May 2010
Reprint Report: UCPRC-RP-2010-03

Highway Noise Abatement: Planning Tools and Danish Examples

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This report is based on research performed by the Danish Road Institute-Road Directorate on behalf of the University of California Pavement Research Center for the California Department of Transportation, and is reprinted here in its original form.

Work Conducted as Part of the "Supplementary Studies for Caltrans QPR Program" Contract

PREPARED FOR:

California Department of Transportation (Caltrans)

Division of Research and Innovation

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DOCUMENT RETRIEVAL PAGE	**Reprint Report** UCPRC-RP-2010-03

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Prepared for: Caltrans	**FHWA No.:** CA101735C	**Date Work Submitted:** July 2009	**Date:** May 2010

Contract/Subcontract Nos.: Caltrans Contract: 65A0293 UC DRI-DK: Subcontract 08-001779-01	**Status:** Final	**Version No:** 1

Abstract:

This report presents a series of methods implemented in Denmark and other European countries for the assessment and control of the impacts of highway noise on the neighboring public. It introduces Danish guidelines for the assessment of noise impact. Also described are examples of noise abatement planning for three different cases: planning of new highways, planning of highway widening projects, and noise abatement on existing highways. Experience shows that there is no single approach that can remove all noise problems along highways. It will be necessary for more effective noise abatement to take different approaches together, including noise-reducing pavements, noise barriers, facade insulation, and proper land use strategies. Harmonized public-private partnership is also critical for successful implementation of public policy and regulations related to noise abatement.

Keywords: Highway noise, Noise abatement, Noise-reducing pavements, noise barriers, facade insulation

Proposals for implementation: No recommendations

Related documents:

- H. Bendtsen, H., Q. Lu, and E. Kohler. 2009. *Temperature Influence on Road Traffic Noise: Californian OBSI Measurement Study.* Reprint Report: UCPRC-RP-2009-02
- Bendtsen, H. 2009. *Noise Barrier Design: Danish and Some European Examples.* Reprint Report: UCPRC-RP-2010-04
- H. Bendtsen, H., Q. Lu, and E. Kohler. 2009. *Acoustic Aging of Asphalt Pavements: A Californian/Danish Comparison.* Reprint Report: UCPRC-RP-2010-01

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Highway noise abatement

Planning tools and Danish examples

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Danish Road Institute
Report 173
2009

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Executive summary

When constructing new buildings or roads in Denmark, special consideration is given to traffic noise. A new national noise map indicates that around 30 % of Danish homes are exposed to noise levels that exceed the threshold value of 58 dB (L_{DEN}) and that noise problems are concentrated in cities. This report presents a series of methods and strategies for noise abatement. There is no single method that can remove all noise problems along highways and in cities. It will be necessary to address the noise abatement on several different levels:

- **At the source:** this covers vehicles, tire, pavements, traffic and speed.
- **Along the propagation path:** in the form of noise barriers etc.
- **At the receiver:** in the form of façade insulation and local barriers.

The background for the report is experiences and ideas from the Danish Road Directorate as well as from other European countries. As an introduction, fourteen recommendations to National Road Administrations for good governance regarding noise management and abatement are presented.

In Denmark dwellings with road traffic noise of more than 58 dB (L_{DEN}) are considered exposed to noise. When planning of new residential areas the national metric of guideline for outside noise exposure is 58 dB (L_{DEN}). The Nordic prediction method, Nord2000, is used for road traffic. The Noise Exposure Factor (NEF) is the basis of all cost-benefit analyses of noise from road traffic. NEF is an expression of the accumulated noise load on all the dwellings in an area. It is calculated as the sum of the weighted noise loads on the individual dwellings in the area, so that dwellings with high noise levels weigh more than dwellings with less noise. The economic valuation of noise effects are based on market prices of dwellings as well as health effects.

As an important part of planning new highway sections in Denmark, an Environmental Impact Assessment (EIA) study is performed. Noise is one of the environmental components included in the EIA. When planning of new highways the noise guideline of 58 dB as L_{DEN} is used whenever possible. The guideline is used when a group of houses/dwellings are exposed to road traffic noise. For single houses in rural districts the noise guideline is normally not taken into account, instead façade insulation is offered if the noise exceeds 63 dB. Different measures of noise abatement can be considered in the planning of new highways. If it is possible and realistic to locate an alignment of the new highway that maximizes the distances to residential areas, this is normally a preferable solution. Noise reducing pavements are normally used when a new highway passes group of houses/dwellings.

Like in new highway projects noise is also taken into consideration when enlargements of existing highways are planned.

During the last decade the Danish Road Directorate has used around 20 mill DKK (2.7 mill € or 3.6 mill USD) every year for noise abatement along the existing highways and other state roads. Noise barriers have been the primarily tool applied for noise abatement. In some situations where it has not been possible to use noise barriers to achieve sufficient noise reduction, façade insulation has been used instead, typically by changing windows and doors to new and better noise reducing types.

In spring 2009 the Danish Road Directorate published a proposal for a new noise action plan for the existing state road network. The purpose of the plan is to describe initiatives that are planned to reduce road traffic noise along the state road network where the noise is considered unacceptable. The plan also describes noise initiatives in relation to maintenance of the road network as well as the improvement and enlargement of the state road network.

Since the mid 1980´s noise has been integrated in municipal land use planning. In the planning process of new residential areas a land use plan has to be developed and approved by the local municipality. A noise guideline at dwellings of 55 dB ($L_{Aeq,24h}$) has to be respected. In 2007 the noise indicator L_{DEN} was introduced to replace $L_{Aeq,24h}$ and the noise guideline was changed to 58 dB (L_{DEN}) to ensure the same protection level.

This report is produced by the Danish Road Directorate/Danish Road Institute for the California Department of Transportation. For comprehensive guidance on traffic sound issues in California please reference Caltrans' *Technical Noise Supplement* and *Traffic Noise Analysis Protocol* manuals.

Sammenfatning

Når der bygges nye veje eller bygninger i Danmark tages der særlige hensyn til vejtrafikstøj. Et nyt nationalt støjkort viser, at omkring 30 % af danske hjem udsættes for støj som overskrider den vejledende grænseværdi på 58 dB (L_{DEN}) og at støjproblemerne hovedsageligt forekommer i byerne. Denne rapport præsenterer metoder og strategier til støjbekæmpelse. Der findes ingen enkel metode for at fjerne alle støjproblemer langs motorveje og i byer. Det er nødvendigt at anvende støjbekæmpelse på forskellige niveauer:

- **Ved kilden:** dette dækker køretøjer, dæk, belægninger, trafik og hastighed.
- **Under udbredselse:** i form af støjskærme, etc.
- **Ved modtageren:** i form af facadeisolering og lokale skærme.

Baggrunden for denne rapport er erfaringer og idéer fra det danske Vejdirektorat samt andre europæiske lande. Som en introduktion præsenteres 14 anbefalinger for " good governance" angående støjledelse og -bekæmpelse.

I Danmark anses boliger at være udsat for støj hvis niveauet er højere end 58 dB (L_{DEN}). Når der planlægges nye boligområder anvendes normalt en grænseværdi på 58 dB (L_{DEN}). Den nordiske støjberegningsmetode, Nord2000, anvendes for vejtrafik. Støjbelastningstallet (SBT) er grundlaget for økonomiske analyser af støj fra vejtrafik. SBT er et udtryk af den samlede støjbelastning på alle boliger i et område. Det er beregnet som summen af de vægtede støjbelastninger på individuelle boliger i området, således at boligerne med høje støjniveauer vægtes tungere end boliger med mindre støj. Den økonomiske vurdering af støj er baseret på markedsværdien af boliger samt indflydelsen på helbred.

Som en vigtig del af planlægning af nye motorvejsstrækninger i Danmark, udføres normalt en VVM analyse. Støj er en af de miljømæssige faktorer, som tages med i VVM undersøgelserne. Når der planlægges nye motorveje, bliver en støjgrænseværdi på 58 dB som L_{DEN} anvendt, hvis det er muligt. Grænseværdien anvendes, når en gruppe huse/boliger er udsat for støj fra vejtrafik. For enkelte huse på landet, tages normalt ikke hensyn til grænseværdien. Der tilbydes i stedet facadeisolering, såfremt støjen overstigen 63 dB. Forskellige virkemidler til at reducere støjen kan anvendes, når der planlægges nye motorveje. Hvis det er muligt og realistisk at finde an linjeføring for den nye motorvej, som giver den maksimale afstand til boligområder, er det normalt den foretrukne løsning. Støjreducerende belægninger bruges normalt, når en motorvej passerer en gruppe huse/boliger.

Som ved nye motorvejsprojekter, tages også støj i betragtning, når der planlægges en udvidelse af eksisterende motorveje.

I løbet af den sidste 10-års periode har Vejdirektoratet gennemsnitlig brugt ca. 20 mio. DKK (€ 2.7 mio. eller USD 3.6 mio.) hvert år på støjbekæmpelse langs eksisterende motorveje og hovedlandsveje. Støjskærme er det vigtigste virkemidel. I nogle situationer, hvor det ikke har været muligt at anvende støjskærme for at opnå tilstrækkelig støjreduktion, er facadeisolering anvendt, typisk ved at udskifte vinduer og døre til mere støjreducerende typer.

I foråret 2009 udgav Vejdirektoratet et forslag for en ny støjhandlingsplan for det eksisterende vejnet. Formålet med planen er at beskrive tiltag for at nedsætte vejstøj langs statsvejene, der hvor støjniveauet anses for at værende uacceptabelt. Planen beskriver også støjinitiativer i forhold til vedligeholdelse og udvidelse af statens vejnet.

