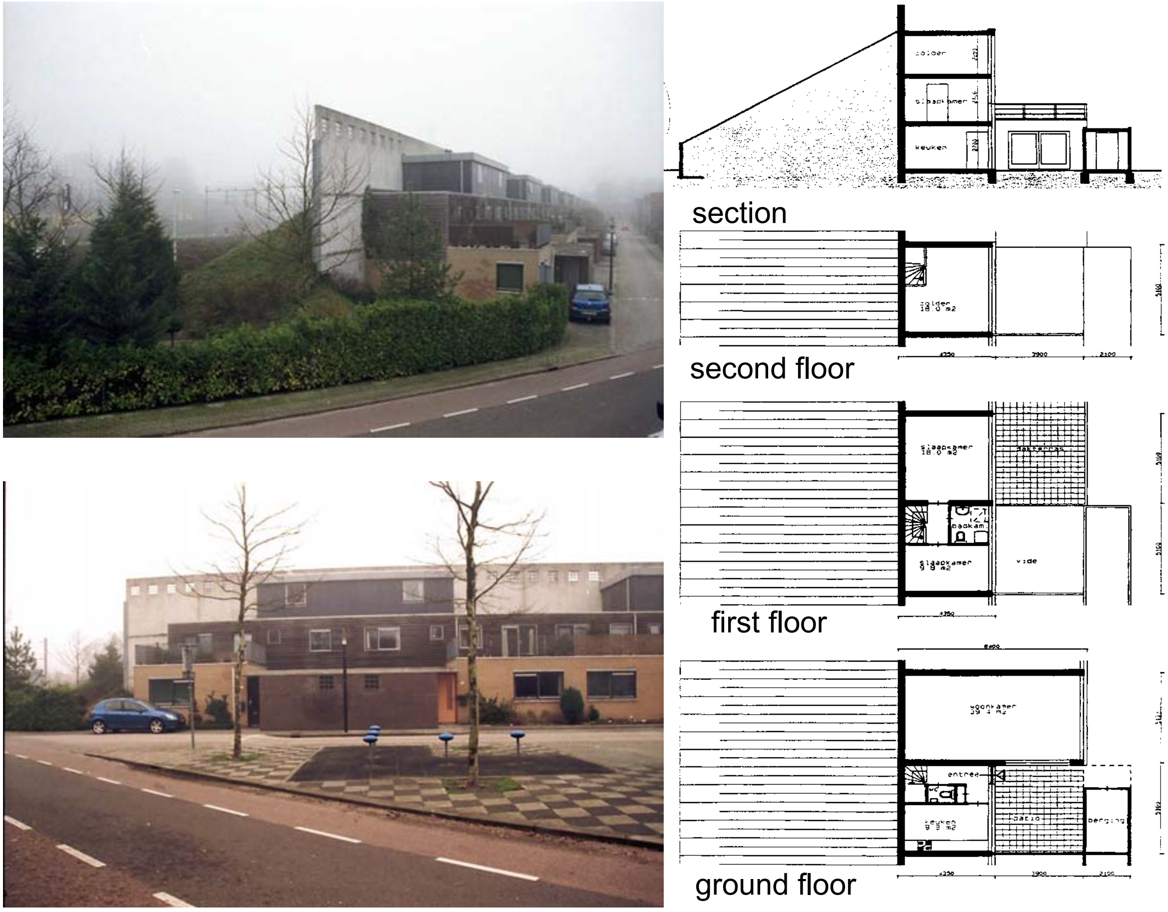


**Figure 67. Utrecht, de Groene Lunet (design: SAS architecten, Rotterdam).**

Not surprisingly, a social survey by Brugge et al. (1996) shows positive experiences of the occupants of the dwellings with regard to the reduction of traffic noise. However, the sound annoyance caused by neighbours (noisiness or lack of speech privacy) is notable. In Table 11 this is shown. The column "Lack of privacy" is not limited to speech privacy, but includes other aspects like visual privacy as well. The last column of Required Masking Noise Levels $L_{mn}$ (see Section 7.5) was calculated from the available sketches of the buildings with their balconies and roof gardens. In each case the difference in path length was determined for the transmission from speaker to listener, and for the reflected speaker and listener as well. The attenuation was calculated as pointed out in Annex B.5, and for the $L_{mn}$-values formula [16] was applied.

These values can be judged using Figure 49. The values of $L_{mn} \geq 50$ dB(A) indicate insufficient speech privacy; the values of $L_{mn} = 45$ dB(A) are marginal. These results are in agreement with the response of the tenants.


**Figure 68. Nieuw-Vennep, de Meerval (design A. Venema, Dordrecht).**

| Project | Neighbour noise annoyance [%] | | | *Very* *annoying [%]* | Lack of privacy [%] | $L_{mn}$ [dB(A)] |
|---|---|---|---|---|---|---|
| | *often* | *sometimes* | *seldom* | | | |
| Utrecht *Groene Lunet*, Figure 67 | 0 | 13 | 87 | 27 | 43 | 56 |
| Nieuw-Vennep *Meerval*,Figure 68 | 18 | 53 | 29 | 55 | 39 | 50 |
| Groningen *Kalverstraat*, Figure 69 | 4 | 38 | 58 | 48 | 16 | 50 |
| Amsterdam *Droogbak*, Figure 70 | 17 | 52 | 31 | 59 | 20 | 45 |
| Etten Leur *Albatros*, Figure 71 | 9 | 27 | 64 | 45 | 18 | 45 |

**Table 11. Results of a social survey into (speech) privacy in some projects of barrier dwellings.**

These projects show, that lack of acoustical privacy can work out negatively on the reported quality of such dwellings. Probably the exposition to traffic noise has taken all the attention, leaving this aspect underexposed.

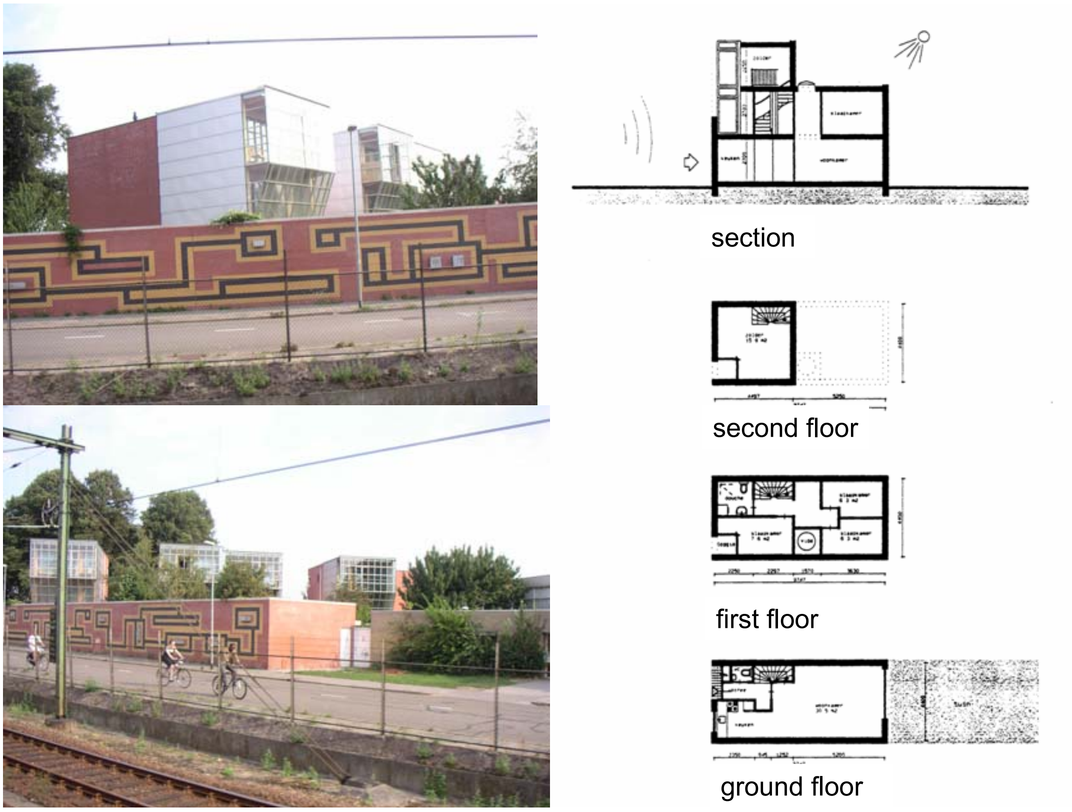


**Figure 69. Groningen, Kalverstraat (design: Architectenbureau Oving, Groningen).**

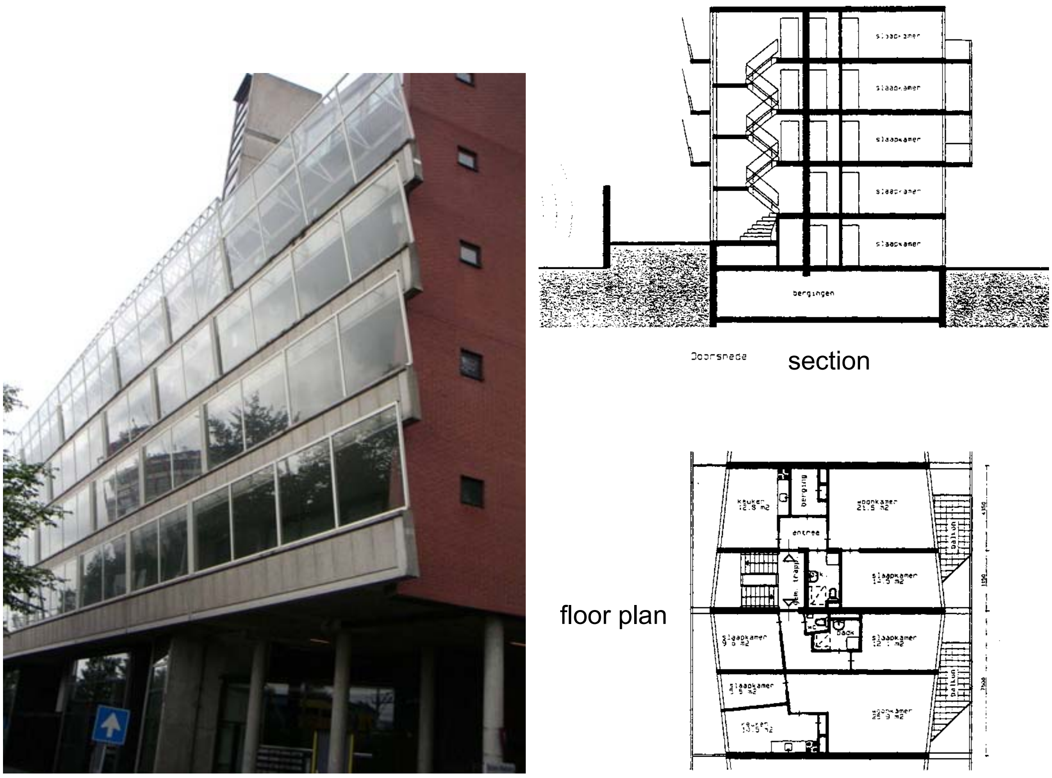


**Figure 70. Amsterdam, Droogbak (design: Rudy Uytenhaak, Amsterdam).**

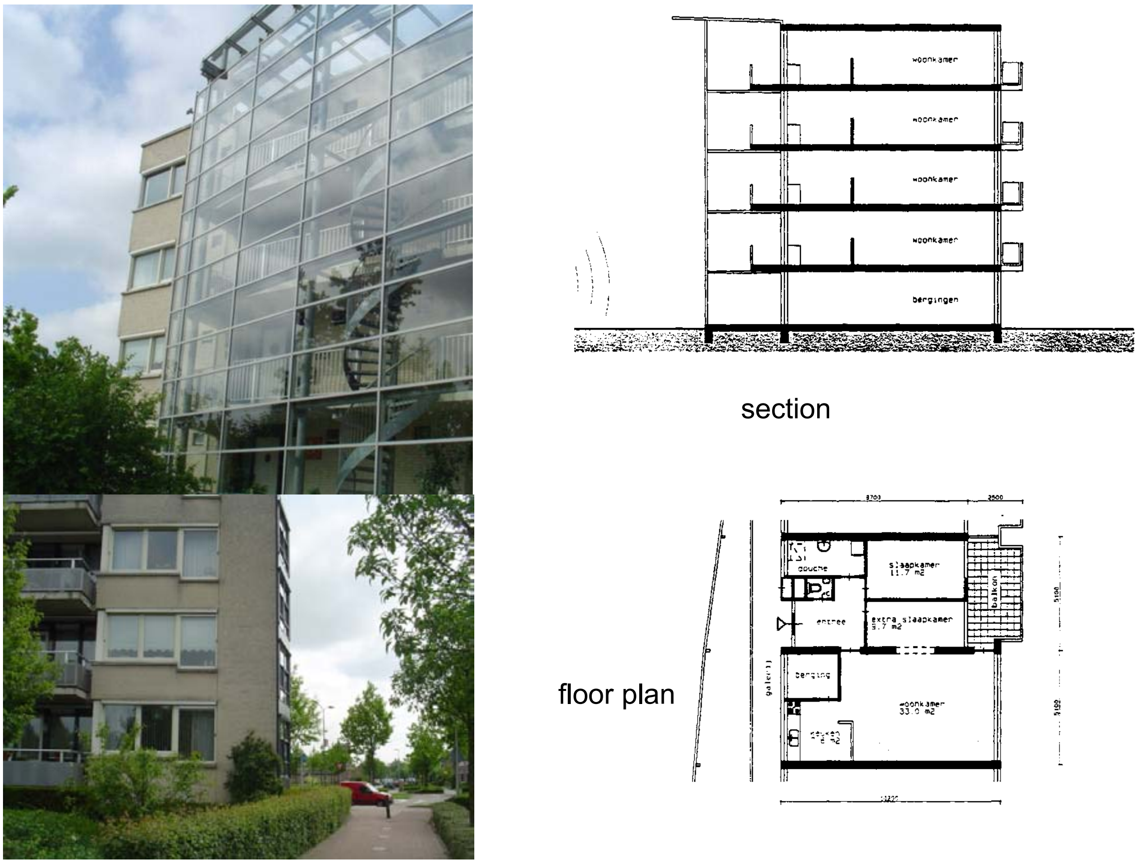


**Figure 71. Etten-Leur, Albatros (design: Van Ardenne Partners Architecten, Arnhem).**

### *8.9. Hedonic pricing of a fictitious residential area with several noise barriers*

High noise loads decrease the value of dwellings, as was shown in Section 2.3. Next it would be useful to have a comparison of the value of a certain area (lot) for several options of noise abatement in casu different barriers. The following simplified approach may be chosen to that purpose.

The initial value of a lot is set equal to the value of the buildings (dwellings) it can bear minus the building cost. The initial value is decreased by the loss of livability as expressed in hedonic pricing (Section 2.3.) and the cost of the noise barriers. This corrected value is the rating value. For the noise depreciation 0,5% per dB(A) in excess of 50 dB(A) seems reasonable, but of course other values can be chosen if appropriate, or even a quadratic function like the curve in Figure 4.

As an example, from a very long main road a section of 100 m length is considered. It is a "standard" road with 10.000 vehicles per 24 hours, as defined in Section 6.2. The 50 dB(A)-contour sits at 400 m from the axis of the road. In the absence of a canyon building; see Figure 72 (upper part), with or without a barrier, the area between 10 m and 400 m from the axis of the road is allocated to general residential use. Barriers of different heights are considered: 1 to 6 m. The last option is a canyon, 10 m high, 10 m wide; see Figure 72 (lower part). The canyon building, 100 m long, contains 30 apartments. The area just behind the canyon is designated "non-residential", being in its shadow zone: in this 25 m wide area dwellings would not receive sufficient sunshine, at least at moderate latitudes. In this case the residential strip is between 45 m and 400 m. The density of dwellings in this strip is set at 25 or 50 per hectare ($10^4$ $m^2$). The total number of dwellings in the strip is then 97 or 195. They are arranged in such a way, that shielding has no influence on the noise load of each dwelling.

The following prices have been assumed:

- Dwelling, apartment € 250.000
- Building cost 60% of price
- Extra glass façade in case of canyon building 500 €/$m^2$
- Noise barrier 700.000 € + 500 €/$m^2$

In a spreadsheet program, the noise loads and the depreciation of all the dwellings were calculated. The noise depreciation of the canyon building was set at 2,5% – because a zero value seems too optimistic – , based on a fictive sound load of 55 dB(A). The noise load on the dwellings nearest to the road in the non-canyon cases can be as high as 70 dB(A), in particular if no or low barriers are applied; actual regulations might prohibit these dwellings in a strip nearest to the road, depending on the actual noise limits. This effect was not taken into account, to keep the comparison as generic as possible. Otherwise, the hedonic prices of the non-canyon cases would have been lower.

The results of the calculations for this example are presented in Table 12. Prices are in M€ (millions of Euros). The base value is the selling price of the dwellings, neglecting the effect of the noise load. The hedonic value of the land is calculated by subtracting from the base value:

- the building cost (60% of base value)
- the noise depreciation
- the barrier cost

The cost of the extra façade in the canyon-case is recorded under "barrier cost".