Siden midten af 1980'erne er støj indgået i lokalplanlægningen i forbindelse med planlægning og bygning af nye boliger. En støjgrænseværdi for boliger på 55 dB ($L_{Aeq,24h}$) skal overholdes. I 2007 blev støjindikatoren L_{DEN} introduceret som erstatning for $L_{Aeq,24h}$ og støjgrænseværdien blev ændret til 58 dB (L_{DEN}) for at sikre samme beskyttelsesniveau.

Denne rapport er udarbejdet at Vejdirektoratet/Vejteknisk Institut i Danmark for California Department of Transportation i USA.

Preface

Noise abatement is a big challenge for European and American transportation agencies.

Noise is an important factor to be considered when it comes to developing, upgrading and maintaining national highway networks in Europe. Significant financial resources are used to incorporate noise abatement measures in developing or upgrading national highways. This report presents a series of methods and strategies for assessing and addressing noise impacts. The background for the report is procedures and experiences from the Danish Road Directorate as wells from other European countries.

The project is carried out under the framework of the research technical agreement titled "Supplementary Studies for the Caltrans Quieter Pavement Research Program" between California Department of Transportation (Caltrans) and University of California Pavement Research Centre (UCPRC) as a part of the task: "Policy documents: guidelines for Caltrans policy". The Danish Road Institute/Road Directorate (DRI-DK) is subcontracted by UCPRC to work on the project.

Caltrans has asked DRI-DK to produce this brief catalogue of ideas on noise abatement and integration of noise considerations when planning and constructing new highways as well as when maintaining existing roads based on Danish experiences. The use of different measures for noise abatement like implementing noise reducing pavements, noise barriers, facade insulation, etc. are included. Land use planning and design of new housing along existing highways as well as noise policies and strategies will are also presented.

The report is compiled and written by Hans Bendtsen DRI-DK. Jakob Fryd from the Planning Division of the Danish Road Directorate and Bruce Rymer from Caltrans, Division of Environmental Analysis has given comments and advice. The author will like to thank everybody who has made it possibly to compile this report for their efforts and qualified work. This report is written from the Danish perspective and does not represent official Caltrans policy. This report is produced by the Danish Road Directorate/Danish Road Institute for the California Department of Transportation. For comprehensive guidance on noise issues in California please reference Caltrans' *Technical Noise Supplement* [8] and *Traffic Noise Analysis Protocol* [9] manuals.

Forord

Støjproblemer er en stor udfordring for vejmyndighederne både i Europa og USA.

Støj er en vigtig faktor som indgår i forbindelse med nybygning, opgradering og vedligeholdelse de nationale vejnetværk i Europa. Væsentlige økonomiske ressourcer anvendes på støjreducerende foranstaltninger. Denne rapport præsenterer en serie metoder og strategier for integration af støjhensyn i vejplanlægningen. Baggrunden for denne rapport er metoder og erfaringer fra det danske Vejdirektorat samt andre europæiske lande.

Projektet er gennemført som en del af den tekniske forskningsaftale "Supplementary Studies for the Caltrans Quieter Pavement Research Program" mellem California Department of Transportation (Caltrans) og University of California Pavement Research Centre (UCPRC), som en del af opgaven: "Policy documents: guidelines for Caltrans policy". Det danske Vejteknisk Institut/Vejdirektorat er underleverandør til UCPRC for at arbejde på projektet.

Caltrans har bedt Vejteknisk Institut/Vejdirektorat om at producere dette idékatalog om støjbekæmpelse og integrering af støjhensyn når der planlægges og bygges nye motorveje samt i forbindelse med vedligeholdelse af eksisterende veje. Anvendelse af forskellige virkemidler som støjreducerende belægninger, støjskærme, facade isolering etc. er medtaget. Fysisk planlægning og design af nye boligområder langs eksisterende motorveje såvel som politikker og strategier for støjbekæmpelse er også medtaget.

Rapporten er udarbejdet og skrevet af Hans Bendtsen Vejdirektorat/Vejteknisk Institut. Jakob Fryd fra Planlægningsafdelingen i Vejdirektoratet i Danmark og Bruce Rymer fra Caltrans, Division of Environmental Analysis har kommenteret rapporten. Forfatteren vil gerne takke alle, som har gjort det muligt at udarbejde denne rapport. Rapporten er skrevet fra et dansk perspektiv og præsenterer derfor ikke officiel Caltrans politik.

1. Introduction

When constructing new buildings or roads in Denmark special consideration is given to traffic noise. A new national noise map indicates that around 30 % of Danish homes are exposed to noise levels that exceed the guideline value of 58 dB (L_{DEN}) and that noise problems are concentrated in cities.

Road traffic noise may impact people in different ways such as impacting communication, and interrupting sleep. New studies show that noise can contribute to an increased risk of cardio-vascular diseases. The effects of noise are also of an economic nature because noise influence housing prices in areas exposed to noise. Furthermore, health related issues caused by noise also incur costs. The socio-economic costs related to road traffic noise have been calculated to amount to between 0.8 and 1.2 billion Euro (1.1 to 1.6 billion USD) annually in Denmark [6].

1.1 Methods for noise abatement

Figure 1.1. Façade insulation by applying a "glass box" in front of an existing window of bedroom or living room. Example from an apartment building in Århus, Denmark [10].

There is no single method that can remove all noise problems along highways and in cities. It will be necessary to address noise abatement on several different levels [7]:

- **At the source:** this covers vehicles tires, pavements, traffic, speed and driving patterns. When noise is reduced at the source, it has an effect on all buildings and open space areas that are affected by the noise along a given roadway section. Noise reduction on pedestrian and bicycle paths along the road will also be an improvement for pedestrians and cyclists.

- **Along the propagation path:** in the form of noise barriers and berms. By using noise barriers, a noise reduction will be experienced in buildings and open space areas that are behind the barriers, but not for the areas in front of the barriers.
- **At the receiver:** in the form of façade insulation and local barriers. Façade insulation is limited to reducing the noise level inside when the windows are closed, whereas the noise level outside remains unaffected.

Additional methods can be applied to reduce noise such as barriers, noise reducing pavements, traffic diversion, speed reductions, limiting heavy vehicle access at night, vegetation, and façade insulation to name a few. Environmental zones with speed limits can also be used to reduce noise levels.

1.2 Organisation of noise abatement

Often nothing is done to reduce noise problems, perhaps due to the fact that there often is no clear "owner" of the problem or a lead organisation has not been identified to take initiatives for improvements. Also, problems might seem overwhelming; there could be a lack of useful ideas or alternatives to finance the proposed activities all resulting in nothing being done. However, it is very important to support and stimulate positive development, even though the hurdles seem insurmountable and the results in the beginning are very limited.

To aid in initiating and carrying out the noise related work in the municipal authorities or road administrations, a special noise secretariat could be established, whose employees would mainly deal with planning, initiating and managing the local efforts. A concerted effort of different municipal departments and other affected parties such as private citizens, owner and tenants' associations and the business community is advisable.

A municipal authority is a large organisation that continuously plans and implements activities in the construction, running and maintenance fields. It could be considered a municipal goal that traffic noise issues become an integral part in all relevant activities such as road maintenance, building maintenance and renovation of open space areas and parks.

City planning and possible adjustments within existing urban areas are tasks that are handled by the municipal authorities. Noise is an important parameter that is normally taken into consideration when building new housing areas. However, it would also be useful to include noise as a parameter when addressing issues such as rebuilding and expanding housing areas as well as in projects on rebuilding and widening roads or traffic calming. A starting point could be drawing up a set of municipal goals for noise related issues in existing urban areas.

There is a need to activate as many assets as possible for the work to reduce noise. A municipal authority can play an important role in relation to private citizens and the business community. Danish research shows that in certain cases private citizens are willing to participate in funding noise reducing measures [34]. It is important to inform citizens of the technical and economic possibilities as these are not always common knowledge.

A noise secretariat can play an important role as an “idea bank”, initiative taker, and coordinator. In this forum one could gather citizens affected by noise and present them with technical solutions as well as helping them to organise noise reducing efforts that could be achieved and paid for, either in part or fully, by the house owners and the citizens themselves. The municipal efforts could consist of organisation and coordination with a view to activating the assets and resources available amongst the citizens, and also to take part in the carrying out of certain tasks. Furthermore the possibility to share the costs of certain activities could be examined.

Figure 1.2. When fences at residential areas are to be renewed by the owner they can be constructed as noise barriers. This might not increase the cost significantly but the noise has to be considered when selecting design, construction and material for the new fence [10].

There are several examples from both Denmark and abroad that show how road traffic noise reducing projects have been financed [35]. House owners can implement noise reducing measures at their own homes at their own cost. A rise in property value as a result of the noise reducing measures can motivate some home owners to finance these measures themselves. Depending on the current tax situation, increased property values mean that the both the state and the municipality receive increased taxes, that can again be reinvested in other noise reducing projects. In apartment buildings noise reduction can be achieved by changing to specialized noise insulating windows that can be financed over the annual maintenance budget that could also be used to finance other noise reducing projects.

Figure 1.3. When the windows of apartment buildings and single family houses along highways have to be replaced by the owner, noise can be taken into consideration when selecting the new windows. Without a significant increase in cost, improved noise reduction and energy reductions can often be achieved [10].

Figure 1.4: Public meeting on noise abatement etc in relation to a highway project.

In connection with noise reducing projects that are planned, it can be recommended to involve those citizens that will be affected by these projects. This will give the citizens influence on which solutions that will be chosen and give them a realistic picture of which level of noise reduction to expect. Citizens can become actively involved and in some cases even be joint partners in the planned projects. Involved citizens might become motivated to implement further measures which can improve the effect and quality of the planned improvements.