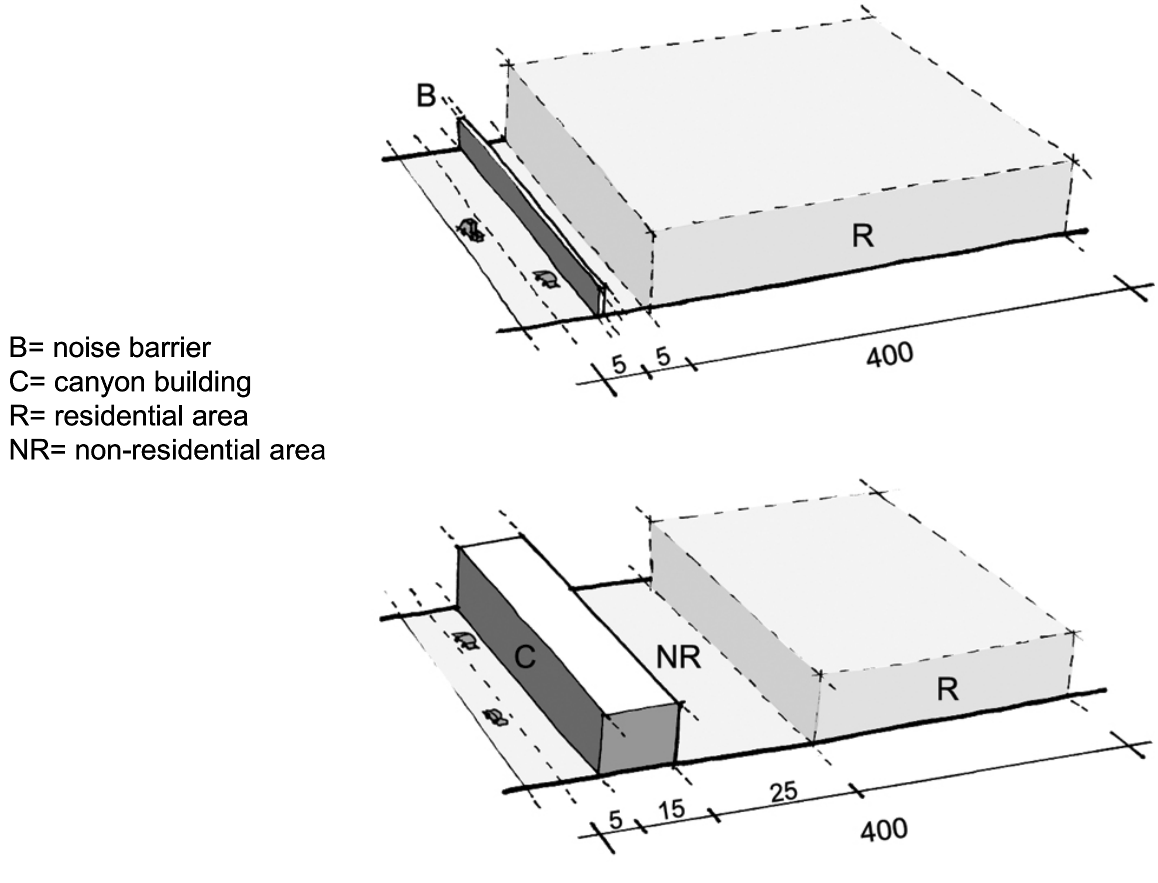


**Figure 72. Section of a road with barrier (upper part) and with canyon building (lower part); land use indicated.**

The table shows that for both variants of dwelling density (50 and 25 per hectare) the hedonic value is higher in the case of canyons. The main cause is the realisation of more dwellings; the noise depreciation is not dominant. Variations in the cost parameters do not change these conclusions. A somewhat higher or lower noise load has little influence on the prices and no influence on the conclusions.

| Options<br>50 dwellings/ha | Number of dwellings | Base value | Noise depreciation | Barrier cost | Hedonic value |
|---|---|---|---|---|---|
| canyon | 207 | 51,75 | 0,19 | 0,5 | **20,01** |
| Barrier 6 m | 195 | 48,75 | 0,05 | 1 | **18,45** |
| 5 m | 195 | 48,75 | 0,10 | 0,95 | **18,45** |
| 4 m | 195 | 48,75 | 0,15 | 0,9 | **18,45** |
| 3 m | 195 | 48,75 | 0,28 | 0,85 | **18,38** |
| 2 m | 195 | 48,75 | 0,50 | 0,8 | **18,20** |
| 1,5m | 195 | 48,75 | 0,73 | 0,775 | **18,00** |
| 1 m | 195 | 48,75 | 1,28 | 0,75 | **17,48** |
| None | 195 | 48,75 | 1,45 | 0 | **18,05** |
| **25 dwellings/ha** | | | | | |
| Canyon | 117 | 29,25 | 0,19 | 0,5 | **11,01** |
| Barrier 6 m | 97 | 24,25 | 0,03 | 1 | **8,68** |
| 5 m | 97 | 24,25 | 0,05 | 0,95 | **8,70** |
| 4 m | 97 | 24,25 | 0,08 | 0,9 | **8,73** |
| 3 m | 97 | 24,25 | 0,13 | 0,85 | **8,73** |
| 2 m | 97 | 24,25 | 0,25 | 0,8 | **8,65** |
| 1,5m | 97 | 24,25 | 0,38 | 0,775 | **8,55** |
| 1 m | 97 | 24,25 | 0,65 | 0,75 | **8,30** |
| none | 97 | 24,25 | 0,73 | 0 | **8,98** |

**Table 12. Calculation of a hedonic value of land, in M€ (Example).**

The canyon principle appears to be supported by this hedonic exercise. In the case of a density of 50 dwellings/ha, the hedonic value does not support the application of noise barriers less than 2 m high; only higher barriers are effective, and the canyon principle most of all. In the other case (25 dwellings/ha) only the canyon solution appears to be effective, with regard to hedonic pricing.

# 9. Review of the tools

## *9.1. Position of the tools*

As a first, rough approach in the conceptual stage concerning the application of urban canyons one could – specific information yet lacking – act purely qualitatively:

- Erect high canyon buildings, and make them uninterrupted
- Make the sound reduction of the building façade and atrium façade high
- Apply sound absorbing surfaces in atria
- Keep distance between balconies, terraces et cetera and use closed privacy screens

In this way the outcome is uncertain. Maybe the resulting noise levels are excessive, or privacy insufficient; maybe it appears that some of the measures are overdimensioned. The tools under discussion here are meant to give a more rational and quantitative basis to decisions regarding the application and design of urban canyons, still in a conceptual phase of design.

Later, when the required specific information is available, the calculations of screening effect, sound reduction of façades, et cetera will be done with the appropriate means, with greater accuracy, and in more detail. Calculation methods are available to that end, but are not the subject here.

In Chapter 8 the examples and applications show how the tools can be used, and that they can fulfill the function they were developed for.

## *9.2. Overview of tools*

A tentative inventory of tools that were used in the realm of sustainable building by participants of DIOC-DGO (see Chapter 1.1) was made by Müller et al. (2003); this concise list of tools, also enables a comparison of the essential characteristics of the tools. The same way of description is applied in Table 13, where only the tools from this research are discussed.

| Name | Output | Benefit | Input | Procedure | Example | Criterion base |
|---|---|---|---|---|---|---|
| *PAI* (Population Annoyance Index) (Section5.2) | *PAI*: a single number expressing the total traffic noise annoyance perceived by the inhabitants of an area near a road | Comparing the effect of shielding or other measures, comparing the impact of different alignment of roads | Sound levels on all residences in the area (or traffic data, incl. road surface), locations of residences, shielding and reflecting objects, ground | a) | Section 5.2.2 Section 8.1 | Response functions for traffic noise in residential areas |
| Canyon shield (Section 6.1) | Admissible traffic intensity for "quiet hinterland" | First estimate of shielding result of canyon | Height of canyon buildings and distance to street façade | b) | Section 8.2 Section 8.5 | Noise load $L_{den}$ = 50 dB(A); shielding Fresnel/Maekawa |
| Aperture in canyon building (Section 6.3.2) | Admissible traffic intensity and size of aperture for "quiet hinterland" | First estimate of acceptability of "holes" in canyon building | Distance from aperture | c) | Section 8.2 Section 8.5.2 | Noise load $L_{den}$ = 50 dB(A);diffuse sound field in canyon |
| Elevated canyon building (Section 6.3.4) | Admissible traffic intensity for "quiet hinterland" | First estimate of acceptability of elevated canyon building | Distance from mound, length of deck | d) | Section 8.2 | Noise load $L_{den}$ = 50 dB(A);diffuse sound field in canyon, sound attenuation in space under building |
| Façade glass (Section 7.1.2) | Admissible traffic intensity in canyon | Estimate of required façade construction | Type of glazing, percentage of glass | d) | Section 8.3 Section 8.5.2 | Interior sound level ($L_{den}$ = 35 dB(A) |
| Atrium façade ( Sections 7.1.3 and 7.3.2) | Admissible traffic intensity in canyon | Estimate of required atrium façade construction | Type of glazing , absorption in atrium | d) | Section 8.4 Section 8.5.3 | Interior sound level ($L_{den}$ = 35 dB(A)) Atrium sound level ($L_{den}$ = 55 dB(A)) |
| Lombard absorption (Section 7.4) | Required amount of sound absorption | Guideline for architectural noise control in atrium | Number of occupants, or accessible area and destination | Not applicable | Section 8.5.3 | Speech communication in conversation circles; S/N-ratio |
| $L_{mn}$ (Required Masking Noise Level) (Section 7.5.1) | (Notional) required masking noise level | Reduction of annoyance from neighbour balconies (= partial indicator of livability) | - Dimensions and positions of balconies, terraces, privacy screens etc. - Acoustical properties of constructions (e.g. parapets, ceilings) | e) | Section 8.6 Section 8.8 | Speech privacy; S/N-ratio |

a) The number of "annoyed people" per dwelling is calculated from noise load, response function and mean number of occupants; the summation over all residences yields the *PAI*
b) In a graph the output can be read directly
c) In a graph the product of intensity and size *F.S* can be read directly
d) Admissible traffic intensity can be found by multiplying *F/w*-value read from graph, by width of canyon, and compared to expected intensity
e) Calculation of sound transmission from speaker to neighbour, judgement based on speech intelligibility

**Table 13. Overview of the tools addressed in this study.**

The columns *Output*, *Benefit* and *Input* (see also Section 1.1) can be used to define the qualities of the tools. *Output* is mentioned first, to allow the user to judge its potential use. *Benefit* answers the question; "What can I do with the results?" The *Input* gives an indication of the effort it takes to "operate" the tool: how many data, are they available, do they need pre-processing et cetera?

In the column *Procedure* a pointer to a concise description of the "interior of the black box" is given, and in the column *Criterion base* the main implicit criteria of each tool; more information can be found in the sections stated in the first column.

The output of each tool is a single number, which is simple to interpret, and unambiguous. The benefit is clear and related to goals in urban planning, design and architecture. The input consists of data that are easily available in early design stages.

### *9.3. Reliability and accuracy of tools*

The tools are based on principles from physics, from social sciences and from other empirical sources. Physics can be regarded as very reliable and accurate; classical physics – the branch acoustics belongs to – in particular. Social science is concerned with human behaviour and properties, and can give reasonable predictions as long as large groups of people are the subjects; accuracy is nevertheless not comparable to physical accuracy. Empirical data embrace technical properties of materials (sound absorption, sound reduction) and sound emission of flows of vehicles. The practical accuracy will be between those of physics and social sciences.

For the tools under consideration, the dependence on the sources of theory and data can be summed up as follows.

| Name tool | From physics | From social sciences | Empirical data |
|---|---|---|---|
| *PAI* (Population Annoyance Index) | | Response functions for residential traffic noise | |
| Canyon shield, aperture, elevated canyon building | Sound transmission | | Sound emission of vehicles |
| Façade glass | Sound transmission | | Sound reduction of materials |
| Lombard absorption | Room acoustics, speech communication | Speech communication | |
| $L_{mn}$ (Required Masking Noise Level) | Sound transmission | Speech communication, noise annoyance, privacy | |

**Table 14. Origins of the basic elements of the tools.**

Apparently none of the tools depends on physics only, but at least partly on social science or empirical data. The reliability and accuracy of physical models in general may be very high. In applied and building acoustics accuracy is significantly lower and a margin of ±1 dB for measurements and calculations is regarded as sufficient. The results of calculation models for sound transmission (traffic noise models, façade sound reduction) are usually within ±2 dB from measured values.

The acousto-social tools are all physical quantities, distilled from well defined experiments with many test subjects in the laboratory, or in the field. The measured physical values can be as accurate as stated above. The response of the test subjects usually shows an inter-individual spread, for example in test of speech communication. In field tests however the measured response is influenced by many known and unknown factors; the spread may be much larger then. This is shown in Figure 73, regarding responses to community noise. For a given sound level e.g. 60 dB(A) the reaction can vary from *none* to *widespread complaints,* whereas *widespread complaints* are noticed for sound levels between 60 and 70 dB(A). Although the trend is clearly present, the spread is considerable.

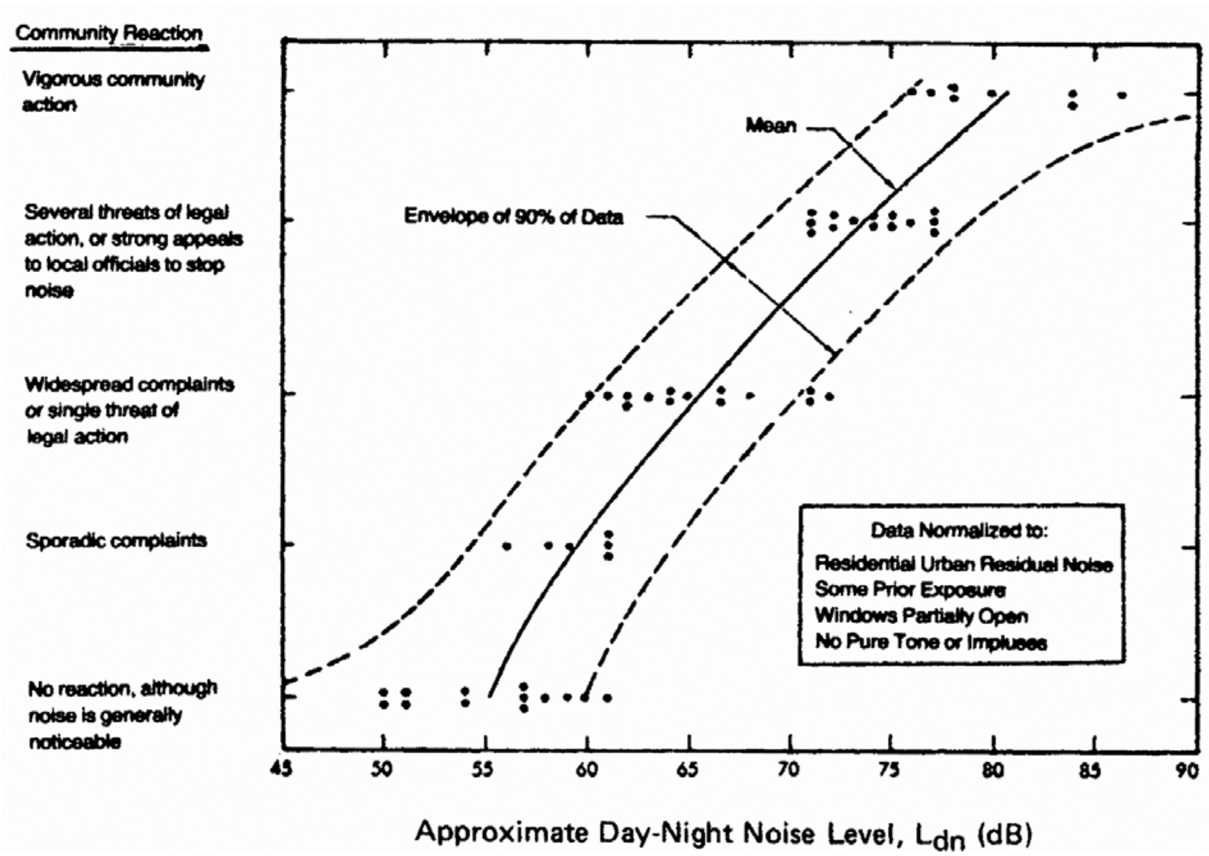


**Figure 73. The spread in a noise response function may be considerable, from Eldred (1974).**

A distinction can be made between acousto-social tools, based on laboratory experiments – like speech communication – and those based on field data – like residential noise response. The last group is the least accurate.

Indicators of speech communication can be determined in a rather exact manner, expressed in fundamental metrics like Speech Transmission Index *STI* (Steeneken and Houtgast, 1999), Articulation Loss of Consonants $AL_{cons}$ (Peutz and Klein, 1973), or Articulation Index, *AI* (ANSI

S3.5, 1997). Whether real life conversation can be understood is influenced by several additional factors like familiarity with the subject, speech quality (articulation), visual clues etc. These factors cause considerable deviation in subjective judgment. The indicators are regarded as valid for the average speaker and listener. The complement of speech intelligibility is speech privacy. Here the same considerations apply.

Concluding: none of the tools described here may claim a high level of accuracy. The context of their use however does not require this. For final calculations in later stages of urban and architectural design, more complex and accurate acoustical methods are available instead of *Canyon Shield* and *Façade Glass*. The other tools are based on the response of people and the spread is more fundamental in these cases. For *PAI* a more accurate alternative does not seem necessary.

Furthermore, application of the tools in practice may indicate the need for certain adaptations; this is inherent in the learning cycle as discussed in Section 1.1.

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# 10. Additional aspects

## *10.1. Air quality, requirements for urban planning and design*

Noise is not the only pollutant caused by road traffic; vibrations play a minor part; see annex C.4. Emissions of gaseous and particulate matter ("fine dust", e.g. from diesel engines) by vehicles, however, are relevant. Concentrations of several agents near the road depend on the magnitude of the emissions, the dilution and background concentrations, and can sometimes reach harmful values.

For each agent, the emission of each vehicle depends on many variables, and is hardly predictable. The average emission of a traffic flow however can be predicted with reasonable accuracy (Pronello and André, 2000; Power and Baldesano,1998), based on the numbers and types of vehicles and their speeds.

The dilution is determined by convection and diffusion, or: airflows and distance, and is not necessarily similar for all agents. The wind itself must be described as a time variant vector field: velocity and direction are dependent of position and time. Although several models for the calculation of the dispersal exist, no manageable model is known that gives reliable results in complex built up situations like dense urban areas. The models of street canyons (Berkowicz, 1998) are usually aimed at concentrations of agents in the canyon, and not at the area behind the buildings.

Not only the wind, but also the traffic flow varies in time. Consequently, concentrations of gases and $PM_{10}$ vary in time. This variation makes the choice of a characteristic quantity necessary, derived from the time-varying concentrations. Averages or percentiles can be defined, with different averaging times. (In noise control the same circumstances lead to the definition of equivalent sound level $L_{eq}$ and statistical values $L_x$. See Annex C.3).

| Agent | Hourly average | | | 8 hours average | 24 hours average | | | Year average | Winter average |
|---|---|---|---|---|---|---|---|---|---|
| | *24 exc.* | *18 exc.* | **P 99,9** | **P 98** | *3 exc.* | *18 exc.* | *35 exc.* | | |
| $SO_2$ | *350* | | | | *125* | | | 20 | 20 |
| $NO_2$ | | *200* | | | | | | 40 | |
| $PM_{10}$ | | | | | | *250* | *50* | 40 | |
| Pb | | | | | | | | 0,5 | |
| CO | | | | 6000 | | | | | |
| $C_6H_6$ | | | | | | | | 10 | |

**Table 15. Limit values for several agents (in μg/m³), Besluit Luchtkwaliteit (2001), [“Resolution air quality”, Dutch law implementing European directives]. The agents are the specified chemical bonds, except *Pb* : a set of plumbic bonds, and *$PM_{10}$* : particulate matter, particles smaller than 10 μm. The *numbers* in italics may be exceeded the specified number of times per year.**

Apart from this, from the viewpoint of public health maximum allowable concentrations are established for several agents. These limit values are expressed in different characteristic quantities; see Table 15 as an example; several ways of averaging are used, and several of the limits may be exceeded the specified number of times per year. These limits can be guarded through more or less continuous measurements (monitoring) at the immission points. Then the required statistical processing of the data can easily be done. A simpler formulation of the criteria for air quality however, would make monitoring and calculations in computer models easier.

Next problem is that the background level is very high in many cases, leaving very little “immission margin” for the emission of the vehicles on the road in study. One of the properties of air pollution is that it consists of a local part, and regional, even global elements. The local part is often hardly relevant, except in “ill-ventilated” areas near sources. It is the regional elements that determine the background level.

The local wind patterns control the dilution of agents. They are influenced strongly by the perimeter blocks. On one hand these can provide shielding to the hinterland, on the other hand locally high concentrations can be the detrimental consequence. The positions of open windows and air intake openings should take the local air quality into account. These effects can be estimated after a wind tunnel test with a scale model of the area in study, and hardly in advance of that.

The presence of certain species of plants in the canyon – integrated in the façades, possibly – can reduce the concentrations of polluting gases and particulate matter (“dust”); the size of the effect is hard to forecast (Varshney et al. 1993). A counter-indication is the circumstance that plants can reduce wind turbulence, and thus decrease dilution of pollutants.

Taken all together, the conclusion seems inevitable that at present no clear requirements for the design of urban canyons can be deduced from the issue of air quality, particularly not in early stages of design. Later on in the specific design process, research can be extended, possibly including wind tunnel tests. In that stage minor adaptations of the plan are still possible. Only after completion of the building project, the final tests can start by means of continuous measurements of relevant agents at certain immission points, but then it is too late for major changes in urban or architectural plans.

Research in 1985 (DGMH, 1985) and more recently (TNO-MEP, 1999), shows that in general the expected air quality behind the canyon buildings is better than it would have been in the absence of the canyon buildings; after all, pollution from the vehicles is mixed in the canyon and released at greater height, where higher wind speeds enhance further dilution. Wind tunnel tests may be employed to optimise the specific canyon and hinterland buildings for air quality.

### *10.2. Mental Barriers*

It is an interesting thought-experiment to consider living in an almost perfectly isolated dwelling, situated in an area with high environmental impact. No noise from the environment would penetrate; air would be conditioned, even filtered if necessary, etc. It is not difficult to realise visual contact with the environment through highly sound insulating and airtight windows. Yet, this type of dwelling is generally not regarded to be acceptable. What is to be added, to make a comfortable living environment? And how is this done, without forsaking the advantages of isolation? How much of the outside world do people need to experience? Is it necessary to feel draught when opening a window? Or smell outdoor fragrances? Do tenants need a place to put smelling objects away (burnt food e.g.)? A low-noise “fume cupboard” (a device in laboratories for conducting certain chemical experiments, provided with strong exhaust ventilation) can be installed instead of a balcony….

It is known that people like to be in contact with the outside world to some extent. For example, dwellings in the vicinity of airports, highly insulated against the high sound level on certain days, can be uncomfortably quiet on days when the noise load is much lower; there can be a large difference in noise loads on different days if various runways are used e.g. to accommodate for varying wind directions. It would again not be difficult to install an electronic system with exterior microphones and concealed loudspeakers in the rooms. The system could simulate the sound transmission into "normal" dwellings until the external sound level exceeds a certain value. Then the transmission is gradually reduced to keep interior sound levels agreeable. This could even be done in a way that would sound rather natural. Technically speaking, the problem can be solved in this way; question is however, if the right problem was solved…

Almost all conceivable, physical demands can be met by technical means. Still, many people do not feel comfortable without natural contact with the environment, and the caprices of the weather. If the design of dwellings starts from these considerations, it might be easier to combine sufficient isolation with quality of life/living, as a compromise between isolation and contact with the environment.

The concept of traffic in canyons, aimed at a high quality of life in the canyon buildings and the hinterland demands a holistic approach, in a technical, multidisciplinary sense and concerning the cooperation between governments, developers and "consumers" (future occupants). The history of the Bijlmermeer – a high-rise example of CIAM-planning in Amsterdam – (Helleman and Wassenberg, 2004) illustrates and underlines this.

### *10.3. Logistic functions*

By definition the canyon buildings are situated close to main roads. In the preceding chapters, these roads were approached as a source of pollution only, almost neglecting their primary function: a means of transport. Transport in general is highly valued. People want to be able to travel easily, organisations aspire excellent accessibility, goods need to be transported. The canyon buildings can play a role in transport of people and freight. Transfer points for persons (commuters) and goods can be integrated in the canyon buildings. Bus lines, underground and surface railroads, taxi stands, bicycle and pedestrian routes can be interconnected here. The space required for transfer, convenience shops, bicycle sheds can all be accommodated in the canyon buildings. Bach and Pressmann (1992) give examples of integration of logistic and other functions, from the perspective of humanizing urban space; noise control is hardly mentioned, however.

Many institutions are studying new systems of transport, often trying to combine the advantages of the efficiency of public transport and the flexibility of private transport. Linking the transport of people and goods, for example in carriers with compartments for containers (freight) and passengers – with or without small (smart) vehicles – can offer new chances. It is expected that these developments will ask for more dedicated transfer points, that may be integrated in the canyon buildings as well. Examples are given by Kristinsson (2002).

# 11. Conclusions and recommendations

That building cities in high densities is necessary to avoid injury of the remaining nature was posed as one premise. "Traffic is necessary" is another one. Although transport by underground, or otherwise encapsulated modalities is imaginable, it is improbable that polluting vehicles (noise, gases) will be phased out in the near future. The combination of high-density cities and surface traffic leads to the concept of accommodating the traffic in "canyons" as a useful concept that is worth considering. The main reason is, that canyons yield effective sound reduction and the canyon buildings themselves contribute to the high density of useful buildings.

Tools are required to increase the chances of the canyon concept, tools that can give insight in the consequences and opportunities in the early stages of urban design. In particular such tools regarding noise control lack. The research described here was aimed at the development of appropriate tools. It was shown, that these tools can make a contribution to the goal of building in high density near roads. In the framework of the transdisciplinary loop (see Section 1.1) the tools are in a first stage of development, in the inner loop; feedback from practice – the outer loop – will be the next stage. It may be necessary to complete several loops in order to finish the tools.

The presence of a design concept and tools is a necessary condition for the application of urban canyons, but not a sufficient one. Designers will have to explore the possibilities and limitations, and convince decision makers of the advantages. Citizens will have to be involved in the planning, implementation and pass a final judgment upon the new urban canyon. Noise control of course is not the only aspect of the quality and livability of the urban canyon and its surroundings. Wind climate, daylight, sun and shade too are relevant physical elements. Next to the urban physical aspects, logistics, aesthetics, practical usability and sustainability play their own role. The designers have to integrate all of these into one holistic approach. Van Vliet (2000) goes further: *"Because there is an inherent unknowable and unpredictable quality to sustainable development, solutions are more likely to be discovered through field attempts rather than central command. Evolving systems require policies and actions that, in addition to meeting social objectives, achieve a continually modified understanding of evolving conditions, and provide flexibility for adaptation to surprises."* The approach he advocates – active experimentation through management – involves double-loop learning; see Section 1.1 (Figure 1), because *"feedback from the urban environment [is essential] in shaping policy, followed by further systematic (non-random) experimentation to shape subsequently policy, action and so on. The process is iterative, based on social and institutional learning"*.

From a different discipline, Saarinen (1976) adds his opinion: *"Regardless of the theory of the ideal urban habitat, one thing is certain: To provide it, we must learn much more about the psychological dimensions of urban life."*

Continued research is necessary; some of the subjects that ask for (more) research were touched on in the preceding chapters already.

The calculation models for traffic noise are not particularly suited for transmission from noise sources in an urban canyon to the areas behind the building (hinterland). Model or full-scale experiments can lead to improved calculation models. Secondly, the way of correction for varying weather conditions might have to be adapted for peculiarities of the climate around urban canyons, like wind and temperature profiles.

The wind and temperature profiles are also essential for predictions of air quality in the hinterland of a canyon. A metric should be developed to express the influence of traffic emissions on air quality in a single number, which can be calculated in an appropriate model, and which is (of course) representative.

In the concept of the Required Masking noise level $L_{mn}$, a positive relationship between lack of speech privacy and annoyance is assumed; the strength of this relationship needs further research. The customs regarding the use of exterior spaces can be different, depending on culture, climate area, etc. When are they used for sojourn, conversation, etc.? By how many people? How do (lack of) visual and acoustical privacy act together?

Which properties do tools need for optimal application in a context of urban planning and design? Which other tools are tools used in this field, and how? Is "urban synthesis" possible: artisan methods based on the systematic application of tools?

Urban synthesis could start with a map of main roads, in the shape of canyons: "urban rivers" between "acoustical dikes". In the quiet areas between – "acoustical polders" – , further residential functions can be planned. The road system can be orthogonal (hippodamian), hexagonal or other. What are the advantages of each system, and what sizes are preferable for the sides of rectangle or hexagons? Paths for cyclists and pedestrians can be aligned through the acoustical polders in several ways; more study is required to find the best ways.

The opportunities for logistics as mentioned in Section 10.3 need to be worked out, taking the conditions of safety, traffic planning, and transport of people and goods into account. This can be based on present systems of urban transport, but maybe better on more desirable future systems.

What influence do the edge conditions of closed ("deaf") façades or atria have on the design of dwellings in canyon buildings? What types of floor plan are favourable?

Because the canyon buildings play an essential role in creating the living conditions for the houses in the hinterland, authorities must ensure their permanence: the buildings must be built and maintained. Until now this is not a common approach. Instruments for urban planning, in casu land use establish possible functions and conditions, but no obligations to erect and maintain buildings. Whether such buildings should be private property or government owned and related questions require a study by real estate scientists.

Control of the thermal climate in atria by natural ventilation, in static situations can be studied in finite element based calculation models. Next the dynamical aspects of accumulation of heat in the façades and the effect of sunshades should be taken into account.

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## Some historical notes

"Noise is sometimes regarded as a waste product of the modern society. This is not true: it is a waste product, but certainly not a modern one." Myncke (1975) wrote this in 1975 already. He illustrated this with a number of citations and facts, some of which are cited below.

Already in Mesopotamian scriptures (1600 BC) the Sumerian god Enlil is said to be angry with the earthlings for the noise they make. He punishes them by sending his sons to chop down the fig trees of the Babylonians, and by withholding rain from them.

The Roman poet Quintus Horatius (65-8 BC) complains about traffic noise, caused by horses and carriages. Later Nero (31- 68 AD) issued decrees interdicting the driving of chariots in the city of Rome during night time, because of the noise of the clatter of hoofs and wheels on the uneven road surface. In the city of Pompeii in the Roman Empire, the tracks in the pavements are silent witnesses of this noise; see Figure 74.

**Figure 74. Street in Pompeii, with tracks caused by the wheels of carriages.**

In medieval England, under Queen Elizabeth (1533-1603) a law was issued, prohibiting men to beat their housewives, after 10 p.m. Otherwise the shouting would disturb the neighbours' night rest.

Traffic noise in London by horses and carriages in the 19th century disturbed church services, and it is reported that policemen forced a speed limit, by seizing the reins of a passing stagecoach. In Havana (Cuba) the pavement in front of the Presidential Palace consists of an upper layer of wood, an early type of quiet pavement; see Figure 75.

In 1906 the Society for the Suppression of Unnecessary Noise in New York City was established. In the thirties of the 20th century, the Acoustical Society of the Netherlands (NAG) was founded and about 1950 Zürich (Switzerland) agitated against noise by means of banners saying: "Die ruhige Stadt hat weniger Kranke". ("A quiet city has fewer sick people")

**Figure 75. Wooden pavement in Havana used to reduce noise from carriage wheels.**

## A. Quick canyon reference guide

The central proposition of this thesis is:

*Erect continuous residential buildings along main roads in urban areas, to shield the hinterland, and offer housing as well. In this way special urban canyons are created.*

The following tools can facilitate the choice for this approach:

- Height of the canyon buildings; see Annex A.1
- Termination of the canyon; see Annex A.2
- The influence of apertures in the canyon buildings; see Annex A.3
- The influence of an elevated canyon building; see Annex A.4
- The main features of the noise loaded façades of the canyon buildings; see Annex A.6
- The sound reduction by insertion of a second façade, creating an atrium; see Annex A.7
- Noise control in the atrium: apply an amount of sound absorption roughly equal to the floor area of the atrium; see Section 7.3

N.B. A noise load of $L_{den}$ = 50 dB(A) on the façades of dwellings in shielded areas, and $L_{den}$ = 35 dB(A) within dwellings are taken as target values.

The effect of adjustments or variations in urban planning of neighbourhoods or alignment of roads can be assessed by means of the *PAI*, a measure for the total noise annoyance in a certain area; see Section 5.2

In general, but more specifically in the exterior rooms in quiet areas on the lee side of the buildings, speech privacy between neighbours deserves more attention. Apply closed balcony screens and fences of sufficient dimensions, and suppress sound reflections; see further Section 7.4

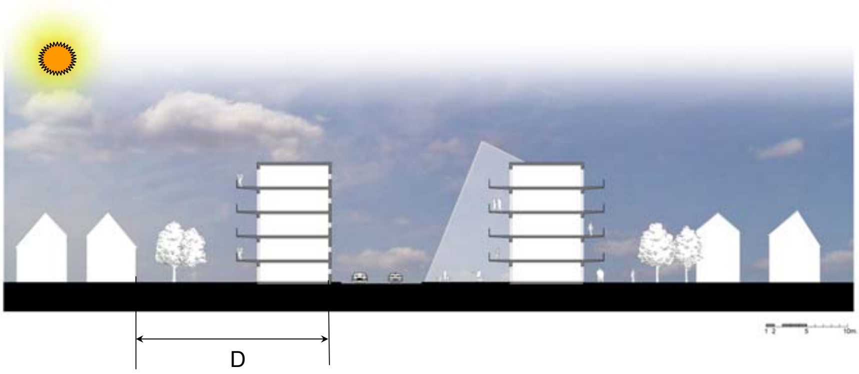
The subjects of Annexes A.1 to A.5 were treated in Sections 6.3 and 6.4; the subjects of Annexes A.6 and A.7 were treated in Section 7.1.

Examples of the application of tools were given in Chapter 8:

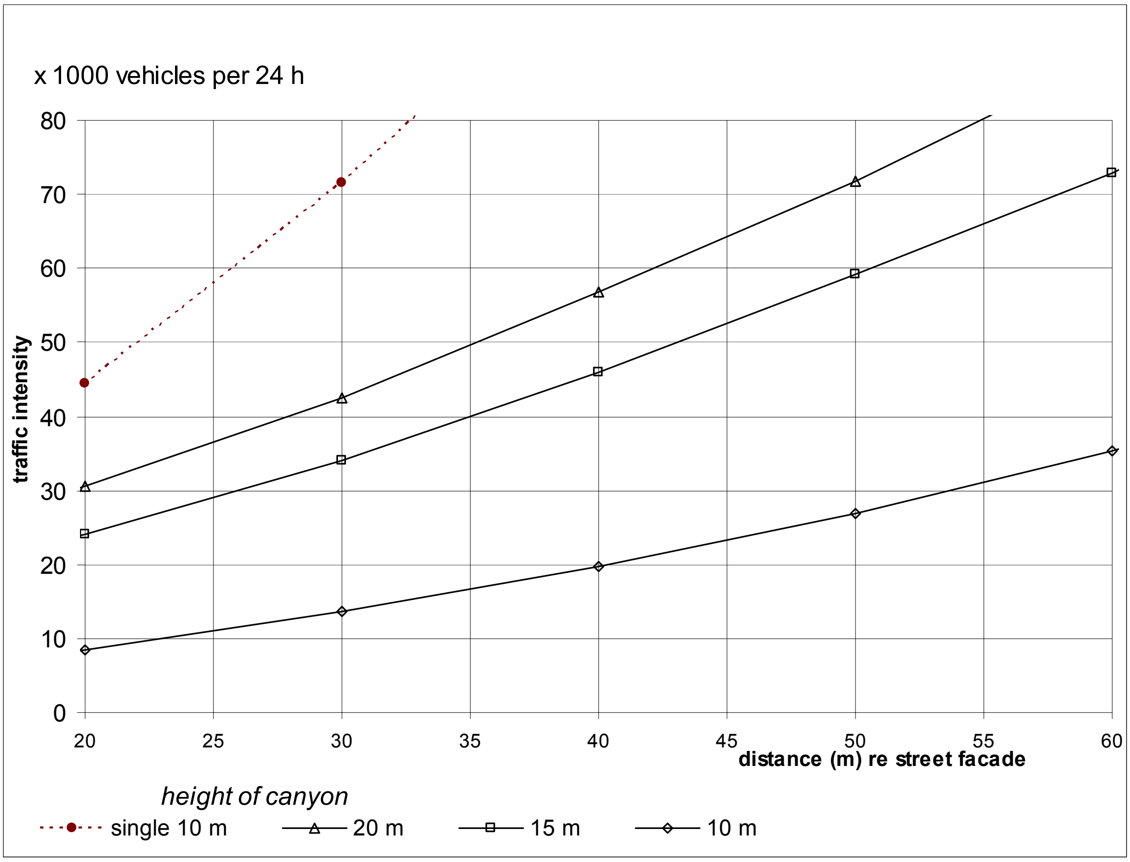
- 8.2 Canyon shielding, aperture and elevated building
- 8.3 Noise exposed façade
- 8.4 Atrium façade
- 8.5 Comprehensive example canyon

## A.1. Height of the canyon buildings, step by step

| | |
|---|---|
| Output | Admissible traffic intensity for "quiet hinterland" |
| Benefit | First estimate of shielding result of canyon |
| Input | Height of canyon buildings and distance to street facade |



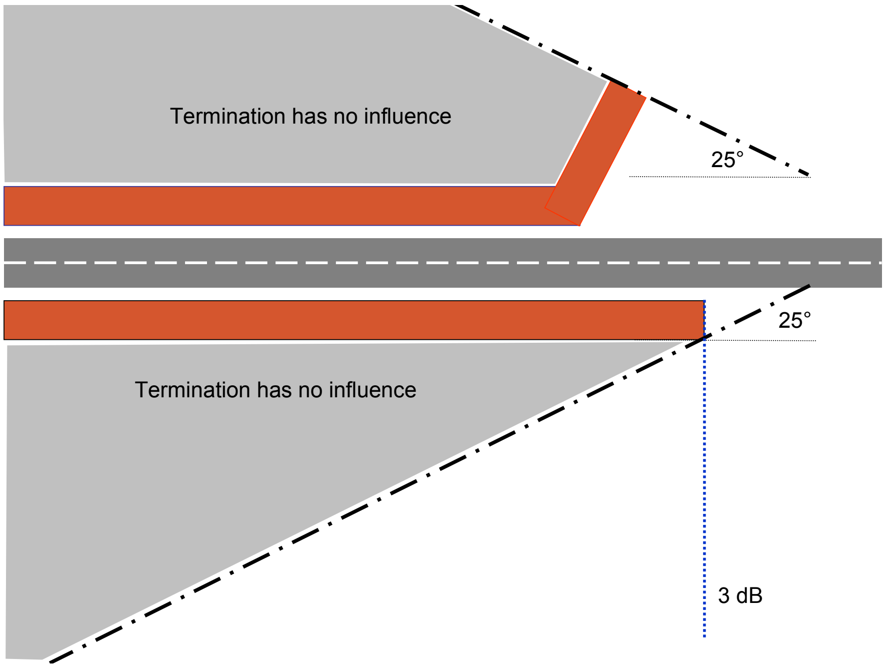

- Determine the distance *D* from the street façade to the building line of the nearest second line buildings.
- Choose the indicated height of the canyon buildings (10, 15 or 20 m)
- In the next graph (a copy of Figure 23 on page 46) start at the distance *D* on the horizontal axis, draw a vertical line up until the sloping line of the canyon height.
- From this intersection in the graph, draw a horizontal line to the left, until the vertical axis
- Read the maximum allowable traffic intensity $F_0$ in the canyon from the vertical axis




If the expected traffic intensity is less than the maximum allowable traffic intensity $F_0$, the shielding by the canyon buildings is sufficient to yield an acceptable noise load ($L_{den}$ < 50 dB(A)) on the second line, and on more distant dwellings.