1.3 Structure of the report

As an introduction, fourteen recommendations to National Road Administrations for good governance regarding noise management and abatement are presented in Chapter 2. Noise guidelines, prediction of noise and socio-economic evaluation of noise are introduced in Chapter 3. This is followed by three typical planning situations where noise can be considered in relation to highways:

- Planning of new highways in Chapter 4.
- Planning of widening existing highways in Chapter 5.
- Noise abatement at existing highways in Chapter 6.

Finally Chapter 7 presents, how noise is taken into consideration when building new residential areas along highways.

All the noise levels presented in this report are A-weighted. The unit “dB” is used in this report and it is equal to what is often denoted “dB(A)” and “dBA”. The following exchange rates are assumed in this report: 1 € = 7.45 DKK and 1 USD = 5.50 DKK.

2. Good governance in noise abatement

The following fourteen recommendations to National Road Administrations (NRA) for good governance regarding noise management and abatement [3] were developed by a European noise group from the Conference of European Directors of Roads (CEDR) [5]:

1. In Europe, the main noise problems occur along the existing road network and the order of magnitude of the problems is increasing with increasing traffic volume. Therefore, noise abatement along these roads is crucial in order to start a process where the noise exposure over the long term is reduced.
2. It is important to include noise issues at the early planning stage for new road developments. In adopting such an approach, future noise problems may be avoided. The basis for such an approach will normally be the national noise guidelines.
3. Noise should be included as an important parameter in projects where existing roads are improved to accommodate increasing traffic volumes or increasing speeds. This can improve the noise environment for people living in close proximity to the upgraded road.
4. When planning to incorporate noise abatement measures on new, existing and reconstructed roads, it is important to adopt a time horizon of 20 to 30 years, when predicting future noise from increasing traffic volumes and planning noise measures. This will enhance the robustness of specific noise projects.
5. When road construction work is carried out in close proximity to residential areas, it is relevant to consider construction noise when planning and realizing such works. Residents close to the construction site should get sufficient information.
6. In projects where noise abatement measures are planned and designed, it is recommended to establish a good communication strategy to ensure a two way communication process with the public. In this way, residents may take ownership of the project and their expectations to what noise mitigation may deliver in terms of noise reductions may be more realistic.
7. Noise barriers erected on roads have not only visual impacts for the residents living in close proximity to the road but also the driver and their passengers. It is therefore, important to use barrier designs that are appropriate to the specific location where they are installed.
8. The use of noise reducing pavements should be considered when selecting noise mitigation measures because such pavements are purported to provide a cost effective tool in noise abatement. In upgrading existing roads, the use of noise reducing pavements is often a low cost measure of noise abatement.

9. Integration of noise as an active component in Pavement Management Systems can increase the optimal use of noise reducing pavements in the ongoing road pavement renewal process.
10. To enhance the current market for noise reducing pavements the development and use of a noise labeling system in member states should be considered.
11. In order to reduce noise emissions from individual vehicles, it would be invaluable if individual NRAs lobby at EU level to promote tighter noise limits for the EU type approval of new vehicles and tires.
12. Like all elements of infrastructure, noise abatement measures such as pavements, barriers, façades, etc. need to be maintained on a regular basis.
13. There is a need for further research and development in improved and long time durable measures of noise abatement like optimized noise reducing pavements, tires, vehicles etc.
14. A continuation of international cooperation on noise abatement and management between the NRAs is value adding and fruitful. In the coming years issues like noise mapping and noise action plans in relation to European Noise Directive (END) [22] seems highly relevant.

Figure 2.1. When road construction work is carried out in close proximity to residential areas, it is relevant to consider construction noise when planning and realizing such works.

3. Guidelines, prediction and evaluation

3.1 Noise guidelines

For many years, the noise indicator $L_{Aeq,24h}$ has been used in Denmark when assessing noise from road traffic. $L_{Aeq,24h}$ is an expression of the "average" noise level over the 24 hours of the day. The guideline for noise exposure outside at the façade of residential buildings has been 55 dB (not including the noise reflected from the façade).

On the background of a European Union Directive on environmental noise [22] the new indicator L_{DEN} was introduced by the Environmental Protection Agency in 2007 in a new guideline on road traffic noise [23]. For L_{DEN} the noise (as L_{Aeq}) is predicted for the day, evening and night period. 5 dB is added to the evening time level and 10 dB is added to the night level in order to make a kind of compensation for when people are more sensitive to noise than during daytime. The three time periods are in Denmark defined as:

- **Day:** 07 – 19, length 12 hours
- **Evening:** 19 – 22, length 3 hours
- **Night:** 22 – 07, length 9 hours

L_{DEN} is then calculated as the weighted sum of the adjusted noise levels for the three periods of the day using the below formula:

$$L_{DEN} = 10 \log \{12 \cdot 10^{Lday/10} + 3 \cdot 10^{(Levening+5)/10} + 9 \cdot 10^{(Lnight+10)/10}\} \quad (1)$$

According to [23] for Danish conditions with a "normal" distribution of the traffic over the 24 hours of the day L_{DEN} can be predicted by adding 3 dB to $L_{Aeq,24h}$:

$$L_{DEN} = L_{Aeq,24h} + 3dB \quad (2)$$

Therefore the existing noise guide lines were adjusted by 3 dB when L_{DEN} was introduced in order to maintain the same level of noise protection as when $L_{Aeq,24h}$ was used. In other European countries other relations between L_{DEN} and $L_{Aeq,24h}$ are used [3].

Table 3.1. Danish noise guidelines for road traffic noise expressed as L_{DEN} [23].

Type of area	Guideline L_{DEN}
Recreational areas at the countryside, summer house areas, camp-sites etc.	53 dB
Residential areas, kindergartens, schools and education facilities, homes for elderly people, hospitals etc. Allotment gardens, outside recreational areas and parks.	58 dB
Hotels and offices etc.	63 dB

The new Danish noise guidelines for road traffic noise, expressed as L_{DEN}, can be seen in Table 3.1. It must be emphasised that it is guidelines and not mandatory noise levels that must not be exceeded anywhere along the highway and road network. These guidelines are generally used when planning and constructing new residential areas etc, but are also taken into account when planning new roads and highways.

Noise metrics and guidelines are not consistent throughout Europe and a report from CEDR [3] gives an overview of noise guidelines used in different European countries. Denmark is currently in a transition period where $L_{Aeq,24h}$ has been replaced with L_{DEN}. This is reflected in this report, where some examples use $L_{Aeq,24h}$ and other examples use L_{DEN}.

3.2 Noise prediction

In Denmark, the Nordic model for road traffic noise has been the official prediction method since the 1970s. In 2007 the Environmental Protection Agency [23] introduced a new version called Nord2000 [25, 26] which was developed as a joint Nordic project. Nord2000 is a completely new model and in principle there are no links to the old model. Both the source data and propagation model are new components.

The idea was to develop a general sound propagation model and source-specific prediction methods for road and rail traffic as well as other types of environmental noise sources. Nord2000 now consists of source models for road and rail traffic and a propagation model. The model works in 1/3 octave bands and for any normal weather type. Noise levels – for historical reasons – have been computed for different weather conditions in the earlier Nordic models. Now all types of environmental (road and rail etc) noise can be computed for the same weather.

The source model distinguishes between: 1) light, 2) medium and 3) heavy vehicles. The 1/3 octave-band sound power level of each source is calculated from input parameters selected by the user, determining the sound power of tire/road noise and propulsion noise, respectively. The noise emission data are based on comprehensive wayside noise measurements. The Danish noise emission data are based on measurements taken during 1999 – 2000 of 4000 vehicle pass bys at 21 sites with speed limits of 30 - 110 km/h on pavements of 2 – 18 year old dense asphalt concrete or stone mastic asphalt and constructed with 8 – 12 mm maximum aggregate.

Emission levels of the new data set tend to be higher than in the former 1996 version of the Nordic method. It is not clear whether the higher emission values are due to changes in vehicle fleet or tyres.

The propagation model is based on geometrical ray theory and gives algorithms for computing 1/3 octave band sound attenuation along the path from source to receiver taking into account the terrain shape as well as ground type (impedance) and roughness.

Nord2000 deals with attenuation under different weather conditions and is suited for computing yearly average noise levels. Various classes of weather have been defined and their frequency of occurrence has been determined based on data from meteorological observations. The yearly average is obtained by computing the noise level for each weather class and then combining these levels weighted with their occurrence. For example: the effect of using precise weather conditions at 300 m from a road with a North-South alignment, the yearly average noise level in Denmark is 2 dB higher at receivers east of the road than at receivers west of the road. The reason for the difference is that the most common wind direction is from the west. The NORD2000 model predicts outdoor noise levels and does not specifically deal with indoor noise.

The Nord2000 method is developed for the environmental and transportation authorities of the Nordic countries. This taxpayer-developed method consists of a users guide [26] and a large series of formulas that are available for free (see reference list of [26]). It is the challenge of private software companies on the open market to provide commercial computer based versions of Nord2000. Currently, there are commercial software products based on the NORD2000 model available on the market. But in order to make NORD2000 available to governmental authorities and the public that supported its development, a simple or 'lite' version of the Nordic model is available. The 'lite' version covers a series of typical standard cases for roads, barriers and geometry with pre-calculated transfer functions for 30 selected cases. Default traffic data for five typical types of road configurations can be edited by the user to fit any specific case. This PC version is working in English language and can be downloaded free of charge from [27]. The user has to define input data like traffic, distribution of traffic over the day, road surface type, noise barriers etc.

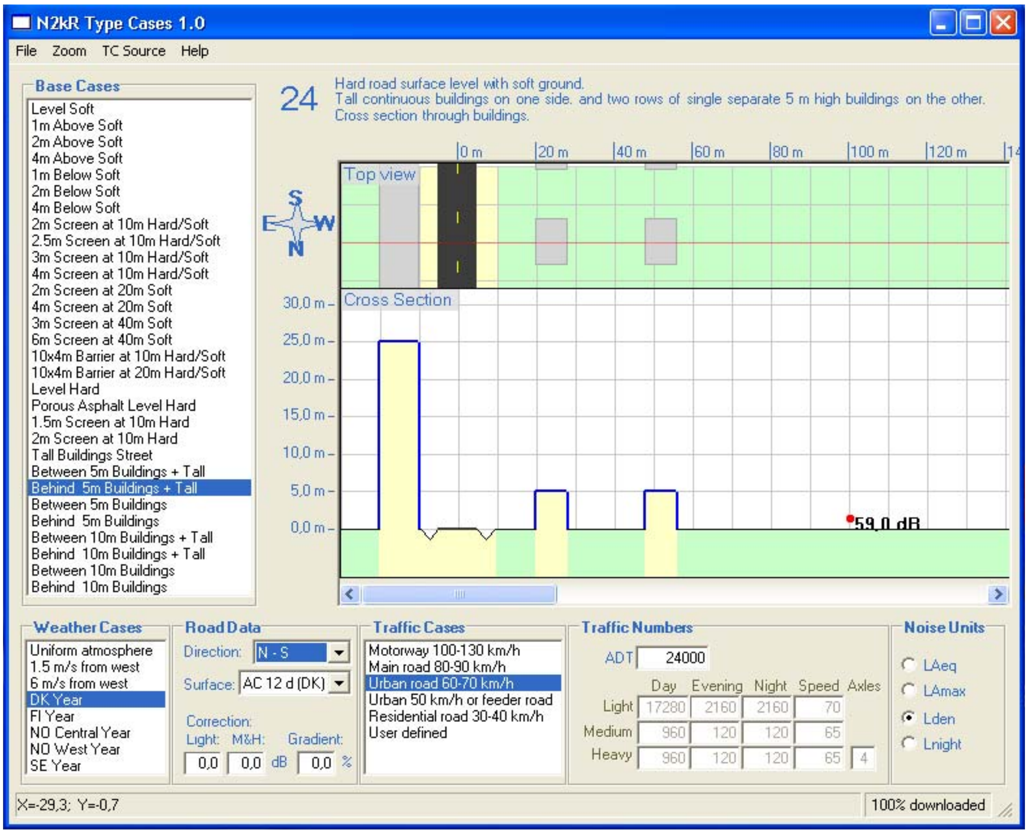

Figure 3.1. "Front page" of the simple PC program for the Nord2000 road traffic noise prediction method used in Denmark and the other Nordic countries [27].

The free downloadable version of the software communicates with a server in Norway with a huge database of pre-predicted results. The results are outdoor noise levels and they can be delivered as $L_{Aeq,24h}$, L_{DEN}, L_{night} and L_{AFmax}. In this way road, traffic and town planners have easy access to Nord2000.

3.3 The Noise Exposure Factor

The Noise Exposure Factor (NEF – in Danish "Støjbelastningstal", "SBT") is the basis of all Danish cost-benefit analyses of noise from road and rail traffic [11]. It is an expression of the accumulated noise load on all the dwellings in an area. It is calculated as the sum of the weighted noise loads on the individual dwellings in the area, so that dwellings with high noise levels weigh more than dwellings with less noise.

Calculations of the NEF are based on noise levels in three locations around a dwelling: inside the dwelling, outside the dwelling, and at outdoor activity areas connected to the dwelling. The noise level outside the dwelling is calculated as free-field values on the facade and can be interpreted as the noise level to which the inhabitants are exposed, when the windows are open. The weight assigned to each of these situations depends on how often it is occupied and whether it is an ordinary dwelling or a weekend cottage/summer house.

The weights can be seen in Table 3.2. The method to calculate NEF values has been developed when $L_{Aeq,24h}$ was used as the noise indicator. In order to use the method for noise predicted as L_{DEN} 3 dB has to be added to all the noise intervals in Table 3.3 and 3.4.

Table 3.2. Weight assigned to various situations when calculating NEF [14].

	Outside dwelling	**Outdoor areas**	**Inside dwelling**
Ordinary dwelling	0.2	0.2	0.6
Weekend cottage etc.	0.1	0.3	0.1

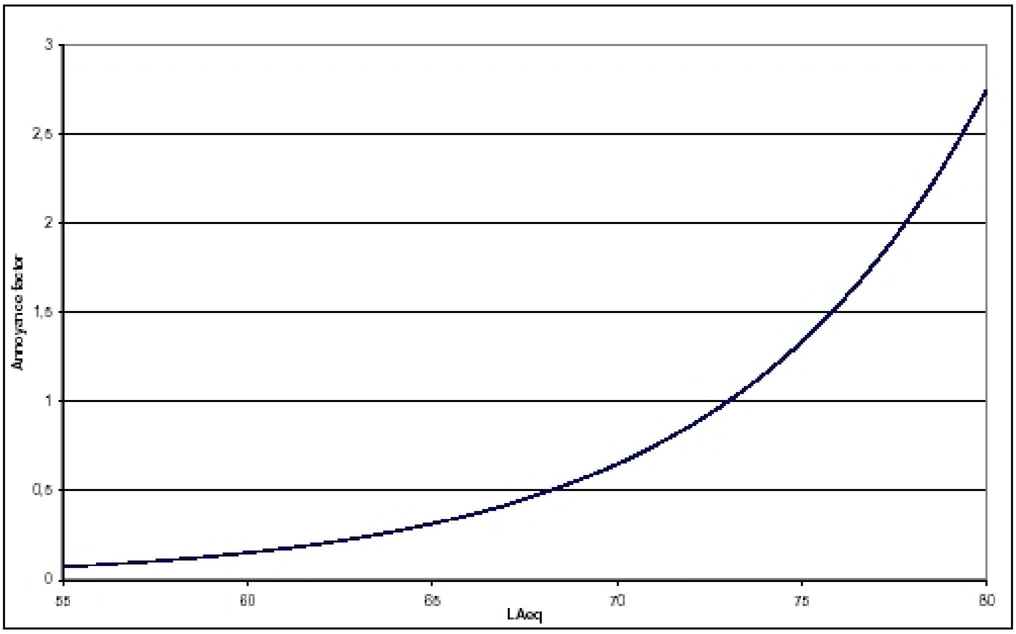

Figure 3.2. The relationship between the annoyance factor and the noise outside ordinary dwellings. Noise levels are free-field levels on the façade [11, 14].

The NEF is based on a dose-response relationship given by:

$$\text{Annoyance factor} = 0.01 * 4.22^{0.1(L_{Aeq} - K)} \quad (3)$$

Where:

K = 16 and L_{Aeq} starts at 30 dB for noise inside dwellings.

K = 41 and L_{Aeq} starts at 55 dB for noise outside ordinary dwellings.

K = 36 and L_{Aeq} starts at 50 dB for noise outside weekend cottages etc.

The actual annoyance factor for a specific noise level is derived from a dose-response relationship for noise outside ordinary dwellings. The relation between the annoyance factor and the noise levels is shown in Figure 3.2.

The number of dwellings subjected to noise in each of the three situations are calculated in intervals of 5 dB using the NORD2000 noise prediction method (see Section 3.2) and multiplied by the corresponding annoyance factor (Table 3.3). The resulting values are summed and multiplied by the corresponding weight from Table 3.2 to give the NEF for the situation for the type of dwelling. Finally the total NEF is calculated by adding the values for each situation and each type of dwelling. An example for calculating the NEF for ordinary dwellings is shown in Table 3.4.

Written as a formula, the NEF can be calculated as:

$$NEF = \sum_{k} \sum_{j} w_{jk} \sum_{i} a_{ijk} N_{ijk} \quad (4)$$

Where:

k = ord, wec (ordinary dwelling, weekend cottage).

j = od, oa, in (outside dwelling, outdoor areas, onside dwelling).

i = 1, 2, 3, 4, 5, 6 (5-dB intervals starting at 30 dB, 55 dB or 50 dB, see table 3.3).

wjk = {0.2, 0.2, 0.6}k= ordinary dwelling, {0.1, 0.3, 0.1}k= weekend cottage.

aijk = 0.11, 0.22, 0.45, 0.93, 1.92, 3.94.

Nijk is the number of dwellings in the various 5-dB intervals

Table 3.3. Annoyance factor for the individual dwellings [14].

Noise level in dB	Type of area			
	Ordinary dwelling		Weekend cottage etc	
	Indoors	Outside	Indoors	Outside
30.1-35.0	0.11	-	0.11	-
35.1-40.0	0.22	-	0.22	-
40.1-45.0	0.45	-	0.45	-
45.1-50.0	0.93	-	0.93	-
50.1-55.0	1.92	-	1.92	0.11
55.1-60.0	3.94	0.11	3.94	0.22
60,1-65.0	-	0.22	-	0.45
65.1-70.0	-	0.45	-	0.93
70.1-75-0	-	0.93	-	1.92
75.1-80.0	-	1.92	-	3.94

The NEF makes it possible to compare the benefits of different noise reducing strategies such as barriers, pavements, and sound insulation in a manner that accounts for the differences in where the noise is reduced. This accounting approach allows several different noise mitigation strategies and combinations of strategies to be compared more equitably. In practice however, NEF-calculations are usually simplified using only the noise level outside the façade of dwellings and assigning this the weight 1, thus omitting the separate valuation of indoor noise and noise on outdoor areas.