## A.2. Termination of the canyon buildings

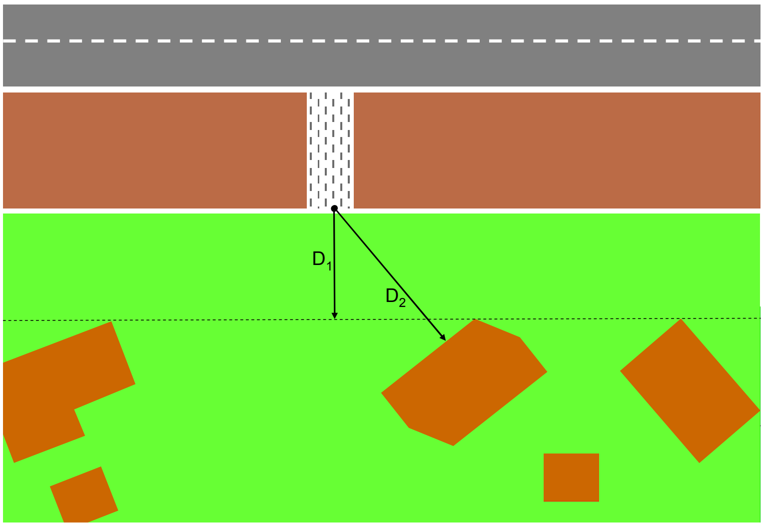
To assess the influence of the limited length of the canyon; in the grey areas this influence can be neglected. To the right of the dot-dash line, this influence increases as the shielding effect decreases.



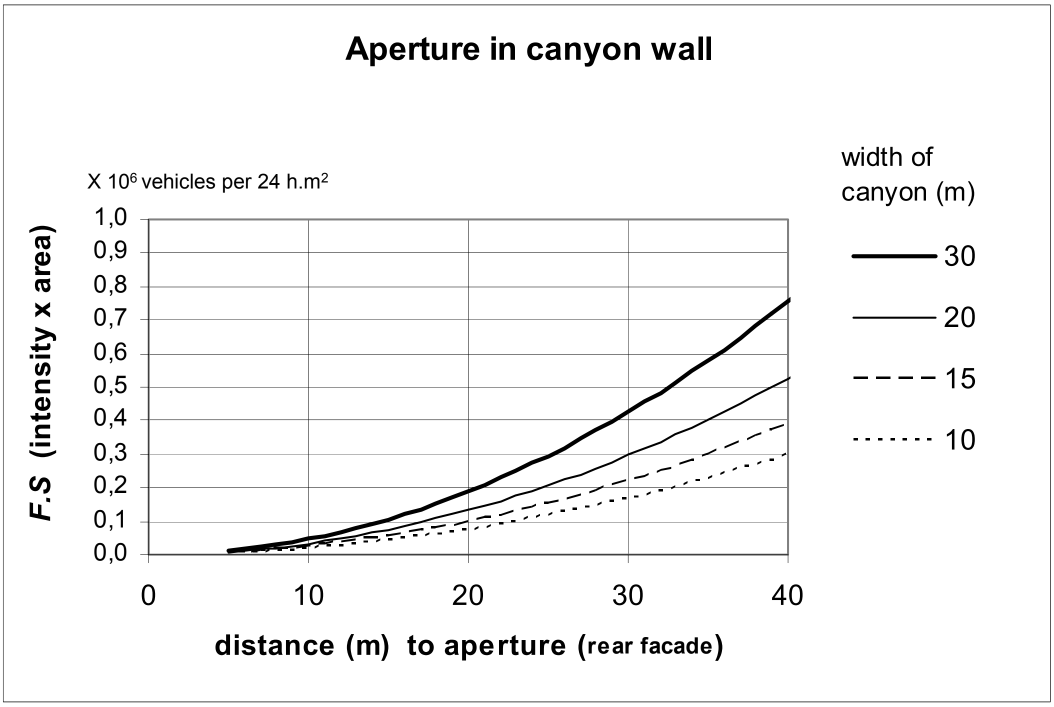

This figure (a copy of Figure 25 on page 48) shows a road between two canyon buildings, and their termination. The lower building is a simple, "full stop". In the upper half the last part of the building is bent to increase the area in grey indicated as "Termination has no influence". The simple approach as used in Annex A.1 cannot be applied outside the grey areas.

## A.3. Apertures in the canyon buildings, step by step

| | |
|---|---|
| Output | Admissible traffic intensity and size of aperture for "quiet hinterland" |
| Benefit | First estimate of acceptability of "holes" in canyon building |
| Input | Distance to rear facade |




- Determine the distance $D_1$ from the aperture in the rear façade to the building line of the second line buildings, or the distance $D_2$ from the aperture in the rear façade to the nearest building, and call it *D*
- Choose the indicated width of the canyon (10, 15, 20 or 30 m)
- In the next graph (a copy of Figure 29 on page 52) start at the distance *D* on the horizontal axis, draw a vertical line up until the sloping line of the canyon width.



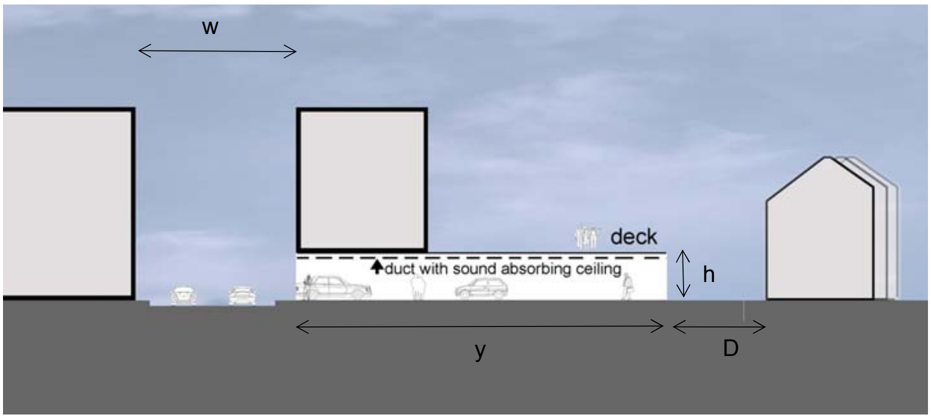

- From this intersection in the graph, draw a horizontal line to the left, until the vertical axis
- Read the number $N$ ($F.S$) from the vertical axis
- Determine the area $S$ of the cross section of the aperture in $m^2$
- Calculate the maximum allowable traffic intensity $F_a = N/S$

The sound contributions of the closed canyon building and of the aperture must be added, by calculating the effective value of the allowable traffic intensity $F_{comb}$ from the number $F_0$ found in Annex A.1, and the number $F_a$:

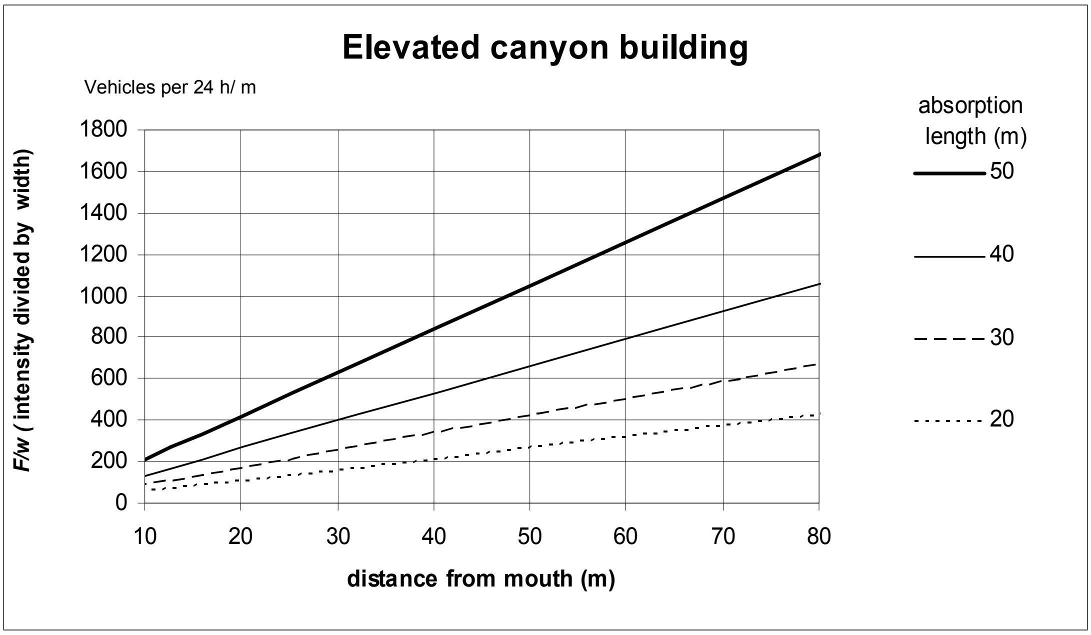
$$F_{comb} = \frac{F_0 \cdot F_a}{F_0 + F_a}$$ ($F_{comb}$ is always less than both $F_a$ and $F_0$.)

### A.4. Elevated canyon building, step by step

| | |
|---|---|
| Output | Admissible traffic intensity for "quiet hinterland" |
| Benefit | First estimate of acceptability of elevated canyon building |
| Input | Distance to mound and length of deck |




- Determine the distance *D* from the mouth line to the building line of the nearest second line buildings
- Choose the indicated absorption length of the canyon building, including the extended deck (20, 30, 40 or 50 m)
- In the next graph (a copy of Figure 32 on page 55) start at the distance *D* on the horizontal axis, draw a vertical line up until the sloping line of the absorption length.
- From this intersection in the graph, draw a horizontal line to the left, until the vertical axis

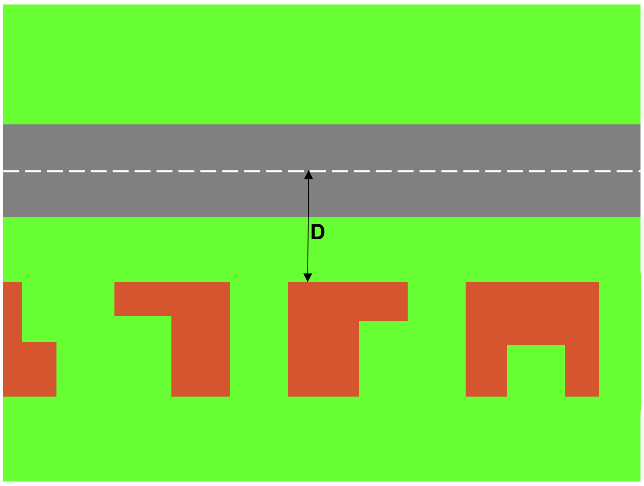


- Read the number $N$ ($F/w$) from the vertical axis
- Determine the width $w$ of the canyon in m.
- Calculate the maximum allowable traffic intensity $F_{el} = N \times w$

The sound contributions of the closed canyon building and of the aperture must be added, by calculating the effective value of the allowable traffic intensity $F_{comb}$ from the number $F_0$ found in Annex A.1, and the number $F_{el}$:

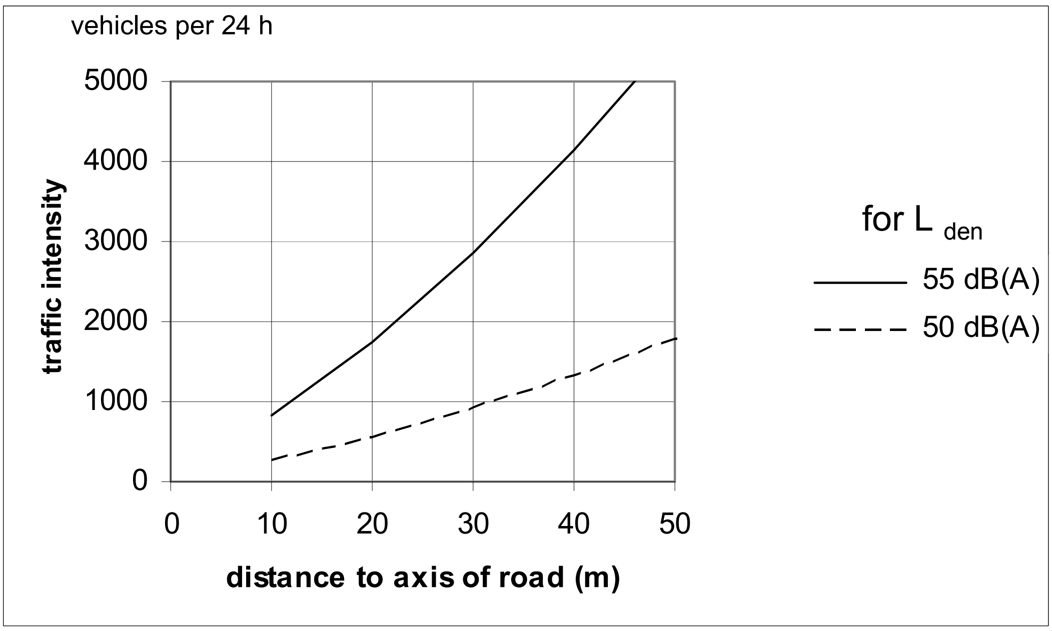
$$F_{comb} = \frac{F_0 \cdot F_{el}}{F_0 + F_{el}}$$

## A.5. Very quiet road, step by step




To determine if a road can be regarded as sufficiently quiet to reach the target value of $L_{den}$ = 50 or 55 dB(A) without measures:

- Determine the distance *D* from the axis of the road to the building line of the unshielded dwellings
- Choose the indicated target noise load (50 or 55 dB(A))
- In the next graph (a copy of Figure 34 on page 56) start at the distance *D* on the horizontal axis, draw a vertical line up until the sloping line of the target noise load ($L_{den}$ = 50 or 55 dB(A))
- From this intersection in the graph, draw a horizontal line to the left, until the vertical axis
- Read the maximum allowable traffic intensity from the vertical axis



## A.6. Noise loaded street façades, step by step

The opaque parts of the façade are taken as concrete or brick cavity wall (mass 600 kg/m$^2$). The façade is closed and carefully sealed.

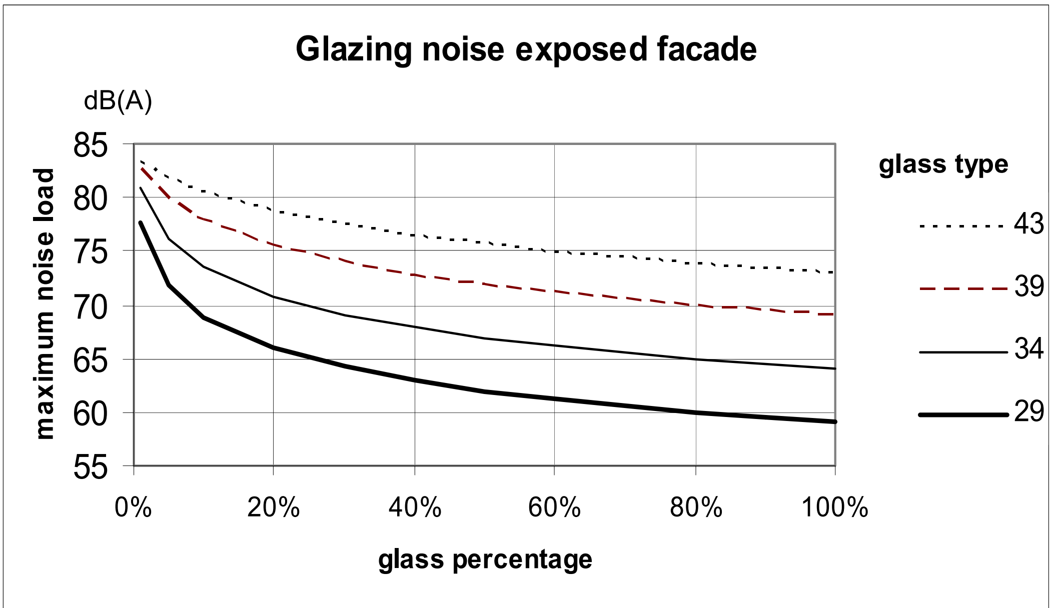
Two cases are distinguished: an indication of the noise load on the street façade is available, or an indication of the traffic intensity is available. In the first case A.6.1 is applicable, in the second case A.6.2. The glass types being considered for application in the façades are listed in the table below, copied from Table 3.

| **Type** | **Typical dimensions** [glass-air gap-glass in mm] [* means laminated pane] | $\boldsymbol{R_{A,tr}}$ [ A-weighted sound reduction relative to the standard spectrum of traffic noise] |
|---|---|---|
| Standard double glazing | 6-12-4 | **29** dB(A) |
| Large air gap glazing | 8-24-12 | **34** dB(A) |
| Laminated glazing with large air gap | 12*-24-12* | **39** dB(A) |
| Double frame (very large air gap) | 8*-120-14* | **43** dB(A) |

### *A.6.1. Glass percentage versus noise load*

| | |
|---|---|
| Output | Admissible noise load on facade |
| Benefit | Estimate of required façade construction |
| Input | Type of glazing, percentage of glass in façade |

- Determine the percentage *P* of glass in the façades of the rooms of the building (interior view).
- Choose the representative type of glazing (26, 34, 39 or 43; see table above)
- In the next graph (a copy of Figure 37 on page 63) start at the percentage *P* on the horizontal axis, draw a vertical line up until the curved line of the glass type
- From this intersection in the graph, draw a horizontal line to the left, until the vertical axis
- Read from the vertical axis the maximum allowable noise load $L_{den}$ on the façade, yielding an indoor noise load of $L_{den}$ = 35 dB(A).