Table 3.4. Example of a calculation of NEF for ordinary dwellings [11].

Outside dwellings			**Outdoor areas**			**Inside dwellings**		
Noise at façade [dB]	**No. of dwellings**	**Annoy. factor**	**Noise outside [dB]**	**No. of dwellings**	**Annoy. factor**	**Noise inside [dB]**	**No. of dwellings**	**An-noy. factor**
65-70	163	0.45	65-70	37	0.45	40-45	163	0.45
60-65	207	0.22	60-65	15	0.22	35-40	207	0.22
55-60	123	0.11	55-60	19	0.11	30-35	123	0.11
Weight		0.2	Weight		0.2	Weight		0.6
NEF		26.5	NEF		4.4	NEF		79.4
Sum of NEF = 110.3								

By using this simplification, it is not possibly to make a correct evaluation of the effect of establishing façade insulation as a tool for noise abatement, and evaluations of noise barriers may also be misleading due to actual differences in noise levels at the façade and on the outdoor areas.

3.4 Socio-economic assessment of noise

In 1999, the Danish Ministry of Finance published a guide to preparing socio-economic assessment of consequences [12] of construction works etc. The aim of this was to achieve greater uniformity in socio-economic assessments of initiatives in the traffic and energy sectors and in relation to investments in administration buildings and investments in the educational sector. The choice of Cost-Benefit Analysis (CBA) or of cost-effectiveness assessment (CEA) depends on the characteristics of the initiative, but CBA is presented as the primary method [12].

The guidelines contain standards and principles for calculation of central parameters in the analyses. Valuation should be based on net present value using a calculation interest rate of 6 percent and a 20 % tax cost factor to account for the costs to society due to financing through taxes. For projects with time horizons of more than 20 years the tax cost factor can be left out if a calculation interest rate of 7 percent is used.

In 2003, the Ministry of Transport published a manual for socio-economic analysis based on the above guidelines from the Ministry of Finance [13]. The assessment of noise is based on annoyance at dwellings whereas noise at occupational buildings and institutions is not included. Noise levels below 55 dB ($L_{Aeq,24h}$) are not included and there is no differentiation between day and night time noise. This relates to the Danish guideline value for road traffic noise at dwellings which is 55 dB ($L_{Aeq,24h}$).

Valuation of noise effects are based on market prices. Ministry of Transport continuously publishes a catalogue of key values for use in analyzes. In the 2004 version of the catalogue [15], the values put on noise are based on a new house price survey (the hedonic method) [16]. The value put on noise annoyance is 35,853 DKK (4,812 € or 6519 USD) per NEF (2003 price level). 23,018 DKK (3,090 € or 4185 USD) per NEF is added for costs to society due to health effects, which are not included in the reduced house prices. The total value of noise is thus 58,871 DKK (7,902 € or 10704 USD) per NEF (2003 price level).

The assessment of health effects is based on a study of the international literature on the subject [17]. It is concluded that the documentation of actual health effects of noise from road traffic is weak and without clear evidence, and the estimates of costs are therefore done with reservation. There is some evidence of a connection between noise and ischaemic heart disease, although the risk factors related to it are uncertain. A risk factor of 1.09 per 5 dB increase in noise levels is adopted, and it is decided also to use this factor for hypertension. Other possible health effects are left out of the assessment of costs.

The catalogue [15] also presents marginal costs of noise from transportation. The noise costs per driven vehicle kilometre (2003 price level) can be seen in Table 3.5. The uncertainty on these values is estimated to be minus 50% to plus 100%.

Table 3.5. Danish estimated noise costs per driven vehicle kilometre (2003 price level) [15].

Vehicle type	DKK/km	€/km	USD/km
Passenger cars	0.12	0.016	0.022
Light Goods Vehicle	0.17	0.023	0.031
Heavy Goods Vehicle	0.25	0.034	0.046
Bus	0.55	0.074	0.100

This subject of socio-economic costs of noise is discussed more in the DRI-DK report “Cost-benefit analysis on noise-reducing pavements” [11].

4. Planning of new highways

As an important part of planning new highway sections in Denmark, an Environmental Impact Assessment (EIA) study is performed. Noise is normally one of the environmental components included in the EIA.

4.1 An example

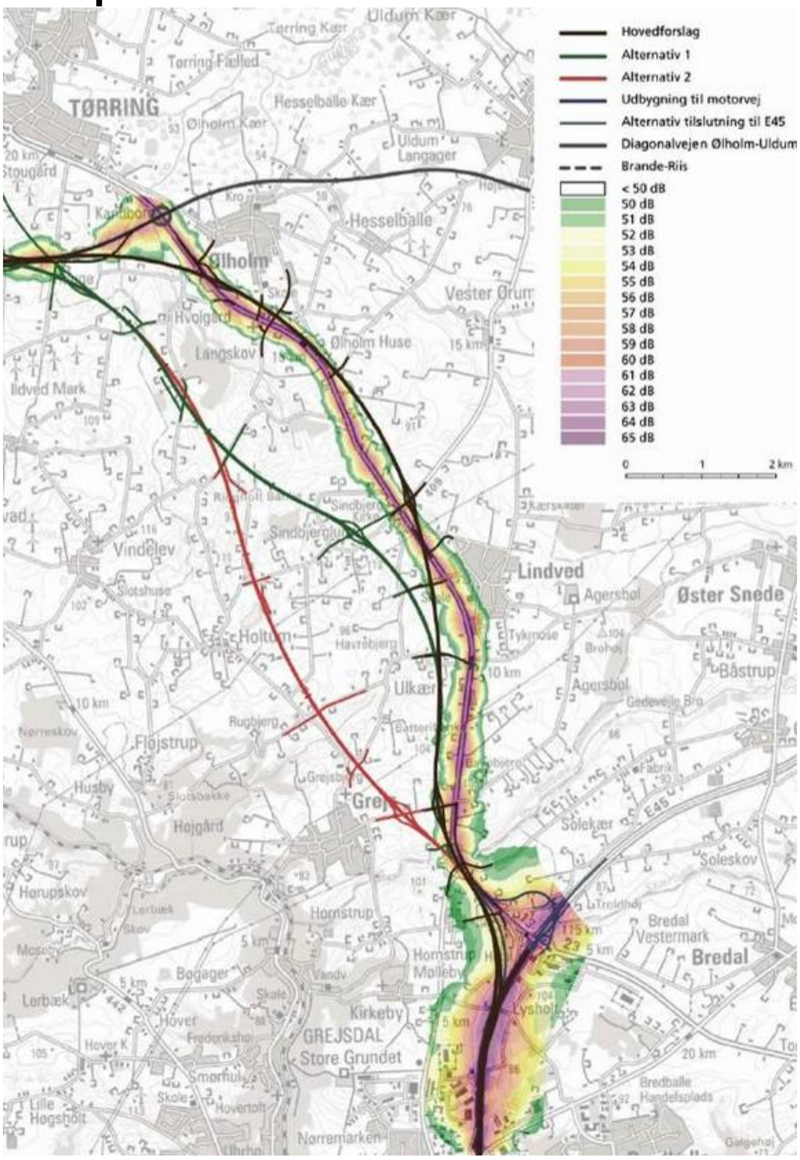

Figure 4.1. Planning of a new highway between Ølholm and Vejle. Noise mapping of the reference situation in 2015 at a receiver height of 1½ m (5 feet). The noise contours along the existing road are presented [21].

The following is an example of how noise was handled in the EIA [21] conducted as a part of planning a new highway in Denmark between Ølholm and Vejle. In this example, $L_{Aeq,24h}$ is used as the indicator for noise.

For the existing road network with no new highway, the noise was mapped for 2015 taking into consideration an increase in traffic - this is called the reference situation. The existing road network includes the existing highway carrying the main traffic as well as the other roads in the district that will have a change (primarily reduction) of traffic of 15 % or more if the new highway is constructed. Three different traces for the new highway have been evaluated:

- Main Solution ("Hovedforslag" in Danish).
- Alternative 1.
- Alternative 2.

Noise mapping has been conducted for these four situations using the $L_{Aeq,24h}$ noise indicator. The noise maps can be seen in Figures 4.1, 4.2 and 4.3.

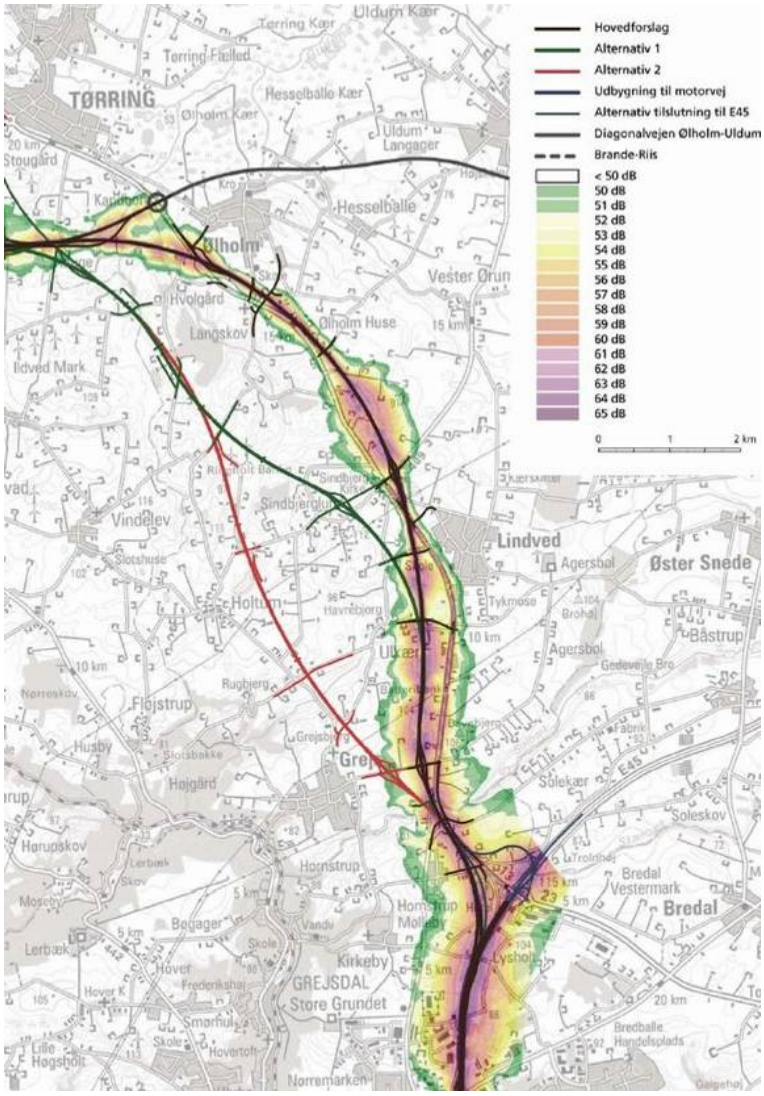

Figure 4.2. Planning of a new highway between Ølholm and Vejle. Noise mapping of the Main Solution in 2015 at a receiver height of 1½ m (5 feet). The noise contours along the existing road as well as the suggested new highway is presented [21].

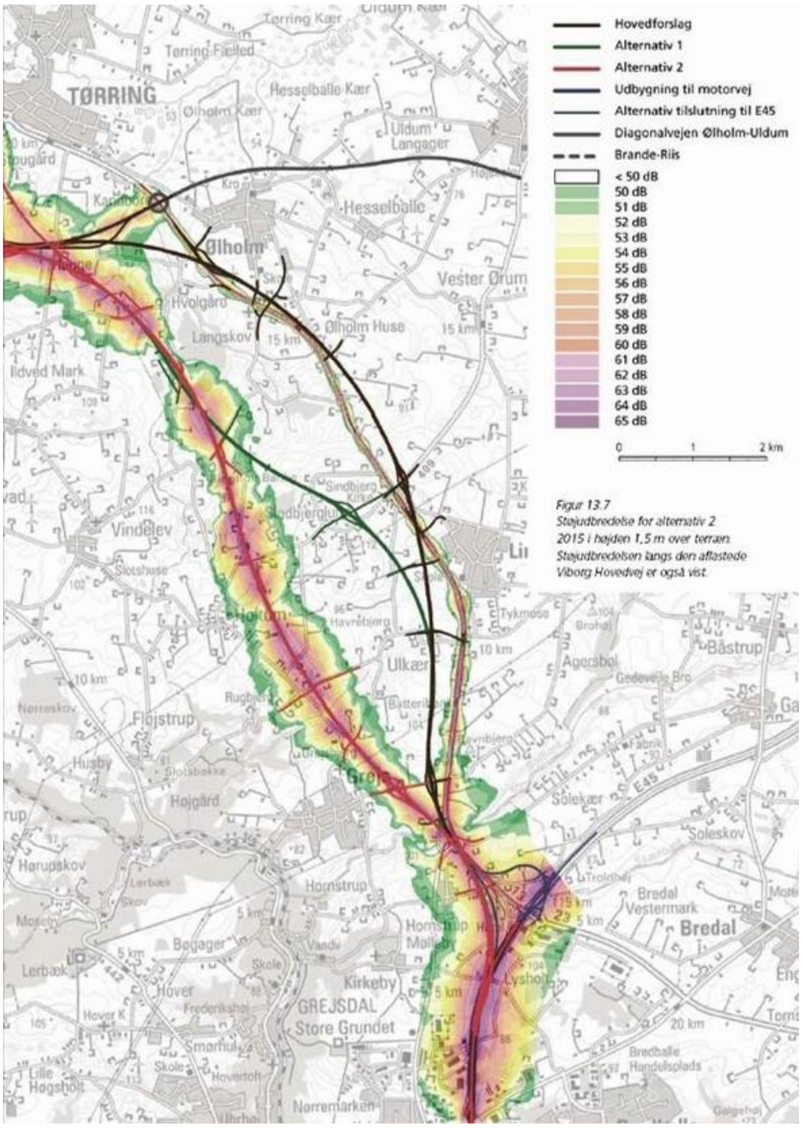

Figure 4.3. Planning of a new highway between Ølholm and Vejle. Noise mapping of Alternative 2 in 2015 at a receiver height of 1½ m (5 feet). The noise contours along the Alternative 2 alignment of the new highway and the existing road are presented [21].

The number of dwellings exposed to different noise levels has been counted on the background of the noise mapping and the Noise Exposure Factor (NEF) which has been predicted (see Table 4.1).

Table 4.1. Summary of noise mapping. Number of dwellings exposed to noise, the NEF and the change of NET in relation to the reference situation [21].

Scenario	**Total of noise exposed dwellings**					**NEF**	**Change in NEF**
	55-60 dB	**60-65 dB**	**65-70 dB**	**>70 dB**	**Total**		
Reference	272	153	197	38	660	153.8	-
Main Solution	189	159	214	0	562	122.3	31.5
Alternative 1	201	132	222	0	555	116.2	37.6
Alternative 2	222	133	221	0	576	119.2	34.6

In the reference situation, 660 dwellings along the road network being studied, are exposed to more than 55 dB. This represents a NEF value of 153.8. In the main solution this is reduced by 98 to 562 dwellings with a reduction of NEF by 31.5. Alternative 1 and 2 represents slightly higher reductions of NEF of respectively 37.6 and 34.6. The EIA [21] discusses noise barriers, noise reducing pavements and wide greenbelts as possible measures of noise abatement, but at this state in the planning process no decisions were taken on which measures of noise abatement to implement.

4.2 General measures of noise abatement

The old noise guideline of 55 dB $L_{Aeq,24h}$ was replaced in 2007 with 58 dB L_{DEN} for use in the planning of new highways. The guideline is used when a group of houses/dwellings are exposed to road traffic noise. For a single, isolated house in rural districts, the noise guideline is normally not taken into consideration. Instead façade insulation is offered to the owners if the noise exceeds 63 dB.

Different measures of noise abatement can be considered in the planning of new highways. If it is possible and realistic to locate an alignment of the new highway that ensures long distances to residential areas, this is a preferred solution. But there can be other environmental, technical and/or economical factors that also have to be taken into consideration and which also have an influence on the final decision of the alignment of the new highway through the terrain and urban areas. The following measures of noise abatement are often considered:

- Placing the highway in a cutting and maybe using the surplus soil/material to establish embankments along the highway.
- Noise barriers and earth walls.
- Total covering of the highway by a applying a cut and cover process.
- Noise reducing asphalt pavements have been more commonly used in recent years.
- Offer façade insulation to the house/dwelling owners (see Section 6.1).

- In limited cases, the road administrations might buy houses with high noise exposure and either demolish the buildings or rebuild the structures for less-noise-sensitive commercial use.
- Using a wide belt of vegetation that has a dense appearance all year round.

The actual noise reducing effects of using these measures are normally assessed using the NORD2000 noise prediction method (see Section 3.2).

Figure 4.4. Combination of wave shaped concrete noise barrier and green noise barrier constructed as a "supported" earth wall along the new ring road in Århus, Denmark.

Figure 4.5. 700 m long section of the new highway to Copenhagen airport, Denmark was constructed as a cut and cover strategy in order to reduce the noise exposure for some nearby multi-storey apartment buildings.

Figure 4.6. Noise insulation of an apartment building by applying glass to cover the façade of the balconies.

Figure 4.7. Close up photo of glass covered balconies. It is possible for the residents to open up the balconies.

5. Planning of widening existing highways

The Danish highway network is primarily developed as four lane roads. Due to increase in traffic, some of the highway sections are being increased to six lanes. One of the projects that was finalized in 2008 is the enlargement of the M3 highway [24].

The M3 is a highway, which functions as a ring road around Copenhagen as well as being part of the E47/E55 European corridor, which connects Sweden and Germany. Being the only ring road around Copenhagen, which is built fully as a motorway, the Average Daily Traffic on the two lanes in each direction is as high as 75,000 vehicles. Congestion is frequent, and during rush hours travelling speeds of 25-30 km/h are normal. In order to improve the traffic situation, it has been decided to widen the M3 from four to six lanes.

The M3 highway passes through densely populated residential districts. As part of the planning of the extension, an Environmental Impact Assessment (EIA) has been carried out, including noise mappings and planning of noise abatement measures. The Road Directorate, which is responsible for the extension, has made a great effort to inform and reach out to the neighbours of the highway.

Figure 5.1. Highway M3 passes through densely built up residential areas around Copenhagen.

5.1 Environmental Impact Assessment

An Environmental Impact Assessment study [19] has been carried out in relation to the road enlargement project considering the following factors:

- Population
- Landscape
- Culture and history
- Flora and Fauna
- Water resources
- Green areas
- Energy and CO_2
- Air pollution
- Health effects
- Noise and vibrations
- Use of resources and waste production
- Light and reflections
- Soil and contaminated soil

Noise mapping has been performed for the existing situation including the noise contribution from other main roads in the area. In this example $L_{Aeq,24h}$ is used as the indicator for noise. On the background of the noise mapping, the consequences of using noise barriers with different height have been analysed. Table 5.1 shows a summary of the results. In the exiting situation 10,305 dwellings were exposed to more than 55 dB equivalent to a Noise Exposure Factor (NEF) value of 1717. By using noise barriers of respectively 3, 4 and 5 meters height, reductions of NEF by 149, 630 and 769 can be achieved.