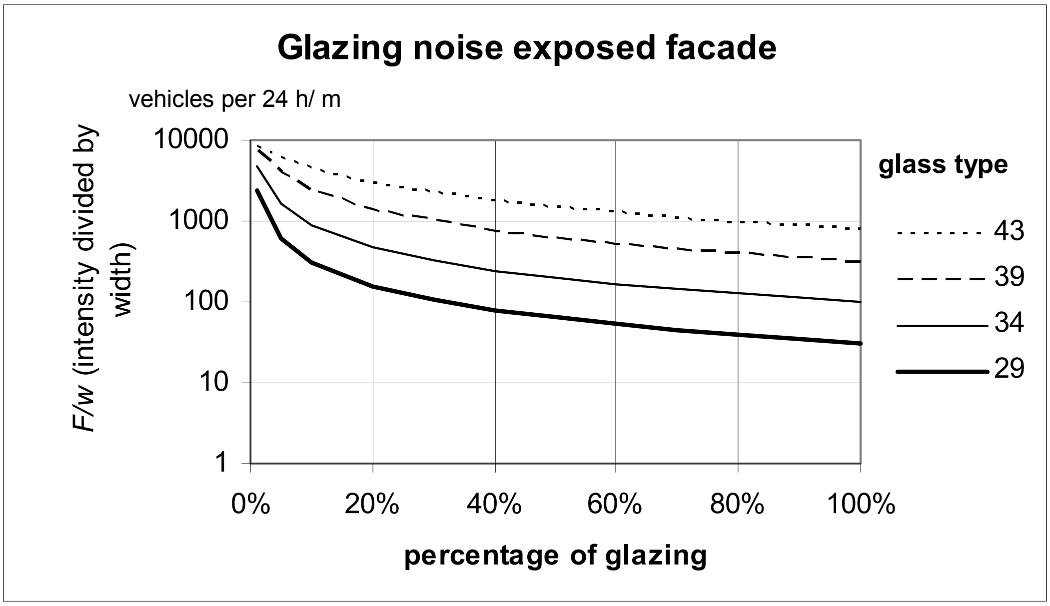


### *A.6.2. Glass percentage versus traffic intensity*

| | |
|---|---|
| Output | Admissible traffic intensity |
| Benefit | Estimate of required façade construction |
| Input | Type of glazing, percentage of glass in façade |

- Determine the percentage *P* of glass in the façades of the rooms of the building (interior view).
- Choose the representative type of glazing (26, 34, 39 or 43; see table)
- In the next graph (a copy of Figure 38 on page 64) start at the percentage *P* on the horizontal axis, draw a vertical line up until the curved line of the glass type
- From this intersection in the graph, draw a horizontal line to the left, until the vertical axis
- Read the number *N* (*F*/*w*) from the vertical axis
- Determine the width w of the canyon in m.
- Calculate the maximum allowable traffic intensity $F_{max} = N \times w$

If the expected traffic intensity is less than the value of $F_{max}$ , the façade design is sufficient, leading to an indoor noise load of $L_{den}$ = 35 dB(A) or less.



### A.7. Sound reduction by atrium façade, step by step

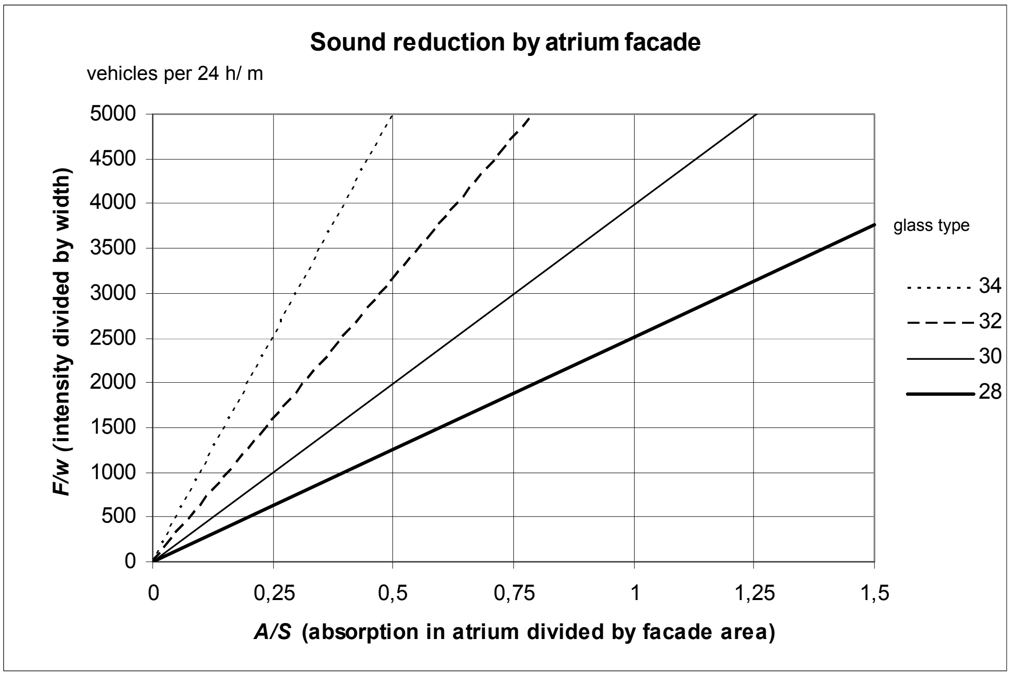
| | |
|---|---|
| Output | Admissible traffic intensity in canyon |
| Benefit | Estimate of required atrium façade construction |
| Input | Type of glazing, absorption in atrium |

N.B. Target is an interior noise load in the dwellings of $L_{den}$ = 35 dB(A) or less, with standard dwelling façades.

The glass types being considered are listed in the table below (a copy of Table 4 on page 65).

| **Type** | ***R'**$_{A;\,extra}$* [ approximate A-weighted extra sound reduction] |
|---|---|
| 10 mm | **28** dB(A) |
| 14 mm, PVB laminated | **30** dB(A) |
| 16 mm, resin laminated | **32** dB(A) |

- Determine the amount of sound absorption *A* in the atrium in m$^2$.
- Determine the area *S* of the (outer) atrium façade in m$^2$.
- Calculate *A*/*S*
- Choose the representative type of glazing (28, 30, or 32 ; see table)
- In the next graph (a copy of Figure 39 on page 66) start at the value of *A*/*S* on the horizontal axis, draw a vertical line up until the sloping line of the glass type



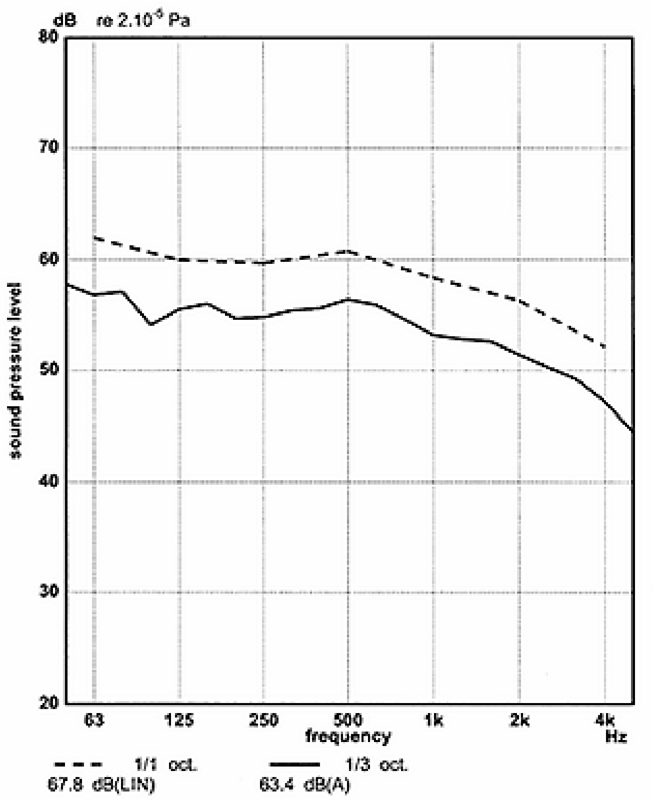
- From this intersection in the graph, draw a horizontal line to the left, until the vertical axis
- Read the number $N$ from the vertical axis
- Determine the width $w$ of the canyon in m.
- Calculate the maximum allowable traffic intensity $F_{max} = N \times w$

If the expected traffic intensity is less than the value of $F_{max}$ , the façade design is sufficient, leading to a noise load within the residences of $L_{den}$ = 35 dB(A) or less, with a standard dwelling façade.

## B. Basics of acoustics

### B.1. Sound

Sound can be loosely defined as “what we hear with our ears”. From the words (in European languages), used to describe sounds, like *whispering, roaring, whistling,* and *humming* the two “dimensions” of sound: loudness and tonality can be noticed. Information regarding the tonal contents of a certain sound can be expressed in a frequency spectrum. (Figure 76) To be able to compare the loudness of sounds with different frequency spectra, *frequency weighting* is used. Each frequency band is weighted according to the properties of the human ear. (The sensitivity of the *ear* is largest in the range 500-2000 Hz, where – not by coincidence – most of the information in the human *voice* is located). The contributions of the frequency bands are then combined, resulting in a single dB(A)-value (A-weighted decibel).




values corresponding with figure:

| freq. | 63 | 125 | 250 | 500 | 1k | 2k | 4k Hz |
|---|---|---|---|---|---|---|---|
| | 57.8 | 54.1 | 54.7 | 55.6 | 54.6 | 52.6 | 49.2 |
| 1/3 oct. | 56.8 | 55.5 | 54.8 | 56.4 | 53.2 | 51.4 | 47.2 dB |
| | 57.1 | 56.0 | 55.4 | 55.9 | 52.8 | 50.3 | 44.5 |
| 1/1 oct. | 62.0 | 60.0 | 59.7 | 60.8 | 58.4 | 56.3 | 52.1 dB |

**Figure 76. Example of frequency spectra.**

For calculations in building acoustics, sound is regarded as a kind of energy, that travels through air; the fact that it is a wave phenomenon that transports the energy is neglected as yet. For the behaviour of sound, the conservation of energy is an essential notion, leading to the principles below. At first, the use of the logarithmic decibel-scale is avoided. Later the derived formulae are transformed to the better-known logarithmic form.

Sound is produced by sound sources, characterised by their sound power $W$ (= energy emission per second).
Transport of sound energy is characterised by the sound intensity $I$ (= sound power per square meter).

The sound energy is "diluted" when travelling away from the source: the energy spreads over the surface ($S$) of the sphere that represents the wave front. Therefore the sound intensity of an omnidirectional source is

$$I = W / S \qquad [17]$$

For a source free in space the sound energy spreads over an entire sphere, $S = 4\pi r^2$ and

$$I = \frac{W}{4\pi r^2} \qquad [18]$$

If the source is located near one or more reflecting planes, the sound energy spreads over less than a whole sphere, which is usually accounted for by the introduction of a directivity factor $Q$:

$$S = \frac{4\pi r^2}{Q} \qquad [19]$$

and hence

$$I = \frac{W \cdot Q}{4\pi r^2} \qquad [20]$$

For a source near one reflecting plane $Q = 2$; for a source in a corner $Q = 4$. These values of $Q$ assume a source that is omnidirectional by nature; in general, the directivity factor $Q$ may take different values in all directions.

When sound meets an obstacle several interactions occur, and the sound energy is divided into several parts; usually the obstacle is a partition (wall, ceiling, floor, façade) or screen. Architectural acoustics deals with sound in rooms in buildings. There the relevant mechanisms are:

- Sound *reflection* (back into the same room)
- Sound *absorption* (sound converted into heat)
- Sound *transmission* (through the wall, to an adjacent room; or through the façade to or from the room).

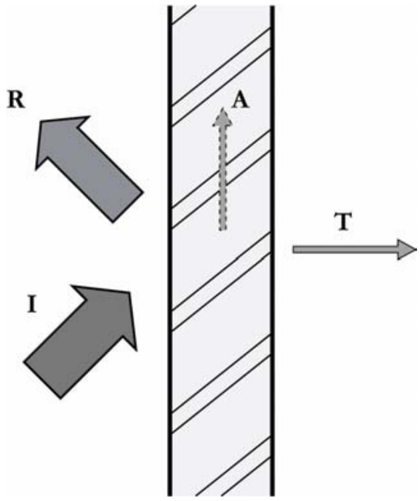



**Figure 77. Division of sound energy (I) impinging on a wall in several parts: reflected (R), transmitted (T) and absorbed (A).**

The fractions transmitted, reflected and absorbed sound energy can be denoted by *t, r* and *a*. The conservation of energy is then expressed by: $t + r + a = 1$. In room acoustics the fraction *t* is usually neglected; for non-porous lightweight constructions (20 kg/m$^2$ or more) this fraction is less than 1%. The fractions *a* and *r* both range from 5 to 95% mostly.

When sound insulation between rooms is regarded, the fraction *t* is dominant. The sound reflecting or absorbing properties of the wall have no influence on the sound transmission.

In environmental acoustics, sound propagation in the open air is studied. Here the phenomenon of *diffraction* at the edges of obstacles (barriers, buildings) is important, next to absorption and reflection. Diffraction is the "bending" of sound around corners, and the cause of the limited effect of noise barriers: a non-negligible part of the sound energy reaches the shadow zone behind a barrier.

In Table 16 an overview is given of the several types of interaction of sound with obstacles, and the dominant phenomena involved:

*a* = *absorption*
*r* = *reflection*
*t* = *transmission*
*d* = *diffraction*

| | **Receiver in room** | | **Receiver in open air** |
|---|---|---|---|
| | **same room** | **adjacent room** | |
| **Source in room** | Room acoustics *[a,r]* | Internal sound insulation *[t]* | external sound insulation, emission *[t]* |
| **Source in open air** | External sound insulation, immission *[t]* | | outdoor propagation *[a,r,t,d]* |

**Table 16. Overview of acoustical interactions between source and receiver.**

## B.2. Sound energy in a room

When a sound source with constant sound production is placed in a room, a constant sound pressure level is observed. Apparently, the sound energy released by the source is compensated by the drain of sound energy by some mechanism. One can imagine the walls of the room being completely sound reflecting (hard, smooth surface), except an aperture which reflects no sound energy at all. The sound field consists of many reflected sound rays; (in the ideal case) a diffuse sound field is the result, which means that the sound energy is evenly distributed over the room, and travels in all directions equally. The definition of the sound intensity in such a room must be adapted to the sound field: the sound intensity $I$ is the sound energy passing through a unit plane in one sense only (if both senses e.g. from left to right and from right to left were taken together, the result would become zero by definition). In the diffuse sound field in the room the sound intensity $I$ is the same in all positions and in all directions. The sound intensity incident on the aperture in the wall is I, and the sound energy leaving the room per second $W_{out} = I.A$; $A$ being the surface of the aperture. From the balance between the sound production of the source and the sound leaving the room, the equality of the sound power of the source $W_{source}$ and the sound drain can be concluded, and:

$$W_{source} = I \cdot A \qquad [21]$$

where

$I$ = sound intensity in the room [W/m$^2$]
$A$ = surface of aperture ("open window") [m$^2$]

Not all materials are hard and smooth, but have properties that cause only a partial reflection of sound energy. The non-reflected part is dissipated (converted into heat) or "absorbed". In this respect, these materials are equivalent to an aperture in the room. For example, a piece of carpet of 10 m$^2$ can behave in the same way as an aperture of 3 m$^2$. This carpet then is equivalent to 3 m$^2$

"open window" (or "Sabine"); its absorption coefficient α is 30% (3/10). Physically the sound absorption coefficient of flat surfaces always lies between 0 and 100%. It is usually measured in a reverberation room. The sound absorbing properties of a room are determined by making an inventory of all parts of the walls, floor and ceiling, with their surfaces and absorption coefficients, resulting in a total amount of sound absorption:

$$A_{tot} = \sum_i \alpha_i \cdot S_i \qquad [22]$$

where

$\alpha_i$ = absorption coefficient of construction i [-]
$S_i$ = surface of construction i [$m^2$]

The term "Sabine" refers to W.C. Sabine (1868-1919) who discovered a simple relationship between the reverberation time in a hall, the amount of sound absorption and the volume of the room. The reverberation time has been defined as the time between the occurrence of an impulsive sound and the moment the sound level has decreased 60 dB. This relationship makes it possible to determine the amount of sound absorption in existing rooms/buildings in a different way: by measuring the reverberation time and the volume of the room. The formula is:

$$T_{60} = \frac{V}{6 \cdot A} \qquad [23]$$

where

$T_{60}$ = reverberation time [s]
$V$ = volume [$m^3$]
$A$ = absorption [$m^2$]

The reverberation time is a major descriptor of the acoustical properties of concert halls, theatres, churches etc. In this field, several enhancements of the Sabine formula have been proposed; for purposes of noise control, the Sabine formula is usually sufficient.

Returning to the sound field in the room, we notice that formula [21] implies that the sound intensity in the reverberant field is independent of the position in the room, and especially of the distance to the source. We must recognise however that we have neglected the direct sound from the source that is also present; in the vicinity of the source the direct field is dominant even.

### B.3. Sound insulation of walls and façades

Sound energy incident on a wall is transmitted for a small part only. Let us consider two adjacent rooms, separated by a wall (area *S*, transmission factor *t*). In one of the rooms (the source room), a sound source is present, a diffuse sound field is assumed and the sound intensity in this room is $I_s$. The sound power incident on the wall is then

$$W_{inc} = I_s \cdot S \qquad [24]$$

The sound power transmitted to the other room, the receiving room, is by definition

$$W_{trans} = I_s \cdot S \cdot t \qquad [25]$$

In this room, again a diffuse sound field is assumed, with sound intensity $I_r$. The amount of sound absorption in this room is denoted by *A*. Application of formula [21] yields:

$$I_r = t \cdot I_s \cdot S / A \qquad [26]$$

For external sound incident on a façade, the same formulae are valid. In the case of sound emission from a room to the environment the last step in the derivation of the formulae cannot be made: the façade is to be regarded as a sound source with sound power

$$W_{out} = I_s \cdot S \cdot t \qquad [27]$$

see next Section (B.4).

### B.4. Outdoor sound propagation

If both sound source and receiver are located in the open-air, sound attenuation by increasing distance is the most important phenomenon. This is expressed in the "dilution formula":

$$I = \frac{W \cdot Q}{4\pi\, r^2} \qquad =[20]$$

where

*I* = sound intensity (W/m$^2$)
*W* = sound power of the source (W)
*Q* = directivity (-)
*r* = distance from source to receiver (m)

For a free radiating, omnidirectional source *Q* = 1. In many practical cases a source is positioned near a reflecting plane (ground, floor, wall); then *Q* = 2.

Secondly acoustical obstacles, reflecting or shielding, are the ground and barriers or screens. Moreover, the atmospheric conditions (wind profile, temperature profile, and humidity) and vegetation play a complicating role. The influence of these factors can be expressed in a transmission factor *t*. The phenomenon of sound reduction by barriers deserves special attention. In contrast to the transmission of light, the acoustical shadow zone behind a barrier is not sharply defined and hardly "dark". The sound transmission to the shadow zone is governed by the difference in path length ε between the direct connecting line from source to receiver and the broken line from source via the edge of the barrier to the receiver. If the source is visible from the position of the receiver, sound reduction is negligible.

### B.5. Sound attenuation by barriers

Under circumstances where the sound source is hidden behind a solid barrier, the source is usually still audible, although a certain sound reduction can be noticed. The phenomenon of sound reaching the "shadow zone" behind a barrier is caused by diffraction at the edges of the barrier, inherent to the wave character of sound. Analogous with diffraction of light, the governing variable is the difference in path length ε between the straight line from source to receiver and the shortest path over the barrier (see Figure 78), compared to the half-wavelength $\lambda/2$. The resulting dimensionless Fresnel-number is $N = 2\,.\varepsilon/\,\lambda$. In noise control near roads barriers tend to be relatively long, and diffraction at the top edge of the barrier only is relevant; then the contribution of diffraction at the vertical edges of the barrier can be neglected.