Table 5.1. Evaluation of the effect on noise exposed dwellings and the NEF value to use 3,4 and 5 m high noise barriers along M3 [20].

Scenario	**Number of noise exposed dwellings**				**Total noise exposed dwellings**	**Total NEF**	**ΔNEF**
	55-60 dB	**60-64 dB**	**65-69 dB**	**≥70 dB**			
Existing	6503	3244	482	76	10305	1717	-
3m barrier	5472	2985	526	78	9061	1568	149
4m barrier	4766	1890	253	36	6945	1087	630
5m barrier	4027	1663	238	35	5963	948	769

Table 5.2. Evaluation of the price and cost effectiveness of the different barrier solutions [20].

Scenario	**Price per m^2 in DKK**	**Total price in mill. DKK**	**Total price in mill. €**	**Total price in mill. USD**	**ΔNEF**	**ΔNEF per 1 mill. DKK**
3m barrier	2600	138	19	25	149	1.1
4m barrier	2380	169	23	31	630	3.7
5m barrier	2400	212	28	39	769	3.6

In order to evaluate the cost effectiveness of noise barriers with different heights, the ΔNEF per mill. DKK invested has been predicted (see Table 5.2). The predictions show that a 1 mill. DKK investment in a 3 m high noise barrier gives a NEF reduction of 1.1 and for a 4 m high barrier the reduction in NEF is 3.7 per million DKK invested. The 4 m high noise barrier is in this prediction slightly more cost effective than the 5 m barrier and the total investment needed for 4 m barriers is 169 mill. DKK (€ 23 mill. or USD 31 mill.) whereas the total investment for 5 m barriers will be 212 mill. DKK (€ 28 mill. or USD 39 mill.).

The cost effectiveness study supported a decision to use a combination of 3 and 4 m high noise barriers. The consequence of this solution was a reduction of the total NEF value by 677 at a total noise barrier cost of 162 mill. DKK (€22 mill. or USD 29 mill.) and with a NEF reduction of 4.2 per 1 mill. DKK invested in noise barriers.

On the background of the Environmental Impact Assessment and an evaluation of cost effectiveness, it was decided in this specific project to use 60 dB ($L_{Aeq,24}$) as the noise guideline for the noise exposure from the M3 highway. 60 dB represents a significant reduction in noise for many of the dwellings situated along the M3 highway. In order to achieve 60 dB, the following measures have been implemented:

- 17,900 m of noise barriers have been constructed.
- Noise reducing pavements have been used.

Where these measures have not been enough to achieve 60 dB noise levels from the highway noise exposure, façade insulation has been offered to the owners.

Figure 5.2. 3 to 4 m high noise barriers have been constructed along highway M3 as part of the enlargement project.

5.2 Evaluation of noise reducing pavements

In order to evaluate the effect of using a noise reducing pavement on M3 instead of the normally used Dense Grade Asphalt Concrete or a Split Mastic Asphalt, some calculations have been performed on the background of the noise mapping analysis along highway M3. The background for these calculations is the noise mapping of all the dwellings affected by noise levels exceeding 55 dB in the initial situation after the (widening) enlargement of the M3 highway with a standard pavement. Four scenarios with a noise reduction of 1, 2, 3 or 4 dB have been included. Special types of noise reducing pavements were not specified in this evaluation.

Table 5.3. Results of using noise reducing pavements on the noise exposure along M3. The results are given as the number of dwellings exposed to different noise levels and the corresponding noise exposure factor (NEF) [18].

Scenario	**Number of noise exposed dwellings**				**Total noise exposed dwellings**	**Total NEF**	**ΔNEF**
	55-60 dB	**60-64 dB**	**65-69 dB**	**≥70 dB**			
Standard	4343	1815	292	34	6484	1040	-
-1 dB	3811	1788	197	34	5830	933	107
-2 dB	3285	1705	196	34	5220	856	184
-3 dB	3165	1376	189	34	4764	768	272
-4 dB	2860	1368	188	34	4450	732	308

The results can be seen in Table 5.3. A total of 6484 dwellings are exposed to noise over 55 dB in the situation using the standard pavement. This represents a total NEF value of 1040.

By using a 2 dB noise reducing pavement, the number of noise exposed dwellings is reduced by 933 and the NEF value is reduced by 184 to 856. Using the pavement with 4 dB noise reduction, the number of noise exposed homes is reduced to 4450 and the NEF value is reduced by 308.

Table 5.4. Value of noise reductions caused by the use of pavements with different noise reduction along the M3 expressed as the annual value in (2001 price level) and the net present value [18].

Scenario	ΔNEF	Annual value of noise reduction			Net Present Value		
		Mill. DKK	Mill. €	Mill. USD	Mill. DKK	Mill. €	Mill. USD
-1 dB	107	5.7	0.8	1.0	85	11	15
-2 dB	184	9.7	1.3	1.8	146	20	27
-3 dB	272	14.4	1.9	2.6	216	29	39
-4 dB	308	16.4	2.1	3.0	244	33	44

The economic benefits from using noise reducing pavements are calculated, based on the reduction in the NEF value achieved for the four scenarios for noise reducing pavements. The calculations are done for noise reductions of 1 to 4 dB. The annual value of the noise reductions is predicted by using the price per NEF unit presented in section 3.4. The results can be seen in Table 5.4. A 2 dB noise reducing pavement is in this project equivalent of a yearly saving of 9.7 mill. DKK (1.3 mill. € or 1.8 mill. USD) due to reduced noise exposure on the dwellings around the highway. This corresponds to a net present value of 146 mill. DKK (€ 20 mill. or USD 27 mill.). These figures can be used in a Cost Benefit Analyses. An example of such an analyses can be seen in “Cost-benefit analysis on noise-reducing pavements” [11] from DRI-DK.

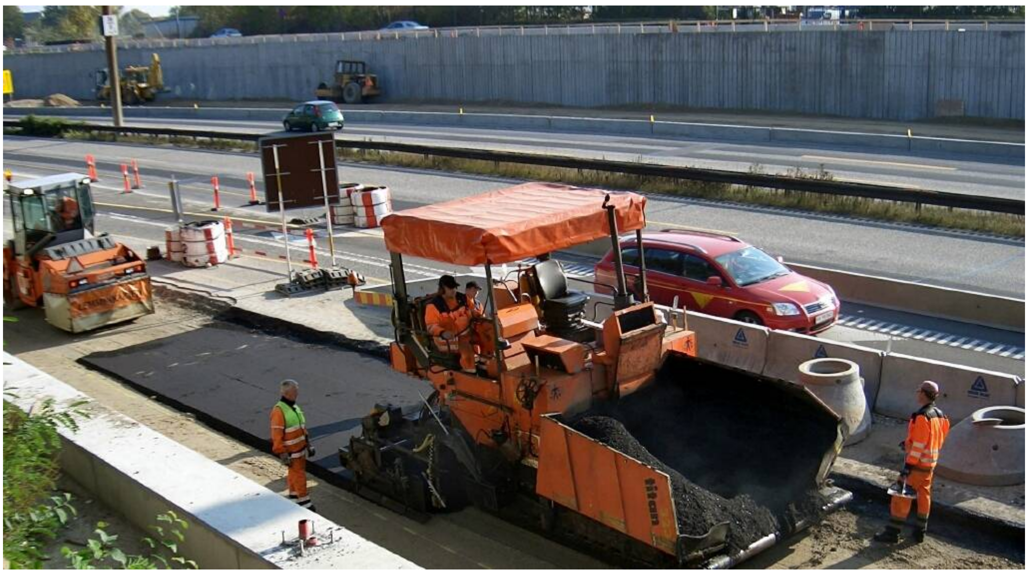

Figure 5.3. Noise reducing pavements were applied on the M3 highway.

Figure 5.4. Close up of the noise barriers designed for the M3 project (roadside left and urban side right).

6. Noise abatement on existing highways

During the last decade the Danish Road Directorate has used around 20 mill. DKK (2.7 mill € or 3.6 mill USD) every year for noise abatement along the existing highways and other state roads. Noise barriers has been the primarily tool applied for noise abatement [2].

Figure 6.1. Wooden noise barrier constructed along an existing Danish highway [2].

6.1 Façade insulation

In some situations where it has not been possible to use noise barriers to achieve sufficient noise reduction façade insulation has been used instead, typically by changing windows and doors to new and better noise reducing types (and often also heat insulation saving energy). Subsidies for noise insulation can be given to bedrooms, living rooms and kitchens with a dining table. An indoor noise reduction of at least 5 dB must be obtained and the resulting indoor noise level must not exceed 30 dB. The Road Directorate does not carry out work on private properties. Instead the Road Directorate contacts the owners of the impacted dwellings and offers to pay them for noise insulation. If the owners accept the offer the procedure is the following [28]:

- An acoustical consultant inspects the building and describes what kind of noise insulation has to be carried out.
- The owner gets a price for the work from a private contractor.
- The Road Directorate has to accept the price.
- The owner orders the contractor to carry out the work.

- An acoustical consultant inspects and approves the work carried out.
- The owner pays the contractor.
- The owner sends the invoice to the Road Directorate for reimbursement.

The Road Directorate does not accept projects that cost more than 96,600 DKK including VAT (€ 13,999 or USD 17,600) per dwelling for reimbursement (price level 2004). The reimbursement depends on the actual noise level as can bee seen in Table 6.1. For noise levels over 70 dB ($L_{Aeq24,h}$) the percentage is 90. The owner of the dwelling does not have to pay income tax on the money received from the Road Directorate for noise insulation.