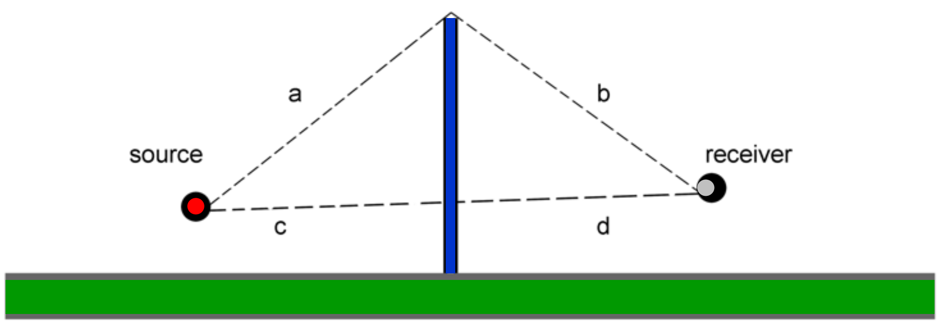



**Figure 78. Geometry of a thin noise barrier; the path lengths indicated. Path length difference ε = a+b-c-d.**

If the line of sight between source and receiver passes the edge of the barrier, the difference in path length is nil, and $N = 0$. In the shadow zone $N$ is signed positive. The excess attenuation $A_e$ of a thin barrier as found by Maekawa (1968 & 2004) can be approximated by:

$$A_e = 10\,\lg\,(20 \cdot N + 3) \quad for\ N > 0{,}1 \qquad [28]$$

For $N < 0{,}1$ the excess attenuation is less than approximately 3 dB.

In this study only barriers are discussed for which the difference in path length is large, and the Fresnel-number $N > 0{,}1$ for all relevant frequencies. This formula means that the effect of barriers depends on the frequency, which makes it obligatory to calculate the attenuation for all relevant frequency bands. For a noise source with a given spectrum however, the sound attenuation of a barrier can be expressed as a function of one variable: the path difference. For the spectrum of the human voice the relationship shown in Figure 79 was used to calculate the attenuation. In the spreadsheet programs interpolation using such relationships is simple.

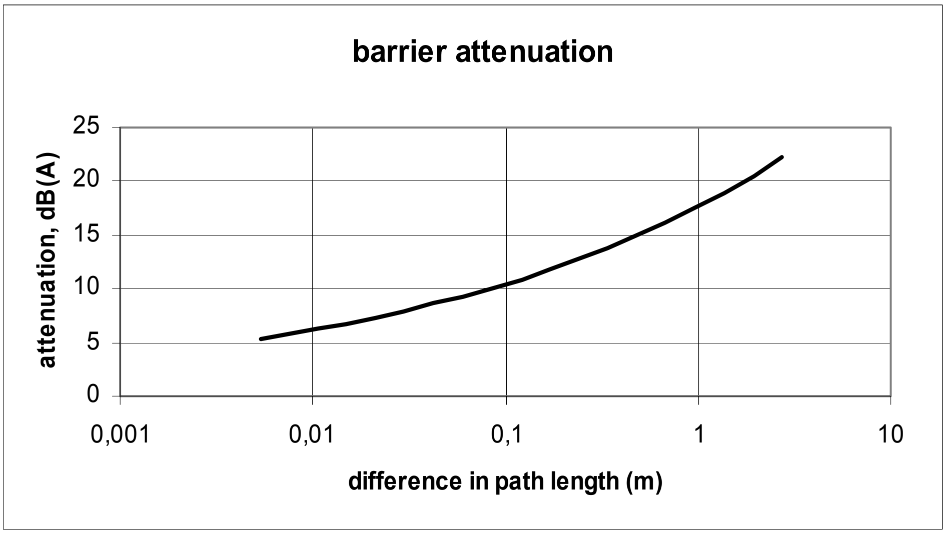



**Figure 79. Attenuation of a thin noise barrier for the spectrum of human voices.**

The effect of barriers is limited in practice by reflections and over longer distances by the curvature of sound rays: gradients of temperature or wind velocity cause the spreading of sound to deviate from straight lines (Beranek, 1971). The "sound rays" can be curved upward or downward. In particular curving downwards can create sound paths across barriers; this type of "short circuit" reduces the effect of barriers greatly. On the other hand, upward curving of sound rays enhances the effect of barriers. A windless atmosphere with a negative temperature gradient (temperature decreases as height increases) can be regarded as the basic weather condition. Under these circumstances, curving is directed upward. In the presence of wind, upward curving occurs for upwind positions relative to the source, but downward curving is found for downwind positions. Sometimes layers in the atmosphere with a positive temperature gradient (temperature increases as height increases*, inversion layers*) occur. They cause downward curving, irrespective of the direction of the source. In calculations of the effect of barriers, these phenomena are usually taken into account in a simplified way: downwind conditions are assumed in all transmission calculations, and a final correction is made for the fact that the wind direction is variable.

## B.6. Linear sound source

Motor vehicles moving over a road can be regarded as individual noise sources, but it is more convenient to assume the sound power they produce, to be emitted from a continuous linear source. Let the sound power per meter road length be *W'*. For a stretch of road *dx* the sound power is then *W'.dx*. The sound intensity *dI* in a point at *r* meter (perpendicular) distance from the road is then

$$dI = \frac{W'dx}{2\pi\left(r^2 + x^2\right)} \qquad [29]$$

The surface is assumed reflecting (emission from the point source into half a sphere, area $2\pi r^2$). Introducing the angle $\varphi$ through the relationship

$$tg\,\varphi = \frac{x}{r} \qquad [30]$$

transforms the formula into:

$$dI = \frac{W'.d\varphi}{2\pi\, r} \qquad [31]$$

The importance of this formula is, that it shows that the contribution of each stretch of the road (*dx*) is proportional to the sight angle (*d*$\varphi$) with the immission point as viewpoint; see Figure 80. Full view of the road in theory means 180° ( – 90° to +90°), but in practice approximately 140° is more appropriate. The contributions of the parts of the road at angles over 70° decrease rapidly, because dissipation in air, and ground effect gain influence at larger distances.

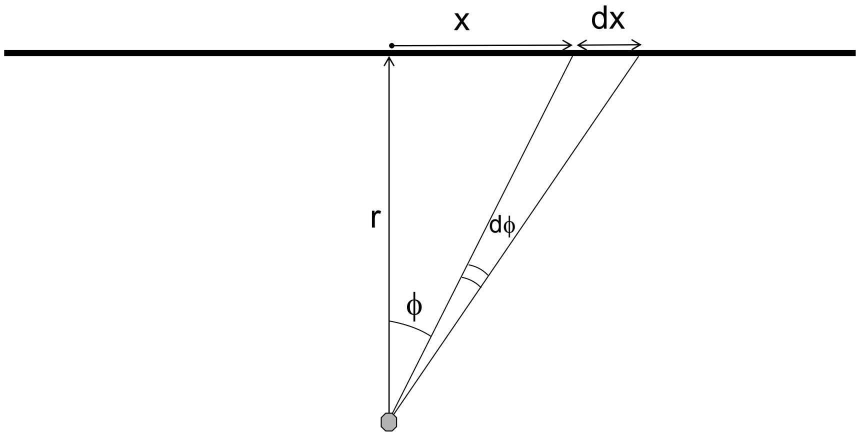



**Figure 80. Line source, contribution of elements *dx* in a point at distance *r*.**

If parts of the road are obscured by buildings or other obstacles, a first approximation of the consequent sound reduction can be made, based on the assumption that the sound energy that is diffracted at the edges of the obstacles is negligible compared to the unobstructed sound transmission between the obstacles. The reduction *T* is then estimated as

$$T = 10 \lg\left(\frac{\varphi}{\varphi_0}\right) \quad [32]$$

where
$\varphi$ = total angle of obstruction by obstacles
$\varphi_0$ = total angle (140°)

If the sound level from a road at a certain position is known with the road in full sight (e.g. 60 dB(A)), and buildings are present that shield the road for an angle of e.g. 60 °, the reduced sight angle will be 140 – 60 = 80 °, and the reduction will be approximately 10 lg 80/140 = – 2,4 dB. The resulting sound level will be 58 dB(A). As long as the obstacles are not too many and too low, this is a reasonable approximation.

## B.7. The decibel scale

Although it is perfectly possible to make calculations in acoustics without decibels or a logarithmic scale, it is not customary to do so. The conversion to decibels requires transformation of the quantities into dimensionless numbers. This can be done by dividing the quantities by the corresponding reference values; for example the sound intensity is expressed in W/m$^2$ (Watt per square meter); the reference value is $I_0 = 10^{-12}$ W/m$^2$ (or 1 pW/m$^2$). The sound intensity *level* $L_I$ is expressed in decibel re 1 pW/m$^2$ and is defined as:

$$L_I = 10 \lg\left(\frac{I}{I_0}\right) dB \quad re\ 1\ pW\ / m^2 \qquad [33]$$

(*re* refers to the reference value)

In the same way the sound power level $L_w$ is expressed in decibel re 1 pW, the reference value is $W_0$ = 1 pW (or $10^{-12}$ W) and is defined as:

$$L_w = 10 \lg\left(\frac{W}{W_0}\right) dB \quad re\ 1\ pW \qquad [34]$$

The sound pressure level $L_p$ has $p_0 = 2.10^{-5}$ Pa as its reference value, which is approximately the hearing threshold. The definition formula is

$$L_p = 10 \lg\left(\frac{p^2}{p_0^2}\right) dB \qquad [35]$$

The human ear is sensible for the sound pressure, not for the sound intensity (although in everyday speech both are often regarded as synonyms). In the direct field of a source a simple relationship exists between the sound pressure level and the sound intensity level: $L_I = L_p$, because of an appropriate choice of reference values. In a perfectly diffuse sound field in a room the relationship is almost as simple: $L_I = L_p - 6$ (dB).
This can be recognised from the fact that in a diffuse sound field, where sound is travelling in all directions, one half is travelling in "wrong" directions; if the other half is projected in the "right direction" only half of the sound energy remains. From all the sound energy crossing a certain point in a diffuse sound field, and contributing to the sound pressure level there, only a quarter contributes effectively to the transport of sound energy, i.e. the sound intensity. And because 10 lg (4)= 6 the sound intensity level here is 6 dB lower than in the direct field. Strictly spoken, by the direct field of a source a spherical wave with such a large radius is meant that it can be regarded as a plane wave; for all practical purposes this is assumed to be the case.

The transformation of formula [21] is conducted as follows.

$$W = I.A$$

$$\frac{W}{W_0} = \frac{I}{I_0} A \cdot \left[\frac{I_0}{W_0}\right] \qquad [36][6]$$

$$10 \lg\left(\frac{W}{W_0}\right) = 10 \lg\left(\frac{I}{I_0}\right) + 10 \lg A \qquad [37]$$

$$L_w = L_I + 10 \lg A \qquad [38]$$

$$L_w = L_p - 6 + 10 \lg A \qquad [39]$$

$$L_w = L_p + 10 \lg \frac{A}{4} \qquad [40]$$

$$L_p = L_w + 10 \lg \frac{4}{A} \qquad [41]$$

The transmission factor *t* is transformed into the sound reduction index *R* through formula [42]; formula [43] is its inverse.

$$R = -10 \lg t \qquad [42]$$

$$t = 10^{-R/10} \qquad [43]$$

The formulae [20], [21], [26] and [27] together with their transformations are recapitulated in Table 17.

[6] The factor in square brackets equals 1 and is thus skipped.

| Basic formula (linear) | | Transformation (logarithmic) | |
|---|---|---|---|
| $I = \frac{W \cdot Q}{4\pi r^2}$ | =[20] | $L_p = L_w + 10\lg\frac{Q}{4\pi r^2}$ | [44] |
| $W_{source} = I \cdot A$ | =[21] | $L_p = L_w + 10\lg\frac{4}{A}$ | =[41] |
| $I_r = t \cdot I_s \cdot \frac{S}{A}$ | =[26] | $L_{p,r} = L_{p,s} - R + 10\lg\frac{S}{A}$ | [45] |
| $W_{out} = I_s \cdot S \cdot t$ | =[27] | $L_{w,out} = L_{p,s} - 6 - R + 10\lg S$ | [46] |

**Table 17. Formulae, linear and logarithmic.**

## B.8. Frequency dependence of hearing and properties of materials

The frequency of sounds humans can hear ranges from 20 Hz to 20000 Hz, approximately for well-hearing (young) persons. Low frequency sounds are perceived to be less loud than mid frequency sounds; this holds for frequencies near the upper hearing limit too. In Figure 81 the curves of equal loudness (isophones) of a normally hearing person are given. From these curves, it is clear, that the sound pressure (or the sound pressure level) as such is not appropriate to indicate the perceived loudness of sounds. Different systems of weighting the frequency bands have been proposed, but the A-weighting according to ISO 1996 is the most commonly used (Konheim, 1999). The A-weighting can be implemented by an electronic filter, which can be built into sound level meters. The values read from a sound level meter with the A- filter switched on are expressed in decibel A, or dB(A).

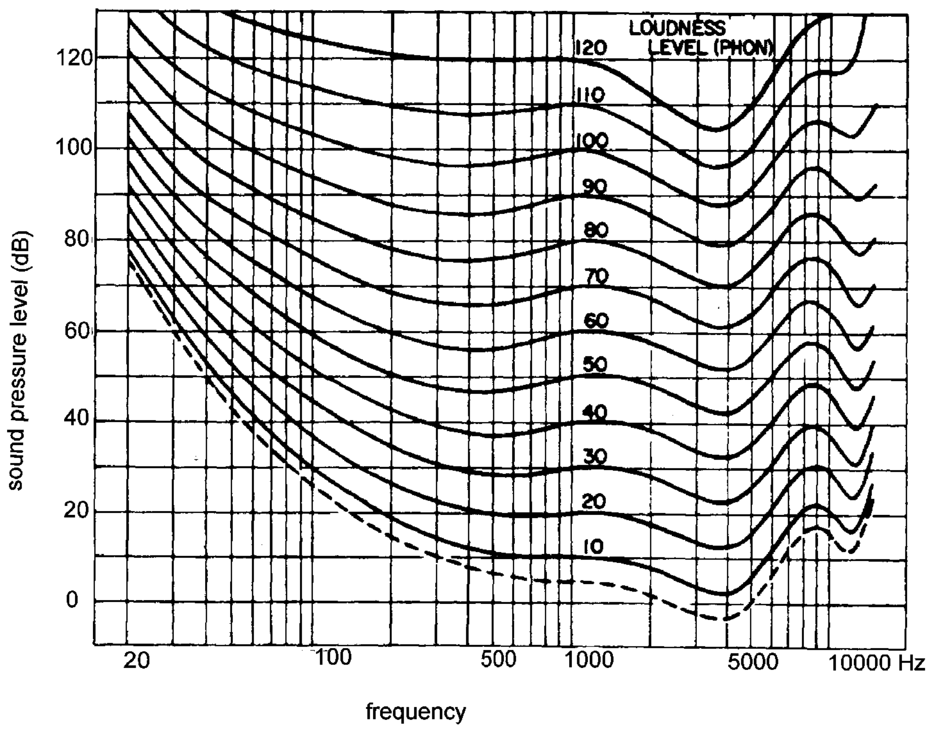



**Figure 81. Isophones (lines of equal loudness) for a normal hearing person.**

The quantities $W$ ($L_w$), $A$, $t$, $R$, $Q$ all depend on the frequency. Calculations of sound transmission cannot be made without taking that into account. In building acoustics it is customary to divide the frequency range that is relevant for hearing in eight octave bands (63-8000 Hz, or 24 third octave bands). Octave bands are assumed further on. Sometimes a noise source has its energy only one octave band, a whistle for example in the 2000 Hz-band. In that case calculations of the behaviour of the sound are done in that octave band only. Most of the time however, sounds in the field of noise control have a wider frequency range. The given formulae are then applied in all relevant bands, sometimes all eight octave bands, often only those from 125 to 2000 Hz.

Many acoustical calculations start with the sound power level of a source, or a sound pressure level in a certain place, in octave bands. The calculations end in most cases with the sound pressure levels at a certain place, in the same bands. From these octave band values, the resulting sound level in dB(A) can be calculated, and compared to the criterion value, which is supposed to be expressed in dB(A) too.

## B.9. Properties of materials

The information necessary for acoustical calculations embraces the octave band values of sound power levels, of sound insulation, sound absorption etc. Only in special cases the values can be calculated from theory. For all practical purposes these values are obtained by means of measurements in acoustical laboratories or in the field. For the *interpretation* of the frequency spectra of these phenomena, knowledge of the character of waves and vibrations – the "true nature" of sound – is indispensable. For example, the sound absorption of porous materials on a concrete wall depends strongly on the wavelength of the sound, compared to the thickness of the material. Therefore, a thick layer of porous material is necessary to yield a high sound absorption coefficient in the low frequencies (large wavelength). The sound insulation of structures is another, more complicated example of a quantity, the behaviour of which can only be understood from the character of waves and vibrations. Nevertheless, if reliable values for the acoustical properties of materials and constructions are available (from measurements, directly or interpolated) they can be used (almost) without further knowledge of the physical background.

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# C. Noise annoyance

## C.1. Introduction

Noise annoyance is a common problem in modern cities, and not only there (see Intermezzo **Some historical notes** on page 123). Noise can be defined as sound that is unwanted in a certain place at a certain point of time. In many cases, the sound is a by-product that is not by all means necessary (traffic noise, industrial noise). In other cases, the noise originates from wanted sound elsewhere (neighbour's conversation or TV). Sound production of mechanical contraptions can be regarded as unwanted; yet, the sound can contain useful information about the functioning of for instance our car or washing machine. From these examples, it is clear that noise control is not simply a matter of reducing all kinds of sound as much as possible.

From time to time newspapers inform us about the (large) numbers of people suffering from noise. Traffic and neighbours are always prominent on the list of annoying noise sources. Traffic noise has become a major source of annoyance in cities, and in large non-urban parts of densely populated countries as well. Annoyance from neighbour noise is predominantly found in urban areas. The combined effect of these sounds can be different: *cumulation* or *masking*. Cumulation means that the nuisance of the two sounds together is higher than the nuisance of each separate sound. On the other hand, continuous traffic noise masks the sounds originating from the neighbours, making them seem less intrusive. Therefore by the way, it would be wise to set higher standards for sound insulation between dwellings in quiet, (suburban) areas.

Noise annoyance can be experienced indoors, in dwellings and outdoors, in public or in private spaces. In Table 18 some characteristics are shown. They can be regarded as indicators, related to noise annoyance, and hence as control variables: setting (formal) limits at appropriate values and guarding these limits should minimise noise annoyance.

| *Source* | *Indoors, dwelling* | *Outdoors, private space* | *Outdoors, public space* |
|---|---|---|---|
| **Traffic** | Noise load *(1)*, sound insulation of façade *(2)* | Noise load *(1)* | Speech interference *SIL*, Annex C.2 *(5)* |
| **Neighbour** | Sound reduction of partition walls/floors *(3)* | Required masking noise level $L_{mn}$, Section 7.5.1 *(4)* | Not relevant here |

**Table 18. Relevant quantities in noise control.**

*Ad 1.* Traffic noise can be controlled by means of limit values of exterior noise levels.
*Ad 2.* Additionally, or as primary measure, indoor noise levels of traffic noise can be controlled through requirements of the sound insulation of façades; setting limits to the internal noise load is equivalent to this.
*Ad 3.* Internal sound reduction is not considered in this dissertation. Where necessary, it is assumed to be sufficient.
*Ad 4.* Until now, little attention has been paid to noise annoyance from neighbours in exterior spaces like balconies and gardens. To provide for this deficiency, an indicator $L_{mn}$, the *required masking noise level* is proposed. In Section 7.5.1 this subject is addressed further.
*Ad 5.* Attention for control of traffic noise in public spaces outdoors also is scarce. Yet excessive sound reduces the quality of public spaces, like parks, sidewalks and cycle tracks. A criterion for setting limits to noise loads in these spaces can be derived from the adverse effect of noise on speech communication. The Speech Interference Level (*SIL*) is a simple indicator for this purpose.

### C.2. Speech Interference

Speech communication between people has always been regarded very important. The intelligibility of speech has been the subject of extensive acoustical research, for example Bradley (1966, 1998), Gerretsen (1975), Chen et al. (2001), Gardner (1971), Van Heusden et al.( 1979), Houtgast (1981), Langhoff et al. (1995), Peutz and Klein (1973), Webster (1970), not to mention medical, audiological research. In distinct cases in practice, intelligibility of speech depends on many factors:

- The loudness, rate and articulation of speech
- The visibility of the speaker
- The clarity of the message
- The familiarity of the receiver with the message
- Ambient noise
- Sound transmission from speaker to receiver
- Reverberation and echoes
- Hearing capacity of the receiver

In general the specific factors of the message and the speaker are replaced by average or normal values; a normally hearing receiver is supposed. In the most frequent and (fortunately) most simple case, only the influence of ambient noise is regarded. In ISO 9921-1 (1996) the Speech Interference Level *SIL* is introduced to characterise the ambient noise. It is the algebraic mean of the sound levels in the octave bands of 500, 1000, 2000 and 4000 Hz. In Figure 82 the limits for speech communication are given: for a given combination of ambient noise in *SIL*, and a certain vocal effort of the speaker, the maximum distance between the interlocutors can be read.

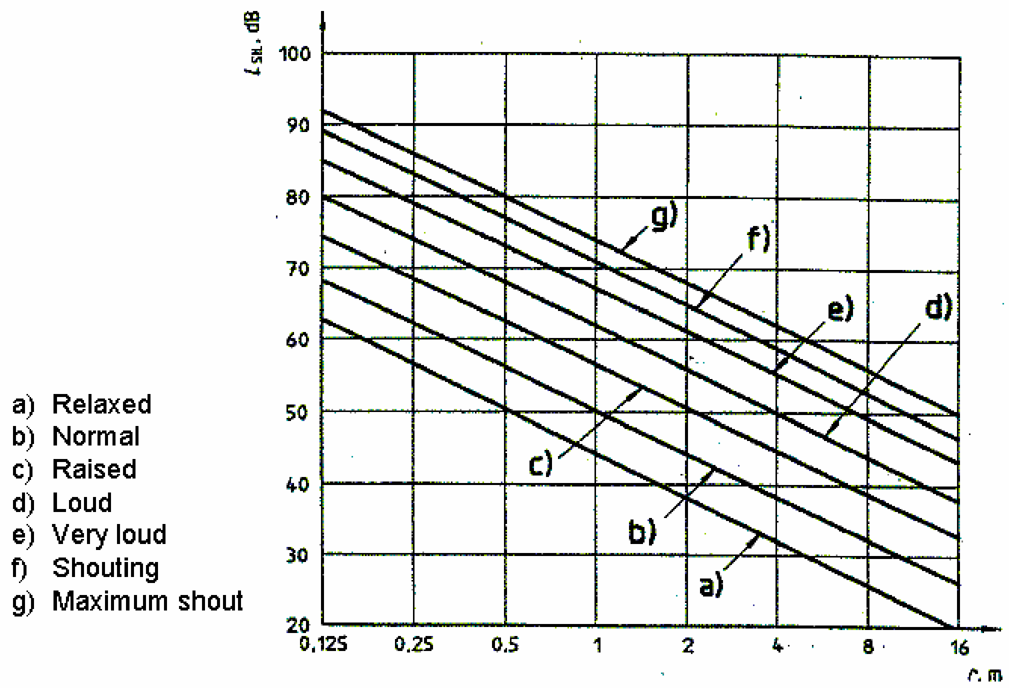


**Figure 82. Speech communication limits; conversation is possible with given vocal effort (a-g) at distance *r* in ambient noise level $L_{SIL}$.**

Other authors give comparable results. Differences occur because of different definitions of speech level. Peutz and Klein (1973) took the combined influence of ambient noise and reverberation into account. In the framework of this thesis however the influence of reverberation and echoes can be neglected.

## C.3. Traffic noise metrics

Regarding noise control, traffic can be divided into several types:

- Air traffic, water traffic
- Railroad traffic
- Urban road traffic
- Motorway traffic

This study aims at urban road traffic noise, because it is present in all cities and the simple solution of creating a complete enclosure, underground or at ground level is not possible. Insofar as railroads are not enclosed, their noise can be treated as road traffic noise.

Like many other sources of noise, traffic noise is not constant. Near urban roads, the vehicles can be noticed separately; at some distance from highways an almost constant hum is heard. The fluctuation requires a method to express the sound level in a single number that corresponds optimally to the nuisance people experience. From a physical point of view, the energy-equivalent sound level or in short: equivalent sound level $L_{eq}$ is the first candidate, because averaging the sound energy is simple, and independent of the time history of vehicle passages. For example, if ten vehicles pass in ten minutes, it makes no difference for the $L_{eq}$ if they pass at one-minute intervals, or if they all pass within two minutes. This is an advantage, as usually only the number of vehicles on a road is known, and not the exact time history. Nevertheless, it is obvious that the time history makes some difference. Additional information on the statistical distribution of the sound level can therefore be useful. For that purpose the statistical levels $L_x$ are defined: the levels that are exceeded for x % of the time. $L_{95}$ is usually denoted as a minimum level, $L_5$ (or $L_1$) as a maximum level. The degree of variation of sound levels can be expressed in the term: $L_{10} – L_{90}$. A metric that takes the equivalent sound level and the degree of variation into account is the Traffic Noise Index (*TNI*). It is based on these statistical levels, and is calculated as:

$$TNI = L_{10} + 3(L_{10} - L_{90}) - 30 \qquad [47]$$

The Noise Pollution Level (*NPL* or $L_{NP}$) also clearly has a statistical base:

$$NPL = L_{eq} + 2,56.\sigma \qquad [48]$$

($\sigma$= standard deviation of instantaneous sound levels).

However, for practical reasons, the $L_{eq}$ is chosen as the indicator for noise annoyance in almost all countries. Versfeld and Vos (2002) show that this is a right choice for traffic noise in general. Moreover, it must be recognised that noise is experienced in different ways, depending on the time of day. During the daytime, more noise is acceptable than during evening or night time. Noise limits often are stated for the different periods, e.g. daytime 50 dB(A), evening 45 dB(A), night 40 dB(A). In general for the evening 5 dB(A) and for the night-time 10 dB(A) lower limits are used. It is however more convenient to express the sound level with its fluctuations and variation over the day, in one number.

Until now, in The Netherlands a special 24h-level is used, defined as the highest value of:

- The equivalent sound level in the daytime (7.00- 19.00 h)
- The equivalent sound level in the evening (19.00- 23.00 h) + 5 dB
- The equivalent sound level in the night time (23.00- 7.00 h) + 10 dB.

Other current measures are the Day Night Level (*DNL* or $L_{dn}$, 24 hour $L_{eq}$ with 10 dB correction for noise in the time between 22.00 and 7.00).

Recently the European Union (2002) has issued a directive that takes the day-evening-night level DNEL or $L_{den}$ as a measure. It is calculated from the equivalent sound levels in the day ($L_{day}$), evening ($L_{ev}$ )and night period ($L_{ni}$), taking the lengths of these periods as weighting factors.

$$L_{den} = 10 \log \left( \tfrac{12}{24} 10^{L_{day}/10} + \tfrac{4}{24} 10^{L_{ev}/10} + \tfrac{8}{24} 10^{L_{ni}/10} \right) \qquad [49]$$

As a rule the $L_{den}$ is used in this thesis.

### C.4. Vibrations

Vibrations intruding dwellings can be annoying too, and cannot always be distinguished from low frequency noise. Vibrations from normal traffic on a well-kept road should be negligible, which means: too heavy or unsprung vehicles (with rigid wheel suspension) are excluded and a smooth road surface is assumed. Railroad vibrations can be controlled by active vibration isolation (tracks placed on a slab on vibration isolators), or passive vibration isolation (buildings placed on vibration isolators); see Section 8.7.

A direct relation between vibration control and urban design is not present; traffic calming measures can be regarded as part of urban design, that sometimes cause vibrations e.g. speed humps or "sleeping policemen". In general however, vibrations are not a part of the conditions for urban or architectural design, or of the design of urban canyons.

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## References

Aarts, R.M. , H. Greten, P.A. Swarte (1999); *A special form of noise reduction*, NAG-journaal 145 (in Dutch)

Alberti, M.(1996); *Measuring urban sustainability*, Environmental Impact Assessment Review 1996:**16**: p. 409, Elsevier.

Altman, I. (1975); *The environment and social behavior; privacy, personal space, territory, crowding*, Monterey : Brooks/Cole, 1975

ANSI S3.5 (1997); *American National Standard, Methods for the calculation of the Articulation Index*, American National Standards Institute, New York.

Arnold, F. (1977); H.-W. Koeppel, W. Mrass, A. Winkelbrandt, M. Sinz, D. Rosenkranz und von Kunowski, *Gesamtökologischer Bewertungsansatz für einen Vergleich von zwei Autobahntrassen [A comprehensive ecological evaluation approach for a comparison of two highway tracks],* Schriftenreihe für Landschaftspflege und Naturschutz, BFANL, H. 16, Bonn- Bad Godesberg. (in German)

Bach, B.; N. Pressmann (1992); *Climate-sensitive urban space concepts and tools for humanizing cities*, Delft, ISBN 90-5269-112-6

Barbaro, S.; R. Caracausi; R.M. Chisesi; E. de Ruiter (2002); *Setting up of priority scales for actions of noise control along the urban areas*, Proc 6th International Symposium Transport Noise and Vibration, June 2002, St Petersburg.

Bateman, I., B. Day, I. Lake and A. Lovett (2001); *The Effect of Road Traffic on Residential Property Values: A Literature Review and Hedonic Pricing Study,* Scottish Executive Development Department, Edinburgh.

Ben-Joseph, E. and D. Gordon (2000); *Hexagonal planning in theory and practice*, J. of Urban Design Vol. 5, no. 3, pp 237-265.

Beranek, L.L. (ed) (1971); *Noise and vibration control*, McGraw-Hill Book Company.

Berg, A. van den, (1999); *Mechanically driven anti-noise generator for vibration screens*, NAG-journaal 145 (in Dutch)

Berkowicz, R.(1998); *Street scale models* in *Urban Air Pollution- European Aspects*, Kluwer Academic Publishers, Dordrecht, ISBN 0-7923-5502-4

Besluit Luchtkwaliteit (2001); *Besluit van 11 juni 2001, houdende uitvoering van richtlijn 1999/30/EG van de Raad van de Europese Unie van 22 april 1999, betreffende grenswaarden voor zwaveldioxide, stikstofdioxide en stikstofoxiden, zwevende deeltjes en lood in de lucht (PbEG L 163) en richtlijn 96/62/EG van de Raad van de Europese Unie van 27 september 1996 inzake de beoordeling en het beheer van de luchtkwaliteit (Pb L 296) (Besluit luchtkwaliteit*), Staatsblad 2001 269, ISSN 0920-2064 Sdu Uitgevers, 's-Gravenhage 2001 (in Dutch)

Bradley, J.S (1966); *Speech intelligibility studies in classrooms,* J.Acoust.Soc.Am **80** (3), September 1966, pp 846-854

Bradley, J.S. (1998); *Relationships among measures of speech intelligibility in rooms,* J.Audio Eng.Soc. **46** (5), May 1998

Brugge, Y.J. van der; Heuvel, H.M.M. van den (1996); *Wonen op geluidbelaste locaties [Living in noise-exposed locations],* Sociaal Geografisch Bureau Dordrecht, november 1996 (in Dutch)

Brundtland, G.H. (1987; ed.), (The World Commission on Environment and Development); *Our common future*, Oxford University Press.

Chen, A.C. and Ken Charuk (2001); *Speech Interference Levels at Airport Noise Impacted Schools*, Sound and Vibration, July 2001

Daigle, G. A. (1999); *Report by the International Institute of Noise Control Engineering Working Party on the effectiveness of Noise Walls*, Noise/News International, September 1999.

De Chiara, J. (1975); *Urban planning and design criteria*, Van Nostrand Reinhold , New York; ISBN 0-442-22055-3

MVROM-DGMH (1985); *Afschermende randbebouwing langs een verkeersweg. Enkele aspecten betreffende geluidhinder, luchtverontreiniging en windhinder [Protective row development along a busy main road. Some aspects of noise nuisance, air pollution and wind nuisance]*, report GE-HR-12-01, The Hague, ISBN 90-346-0924-3. (in Dutch)

DTLR + CABE (2001); *Better places to live, by design*; *a companion guide to PPG3*, London, The Stationery Office; ISBN 0-7277-3037-1.

DIN 4150 (1992); *Teil 2, Erschütterungen im Bauwesen, Einwirkungen auf Menschen in Gebäuden [part 2, Vibrations in buildings, effects on persons in buildings],* Deutsches Institut für Normiering, 1992. (in German)

Dongen, J.E.F. van, H. Vos, L.C.J. van Luxemburg, T.M.J. Raijmakers (1998); *Dosis-effect relaties voor geluid van buren [Response functions for neighbour's noise]*, Ministerie VROM/DGM Publikatiereeks Verstoring nr 2.

Dunayevsky, L. (2002); *Relations between dwelling price and noise factor in Moscow*, Electronic Journal "Technical Acoustics", http://webcenter.ru/~eeaa/ejta , 23-5-2002 (in Russian, with English abstract)

Ehrlich, P. and A. Ehrlich (1990); *The population explosion*, London, Hutchinson.

Eldred, K.M.(1974);"*Assessment of community noise*", Noise Control Engineering, vol **3**, nr 2,1974

European Standard EN 12354-3:2000; *Building acoustics – Estimation of acoustic performance of buildings from the performance of elements – part 3: Airborne sound insulation against outdoor sound.*

European Union (2002); *Directive 2002/49/EC of the European Parliament and of the Council relating to the assessment and management of environmental noise*, Luxembourg, 25 June 2002.

Fiebelkorn, S. et al (1979); *VL-DR-23-03 Stedebouwkundig ontwerpen met geluid [Urban design and noise]*, Ministerie van Volksgezondheid en Milieuhygiëne, november 1979. (in Dutch)

García, A. (ed.) (2001); *Environmental urban noise*, WIT Press, Southampton.

Gardner, M.B. ( 1971); *Factors affecting individual and group levels in verbal communication*, JAES vol 19 nr 7 (July, August 1971)

Gerretsen, E.(1975); *Het verband tussen spraakverstaanbaarheid en de sterkte van wegverkeersgeluid [The relationship between speech intelligibility and the volume of road traffic noise]*, ICG-report VL-DR-17-03, TPD TNO-TH Delft , September 1975 (in Dutch).

Gjestland, T., H. Olsen and R.T. Randeberg (2003); *Noise in Norwegian Cities and Rural Areas*, Proc. EuroNoise, Naples 2003.

Heimans, A. (1966); *Bebouwingsdichtheid en grondgebruik voor de woningbouw in stadsuitbreidingen [Building density and residential land use in urban extensions]*, dissertation TH Delft. (in Dutch).

Helleman, G. and F. Wassenberg (2004); *The renewal of what was tomorrow's idealistic city. Amsterdam's Bijlmermeer high-rise*, J. Cities, vol 21, no. 1, pp 3-17

Heusden, E. van, R. Plomp and L.C.W. Pols (1979); *Effect of ambient noise on the vocal output and the preferred listening level of conversational speech*, Applied Acoustics **12** (1979), pp 31-73

Houtgast,T.(1981); *The effect of ambient noise on speech intelligibility in classrooms*, Applied Acoustics **14** (1981), pp 15-25

IEC 60651 (1979); -00-00 Sound Level Meters First Edition; International Electrotechnical Commission, 1979 and EN 60651 1994-00-00 European Norm, *Sound Level Meters* (1994)

Ishizuka, T. and K. Fujiwara; *Performance of noise barriers with various edge shapes and acoustical conditions*, Applied Acoustics **65** (2004) pp 125-141.

ISO 1996/1 (1982); International Standard, *Acoustics – Description and measurement of environmental noise – Part 1: Basic quantities and procedures*, International Organization for Standardization, 1982-09-15.

ISO 1996-2 (1987); International Standard, *Acoustics – Description and measurement of environmental noise – Part 2: Acquisition of data pertinent to land use*, International Organization for Standardization, 1987-04-15.

ISO 1996-3 (1987), International Standard, *Acoustics – Description and measurement of environmental noise – Part 3, Application to noise limits,* International Organization for Standardization, 1987.

ISO 8253-3 (1996), International Standard, *Acoustics – Audiometric test methods – Part 3: speech audiometry,* International Organization for Standardization, 1996.

ISO 9921-1 (1996); International Standard, *Ergonomic assessment of speech communication – part 1*, International Organization for Standardization, 1996.

ISO/TR 3352 (1974); *Acoustics, Assessment of noise with respect to its effect on the intelligibility of speech*, Technical Report 3352-1974 (E)

Ivanov, N. I. and N. V. Tyurina (2000); *A problem of transport noise control in cities*, Proc. 7th Int. Congress on Sound and Vibration, Garmisch-Partenkirchen, July 2000

Kihlman, T. (2001); *Noise abatement and improvement: the systematic approach*, Noise/News International (I.INCE), June 2001

Kihlman, T. (2001); *Quiet side and high façade insulation – means to solve the city noise problem*, Proc.Inter-Noise 2001, The Hague, The Netherlands, pp 1227-1235.

Kihlman, T.(1999); *City traffic noise – a local or a global problem?* Proc. InterNoise 1999, Fort Lauderdale, USA.

Kluijver, Henk de (2003) and Stoter, Jantien; *Noise mapping and GIS: optimising quality and efficiency of noise effect studies*, Computers, Environment and Urban Systems 27 (2003) pp 85-102, Pergamon.

Konheim, A.G. (1999); *A-weighting for environmental noise assessment*, Inter-Noise 99, Fort Lauderdale, Florida, USA, December 1999.

Kotzen, B and English, C.(1999); *Environmental noise barriers*, E& FN Spon, London.

Kristinsson, J. (2002); *Integraal ontwerpen – vitale architectuur [Holistic design – vital architecture],* ISBN 90-75365-58-6, Deventer, The Netherlands (in Dutch) pp 235-239.

Langhoff,Th, A.; Köchling, U. Trautmann( 1995); *Sprachkommunikation/ Ihre Störung, Beeinträchtigung und Einschränkung[Speech communication/ its disturbance, interference and restriction]*, Schriftenreihe der Bundesanstalt für Arbeitsschutz; Dortmund 1995

Lindemann, H.-E. (1999); *Stadt im Quadrat, Geschichte und gegenwart einer einprägsamen Stadtgestalt,[City squared, history and present of an expressive city shape]*, Vieweg, Braunschweig/Wiesbaden, ISBN 3-528-06121-2 (in German)

Maekawa, Z. (1968); *Noise reduction by screens*, Applied Acoustics **1**, 157-173

Maekawa, Z. (2004); *Shielding highway noise*, Noise Control Eng. J. **52** (3), 86-92.

Mecanoo Architecten (2003); *Holland Avenue*, Ministry of Transport, Public Works and Water Management, ISBN 90 369 1862 6

Menzel, M.A.(1989); *Bijlmermeer, grensverleggend ideaal [Bijlmermeer, innovative ideal]*, dissertation Delft University Press, Delft, The Netherlands (in Dutch)

Meijdam, J.C.(2000); *Akoestische kwaliteit*; *[Acoustical quality]*, Geluid nr 3, July 2000 (in Dutch).

Miedema, H.M.E (2001);"*Noise & Health: How Does Noise Affect Us?*" Proc. InterNoise 2001, The Hague, The Netherlands, pp 3-20

Miedema, H.M.E. and C.G.M. Oudshoorn (2001); "*Annoyance from transportation noise: Relationships with exposure metrics DNL and DENL and their confidence intervals*", Environmental Health; vol 109: 4, 2001,pp 409-416.

Morioka, T., T. Fujita, N. Yoshida (1996); *Performance and shortcomings of typical environmental pollution control programs for automobile traffic in Kobe city and surrounding areas. Social cost evaluation of noise pollution by hedonic price method*, The Science of the Total Environment, 189/190, pp 99-105, Elsevier.

Müller, D.B., K.J. Canters, S.P. Tjallingii (2004). *A transdisciplinary learning approach to foster convergence of design, science, and deliberation in urban and regional planning*, Systems Research and Behavioural Science. (to be published in late 2004 or early 2005)

Müller, D.B., A. Dijkstra, E.P.H. van Keeken, G. Klunder and E.Ph.J. de Ruiter (2005); *Comparison of effect tools for a sustainably built environment* in *DIOC-toolbook (to be published)*

Mumford, E. (2000); *The CIAM discourse on urbanism*, *1928-1960*, MIT Press, Cambridge-Massachusetts / London-England, ISBN 0-262-13364-4

MVROM-DGV (1993); *Hinder van geluid van buren*, Kwaliteit van de woning en woonomgeving, *[Annoyance of neighbour's noise*, quality of dwellings and environment], 1993 nr 11 (in Dutch).

Myncke, H. (1975); *Geluid en geluidshinder [Sound and sound annoyance]*, De Nederlandsche Boekhandel Antwerpen- Amsterdam, ISBN 90 289 00543 (in Dutch)

Neufert , E. and P. (2000); *Architects' Data Third Edition*, Blackwell Science, Oxford.

Nijs, L. (1978); *Een methode voor de berekening van de akoestische kwaliteit van een stedebouwkundig plan [A method for the calculation of the acoustical quality of an urban plan]*, Stedebouw en Volkshuisvesting, september 1978, pp 412-424 (in Dutch)

NMPB-routes-96 (1996); SETRA-CERTU-LCPC-CSTB (French national computation method for road traffic noise), in conjunction with "*Guide du bruit des transports terrestres, fascicule prévision des niveaux sonores*", CETUR 1980, for data concerning emission. (in French).

OAG, AGV, ACE, PEUTZ, DHV (2002); *MER/Tracénota N284 Eersel-Reusel*, Provincie Noord-Brabant.

Onuu, M.U. (2000); *Road traffic noise in Nigeria: measurements, analysis and evaluation of nuisance,* Journal of Sound and Vibration (2000) **233** (3), pp 391-405.

Peutz, V.M.A. and W. Klein (1973), *Articulation loss of consonants influenced by noise, reverberation and echo*, Proc. FASE Symposium on Speech intelligibility, Luik (B) 1973.

Peutz, V.M.A. (1971), *Articulation loss of consonants as a criterion for Speech Transmission*, J. Audio Eng. Soc., **19**, 915-919

Power, H. and J.M. Baldesano, ed. (1998); *Air Pollution Emissions Inventory*, Computational Mechanics Publications, Southampton, ISBN 1 85312 5172.

Pronello, C. and M. André (2000); *Estimation tool of traffic pollutant emissions in function of macroscopic driving variables*, Report INRETS-LTE N° 2006, March 2000 , BRON- Cedex France

Ramis, J., J. Alba, D.García, F. Hernández (2003); *Noise effects of reducing traffic flow through a Spanish city*, Applied Acoustics **64**, pp 343-364

Rathé, E.J. (1969); *Note on two common problems of sound propagation*, Journal of Sound and Vibration, (1969) **10** (3), pp 472-479

RMW(2002); *Reken- en meetvoorschrift wegverkeerslawaai 2002*, Staatscourant 28 March 2002, nr. 62 (in Dutch)

Roo, G. de (2000); *Compact cities, environmental conflicts and policy strategies: Complexity as a criterion for decision making*, in *Achieving Sustainable Urban Form;* E & FN Spon, London; ISBN 0-419-24450-6.

Ruiter, E.Ph.J. de (1988); *Atria in shopping centres, office buildings and hospitals*, Proc. Inst. of Acoustics, vol **10**, part 8 ( 1988)

Ruiter, E.Ph.J. de (1999)*; De planologische hinderindex (PHI)[The index for community annoyance in urban planning],* KenMERken, 1-12-99, pp 16-18, Aebele Kluwer (in Dutch)

Ruiter, E.Ph.J. de (2000); *Noise control in the compact city*, Proc. 7th Int. Congress on Sound and Vibration, Garmisch-Partenkirchen, July 2000

Ruiter, E.Ph.J. de (2001); *Apartment buildings in nuisance zones along main roads; noise control with and within "glass houses "*, Proc. 8th Int. Congress on Sound and Vibration, Hong Kong, July 2001

Rylander, R. and M. Björkman (2002); *Road traffic noise annoyance and window orientation in dwellings*, Journal of Sound and Vibration **294**(4), pp 828-831

Saarinen, Th.F. (1976); *Environmental planning, perception and behaviour*, Houghton Mifflin, ISBN 0-395-20618-9

Samuels,S. and E. Ancich (2002); *Recent developments in the design and performance of road traffic noise barriers*, Noise & Vibration Worldwide, March 2002.

Sandberg, U. (2001); *Tyre/road noise – Myths and realities*, Proc. InterNoise 2001, The Hague, The Netherlands, pp 35-56

Scheuren, J. (1987); *Active noise and vibration control*, NAG-journaal nr 84 (in German)

Schreiber, L. (1970); *Lärmschutz im Städtebau [Noise control in urban design]*, Bauverlag GmbH, Wiesbaden und Berlin. (in German)

Schwedler, H.-U. (ed.)(1999); *Noise abatement in European towns and cities*, European Academy of the Urban Environment, Berlin

Steele, C. (2001); *A critical review of some traffic noise prediction models*, Applied Acoustics **62**, pp 271-287

Steeneken, H.J.M. and T. Houtgast (1999); *Mutual dependence of the octave-band weights in predicting speech intelligibility*, Speech Communication **28**, pp 109-123.

TNO-MEP (1999); *Handboek voor het ontwerp van bijzondere afschermende constructies langs rijkswegen – Luchtkwaliteit, eerste versie; [Handbook for the design of special shielding constructions along freeways – Air quality, first version]*, TNO-MEP, Apeldoorn, report nr. R 99/474 (in Dutch).

Varshney, C.K. and I. Mitra (1993); *Importance of hedges in improving urban air quality*, Landscape and Urban Planning, **25** (1993), 75-83

Verhoef, E.(1994); *External effects and social costs of road transport*, Transportation Research, vol. **28A**, 1994, p. 286.

Vermeir, G. (1994); *Akoestische voorzieningen in overdekte zwembaden, verwachtingen, eisen, praktijk (Acoustical measures in swimming pools, expectations, requirements, practice),* Bouwfysica, vol. **5.** 1994, pp 14-18.

Versfeld, N.J. and J.Vos (2002); *A-weighted equivalent sound level as a predictor of the annoyance caused by road traffic consisting of various proportions of light and heavy vehicles*, Journal of Sound and Vibration **253**(2), pp 389-399.

Vliet, D. van (2000); *Development/demonstration: an adaptive strategy* in *Achieving Sustainable Urban Form*, E & FN Spon, London; ISBN 0-419-24450-6.

Wackernagel, M. and William E. Rees (1996); *Our ecological footprint: reducing human impact on the earth*, Publisher Gabriola Island: New Society.

Webster, John C. (1970); *Updating and Interpreting the Speech Interference Level (SIL)*, JAES vol **18** nr 2 (April 1970)

WHO (2000); *Noise and health*, World Health Organization, Local authorities, health and environment briefing pamphlet series; 35.

Williams, K. (2000); *Does intensifying cities make them more sustainable?* in *Achieving Sustainable Urban Form;* E & FN Spon, London; ISBN 0-419-24450-6.

Young, R.W. (1965); *Re-vision of the Speech Privacy Calculation*, J.Acoust.Soc.Am. 38, 524 (1965).

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## Acknowledgements

This research project has been carried out as a co-operation between my employer Peutz BV and the Delft University of Technology, Delft Interfaculty Research Centre DIOC-DGO ("The ecological city"). I want to thank Peutz in the first place for their readiness to take part in this research and relieving me from a part of my usual obligations. My Peutz-colleagues too did collaborate in several ways: taking over my tasks, feeding back, and supplying information. Without this helpful attitude, this thesis had not come into existence.

The "life cycle" of DIOC-DGO (see Section 1.1) ended in December 2002, but the memories of many inspiring interdisciplinary discussions, excursions, "vertical" meetings and celebrations remain. Therefore I thank the staff and colleagues of DIOC "The ecological city". After the decease of DIOC, certainly the work became less exciting.

In the social field congenial colleagues are indispensable. I am lucky having (had) many of those in several frameworks: DIOC, MTO-B (Jón Kristinsson's chair), Building Technology and Peutz. For the pleasant time during lunch breaks and social hours I want to thank them all.

Apart from the scientific support I received from both my supervisors and the "promotiecommissie", the contributions of two other scientists from outside the faculty are thankfully mentioned: Diemer de Vries (Delft University of Technology) and Eddy Gerretsen (Eindhoven University of Technology).

In the crystallisation process leading from research to thesis, Hans Cauberg as a "co-promotor" and Kees van der Linden played an important role, in particular by asking the right questions. I want to thank them for their critical, positive attitude.

Finally I want to express my gratitude to Jón Kristinsson, for taking the initiative and the risk of the adventure that now has come to an end; thank you for your inspiration and exemplary demonstration of continuous curiosity.

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## Curriculum vitae

Surname: de Ruiter

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### *In short*

Evert Ph.J. de Ruiter visited high school in his birth place Veenendaal from 1958 until 1963. Next he started his study Applied Physics at the Delft University of Technology. His graduation research took place in cooperation with the Sophia Paediatric Clinic in Rotterdam, and concerned the thermoregulation of premature infants in incubators.

After receiving his masters degree in 1971, and with negligible knowledge of acoustics he started with Peutz in The Hague as a staff engineer. In 1976 he became a senior consulting engineer. He was involved in the design and building process of many office buildings, hospitals, airport buildings and traffic noise projects.

From 1965 on he has been a member of several committees, boards and representative bodies, in the field of education, profession and other. From 1975-2000 he was a teacher in several courses in the field of acoustics.

### *Various publications:*

*Ankerloze spouwwanden*, NAG-journaal 37 (1976); with R.A Metkemeijer

*Geluidbeheersing met verlaagde plafonds*, Bouwwereld (1980)

*Contrôle du bruit en milieu industriel (1981),* Eyrolles, Paris ; with W.M. Schuller, V.M.A. Peutz, A.P.P.J. Stevens and H. Straatsma

*Overlangsisolatie in de praktijk*, NAG-journaal 62 (1982)

*Bouwfysische aspecten van het overkappen van winkelstraten*, PT-Bouw 38 (1983); with G.M.A. Perquin

*Ueberdachte Ladenstrassen und ihre bauphysikalischen Probleme,* Bauwelt nr 25 (1983); with G.M.A. Perquin

*Wet, geluid en hinder*, BOUW (1983)

*Gevels, het raam van de wet geluidhinder kiert*, BOUW (1985)

*"Is er leven boven het plafond ?"*, Klimaatbeheersing (1986)

*Universiteitsbibliotheek Groningen: akoestiek en bouwfysica*,Open (bibl.e.d.) (1987)

*De serres van VROM akoestisch bekeken*, Architectuur/Bouwen (1987)

*De piano als bron van geluidhinder*, NAG-journaal 98 (1989);

*Akoestiek* [van grote glasoverkapte ruimten], Bouwspecial (1990)

*Geluidwering van uitwendige scheidingsconstructies*, BouwWereld (1993)

*"Geluid"* in Handboek installatietechniek, TVVL, ISSO, Novem (1994)

*"Muziekinstrumenten en elektro-akoestische apparaten (I-2400)"* in Lawaaibeheersing – Handboek Milieubeheer, ISBN 90-6500-493-9 (1994).

*"Minder lawaai, dat zou heerlijk zijn"*, Onze Eigen tuin (1995)

*Akoestische eigenschappen van gipskartonwanden*, Wand-& PlafondInfo (1995)

*Isola deci Bella (geluidisolatie in kantoren)*, "Bouwfysica" vol 7 (1996)

*Geluidbeheersing* [C-15: Grondslagen bouwfysica] in PBNA Praktijkhandboek Bouw- en Installatietechniek (1999)

*De planologische hinderindex (PHI),* KenMERken (1999)

*"Farewell Symphony" or Terminal Building Acoustics*, International Airport Review, volume 4, issue 3 (2000)

*Noise control in the compact city,* Proc. 7th International Congress on Sound and Vibration (ICSV7), Garmisch-Partenkirchen (2000)

*Building in noise impact zones,* Proc. International Conference Sustainable Building, Maastricht (2000)

*Apartment buildings in nuisance zones along main roads; noise control with and within "glass houses ",* Proc. 8th International Congress on Sound and Vibration (ICSV8), Hong Kong (2001)

*Akoestische dijkwoningen,* Dubo Jaarboek 2001

*Leven tussen twee gevels,* NAG-journaal 155 (2002)

*Grensverleggend bouwen in milieubelaste gebieden,* Dubo Jaarboek 2002

*Stadscanyons in woongebieden,* Symposium KIVI-NTV Bouwen langs spoor- en snelwegen (2003)

*Noise control by canyonisation of roads,* Proc. 5th European Conference on Noise Control, Napoli, (2003)

*Reclaiming land from urban traffic noise impact zones,* Proc. SASBE 2003, Brisbane (2003)

*"Geluid"* in PolyInstallatie zakboekje, Reed Business Information (2004)

*Stadscanyons-woongebieden,* Proc. "Geluid en Trillingen in Nederland", Nieuwegein (2004)

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|---|---|---|
| ***Opleiding:*** | 1958-1963 | Christelijk Lyceum Veenendaal |
| | 1963-1971 | TU Delft afdeling Technische Natuurkunde; afstudeeronderzoek "*Onderzoek naar de thermoregulatie bij couveusebabys*". |
| ***Werk:*** | 1971-heden | Peutz bv Den Haag/ Zoetermeer, vanaf 1976 medewerkend raadgevend ingenieur |
| | 1975-2000 | docent TVVL-cursus *Geluid in technische installaties* |
| | 1987-1993 | Bestuurslid Nederlands Akoestisch Genootschap (NAG) |
| | 1988-1993 | Lid Algemeen Bestuur Nederlandse Stichting Geluidhinder |
| | 1996-2000 | docent post HBO cursus CVL HIT Den Bosch |
| | 1991-heden | lid Commissie voor de milieu-effectrapportage (m.e.r.) |

*Selectie van projecten bij Peutz bv*

| Project | Architect | Periode |
|---|---|---|
| Sint Franciscus Gasthuis Rotterdam | Kraayvanger / Hendriks Campman Tennekes | 1972-1978 |
| (ABN-)Amro hoofdkantoor Rotterdam | Kraayvanger Architecten | 1973-1980 |
| Academisch Ziekenhuis Groningen | Kruisheer Hallink, Team 4, Wytze Patijn | 1976-2000 |
| Instituut voor Aardwetenschappen Universiteit Utrecht | Haskoning | 1977-1980 |
| Sint Antonius Ziekenhuis Nieuwegein, | Hendriks Campman Tennekes | 1977-1984 |
| Bank Nederlandse Gemeenten te Den Haag | Thunissen Kranendonk Bečka | 1981-1985 |
| Universiteitsbibliotheek Groningen | Tauber | 1982-1987 |
| Overdekt winkelcentrum Nieuwegein | Hoogstad Weeber Schulze Van Tilburg | 1983 |
| Winkelpassages Almere | Bureau H.D. Bakker | 1983-1987 |
| Overdekt winkelcentrum Arnhem Presikhaaf | Treffers Polgar | 1984-1988 |
| Hotels Golden Tulip Barbizon Amsterdam | NACO | 1985-1988 |
| Gerechtsgebouwen te Amsterdam (Parnas) | Loerakker Rijnboutt Ruijssenaars Hendriks | 1985-1997 |
| Hoofdkantoor Unilever Rotterdam | Hoogstad | 1987-1989 |
| Luchthaven Schiphol: terminalgebouwen, nieuwe pieren, verkeerstorens etc. | Benthem Crouwel NACO | 1988-2004 |
| Rotterdam Plaza (Weena) | Lucas Ellerman | 1989 |
| Stadhuis Den Haag | Richard Meier | 1989-1992 |
| Revalidatiecentrum Amsterdam | Architectengroep 69 | 1990-1993 |
| Gerechtsgebouw te Leeuwarden | A. Bonnema | 1992-1995 |
| Luchtverkeersbeveiliging Schiphol | Groosman Partners | 1993-1995 |
| Auto HTS Arnhem | LIAG | 1994-1996 |
| Algemene Rekenkamer te Den Haag | Aldo van Eyk | 1994-1997 |
| HEAO Arnhem | LIAG | 1995-1997 |
| Onderzoek tramgeluid De Resident Den Haag | n.v.t. | 1995-2000 |
| Hoofdkantoor Shell Den Haag | LIAG | 1996-1997 |
| Sint Lucas Andreas Ziekenhuis Amsterdam, | Wiegerinck Architecten | 1996-2005 |
| Spoorzichtwoningen te Elst | Kristinsson | 1998-2004 |
| Onderzoek tramgeluid Ypenburg | n.v.t. | 2003-2004 |