Table 6.1. Reimbursement of costs of façade insulation against noise from the Road Directorate in approved projects [28].

Noise zone ($L_{Aeq24,h}$)	Noise level	Reimbursement percentage
Zone 1	>70 dB	90 %
Zone 2	65 – 70 dB	75 %
Zone 3	60 – 65 dB	50 %

Figure 6.2. Façade insulation against noise has been carried out at dwellings along the Danish highway network and the Road Directorate has reimbursed parts of the costs.

Figure 6.3. Elevated highway through a densely built up urban area in Frederiksberg/Copenhagen with five to six storey apartment buildings. Transparent noise barriers have been used in combination with façade insulation.

6.2 Noise action plan

In spring 2009, the Danish Road Directorate published a proposal for a new noise action plan for the existing state road network [1]. The purpose of the plan is to rank/rate initiatives that are planned to reduce road traffic noise along the state road network, where the noise is considered unacceptable. Another purpose to rank/rate noise initiatives in relation to planned maintenance of the road network.

New noise mapping using the (new) L_{DEN} indicator has been performed along 950 km (694 miles) of the 3,800 km (2,375 miles) state road network where the traffic is higher than 16,000. A total of 58,277 dwellings are exposed to more than the guideline of 58 dB (see Table 6.2). Of these, nearly 4,400 are heavily exposed to noise higher than 68 dB.

Table 6.2. Number of dwellings exposed to road noise (L_{DEN}) along state roads with more than 16000 vehicles daily [1] at a height of 1.5 m (5 feet).

	58 – 63 dB	63 - 68 dB	68 – 73 dB	> 73 dB	Total
Number of dwellings	39,216	14,660	2,984	1,417	58,277

Noise maps have been produced for all the municipalities with state roads passing through with more than 16,000 vehicles daily. Figure 6.4 shows an example of one of these noise maps for the municipality of Solrød.

The noise mapping statistics for Solrød can be seen in Table 6.3. 1,388 dwellings are exposed to more than 58 dB and 7 dwellings are exposed to over 68 dB. The sky blue dots on the noise map represent highly exposed noise areas with more than five dwellings where at least one dwelling is exposed to more than 68 dB. There are three such areas along the highway through Solrød.

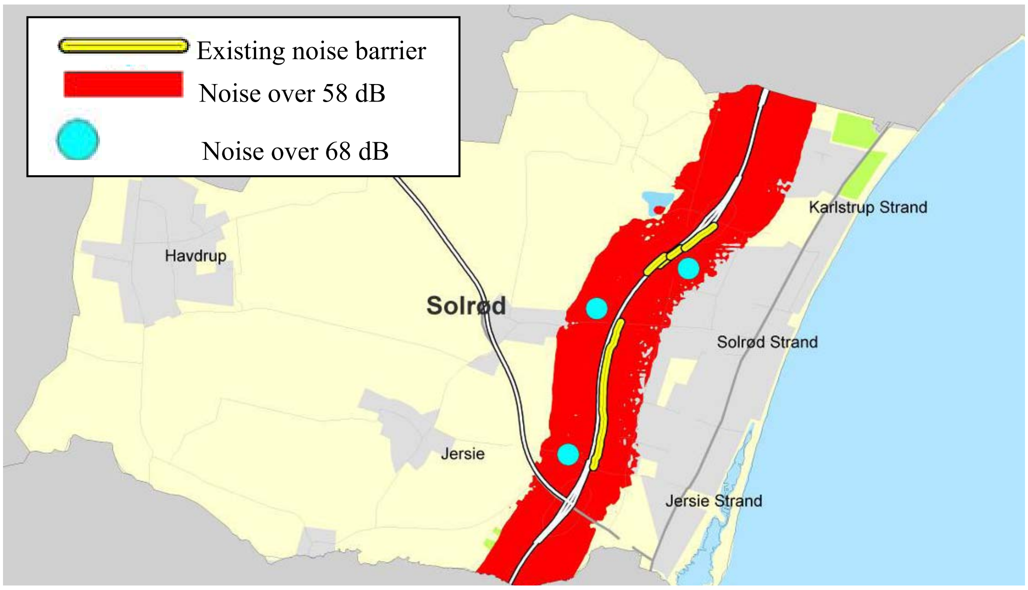

Figure 6.4. Noise map of the state highway through the municipality of Solrød [1].

Table 6.3. Statistics for the noise map of the state highway through the municipality of Solrød [1].

	58 – 63 dB	**63 - 68 dB**	**68 – 73 dB**	**> 73 dB**	**Total**
Number of dwellings	898	483	7	0	1,388

The five year goal of the noise action plan is to reduce the noise annoyance for as many dwellings as possible along the highway sections with the highest noise levels.

In the "Green Transport Policy" from the Danish government in 2009, a budget of 400 mill. DKK (€ 54 mill. or USD 72.7 mill.) has been allocated for noise abatement in the period from 2009 to 2014. The actual resources for noise abatement will be set aside in the yearly national budgets. The first priority is to focus on dwellings exposed to more than 68 dB and to get noise reduction at as many dwellings as possible for the invested money. The second priority is to use noise barriers at road sections where the most cost effective solutions can be reached. The third priority is to use façade insulation along sections where it is not physically possible to use noise barriers and where the solution is cost effective.

In relation to the ongoing maintenance of roads, another goal of the noise action plan [29] is that the Danish Road Directorate will use noise reducing pavements wherever pavements need to be renewed.

This goal will be applied at road sections where the noise exposure is over the 58 dB guideline and the road passes through large residential areas.

6.3 System for tendering noise reducing pavements

In order to facilitate the use of noise reducing pavements, a system for tendering such pavements has been developed in Denmark. In 2006, Danish road authorities in conjunction with pavement industry and consultants worked out a system for the specification and documentation of noise reducing asphalt pavement [30], the SRS-system, SRS being the acronym for the Danish wording of Noise Reducing Surfacing. The system is based on the Close Proximity Method (CPX) [31] similar to the On Board Sound Intensity (OBSI) method [32] commonly used in California and USA for noise measurements. In order to ensure reliability and transparency, it allows various independent providers of CPX measurements to offer their service as long as they participate in an annual field calibration of equipment.

Figure 6.5. The CPX-trailer "deciBellA" operated by the Danish Road Directorate/Danish Road Institute.

The system encompasses:

- A guide to the use of asphalt surfacing in traffic noise abatement.
- A system for the documentation and declaration in classes of the noise reduction of the asphalt surfacing.
- Three classes A, B & C, where class A surfacings exhibit the highest noise reducing effect and class B & C exhibit lower noise reducing effects as compared to regular dense graded asphalt surfacings at eight years of age.
- Reference values of the noise emission as determined by the CPX method.
- A description of the CPX method including the definition of method variables and requirements on supplementary calibration of the measuring device.
- A paradigm for the contracting and preparation of tender documents.

This is the first Danish attempt to provide a process for contracting noise reducing asphalt surfacings. It has limitations and several subjects need addressing. In particular, there is a need for better knowledge on the accuracy of CPX measurement, and for the development of appropriate acceptance criteria for contracting. The intention is for the classification system to certify the noise reduction ability of road surfacings including new products as well as to improve the ability of the local road administrations (which typically lack expertise in noise considerations) to purchase proven solutions fit for use.

A contractor who wants to declare a SRS (Noise Reducing Surface) must work out a declaration form. In this form the contractor declares the actual noise class and presents the documentation achieved during CPX measurements on a trial section. The contractor must build a test section of at least 100 m length. The CPX-trailer must run over the trial section at the appropriate reference speed while recording the noise levels with its two standard reference tires.

The system to declare the noise reducing ability enables the contractor to produce documentation of the noise reduction of a specific SRS by comparing measured values with a national reference value. The reduction in noise emission (compared to the reference) is used by the contractor in the declaration of the SRS in a specific noise class. The first generation system describes three noise classes – A, B, and C.

The reference values were derived as pass-by noise levels [33] calculated for reference conditions using the Danish noise emission data of the Nordic prediction method for road traffic noise, Nord2000 [26]. Using data between vehicle pass-by noise levels and CPX noise levels, the Nord2000 pass-by noise levels were transformed to their corresponding CPX_{DK} values, which are used in the first generation system.

When declaring the noise reduction of an asphalt surfacing (by comparison to the reference used in Denmark), one of the following noise classes A, B, or C should be used.

Table 6.4. Noise classes in the Danish "SRS" (Noise Reducing Surface) system for noise labeling of asphalt pavements [30].

Noise class	Description	Noise reduction in dB
A	Very good noise reduction	$x \geq 7.0$
B	Good noise reduction	$5.0 \leq x < 7.0$
C	Noise reduction	$3.0 \leq x < 5.0$

The Danish SRS-system is a voluntary road standard for contracting of noise reducing pavements. In the contract for a specific job, the voluntary standards become legally binding. However, at present the system is in an experimental phase with no legal ramifications if the pavement fails to fulfill the noise performance requirements.

Figure 6.6. When the pavement on an existing highway has to be replaced, the road administration might consider using a new noise reducing pavement type. Here noise reducing two-layer porous asphalt is applied on a highway in a densely built up area in the municipality of Copenhagen.

6.4 Other measures of noise abatement

The following represents different kind of measures of noise abatement that can be applied along existing highways and other main roads.

Figure 6.7. Earth embankment with a path on the top designed to fit into the urban landscape along a highway. Earth embankments can be made of surplus soil from road or housing construction projects in the region where a plan for the earth embankment is made and over a period of many years, dirt is delivered to the site before the embankment is finished. It is important to have a plan for the embankment in order to get a good final appearance in the visual environment.

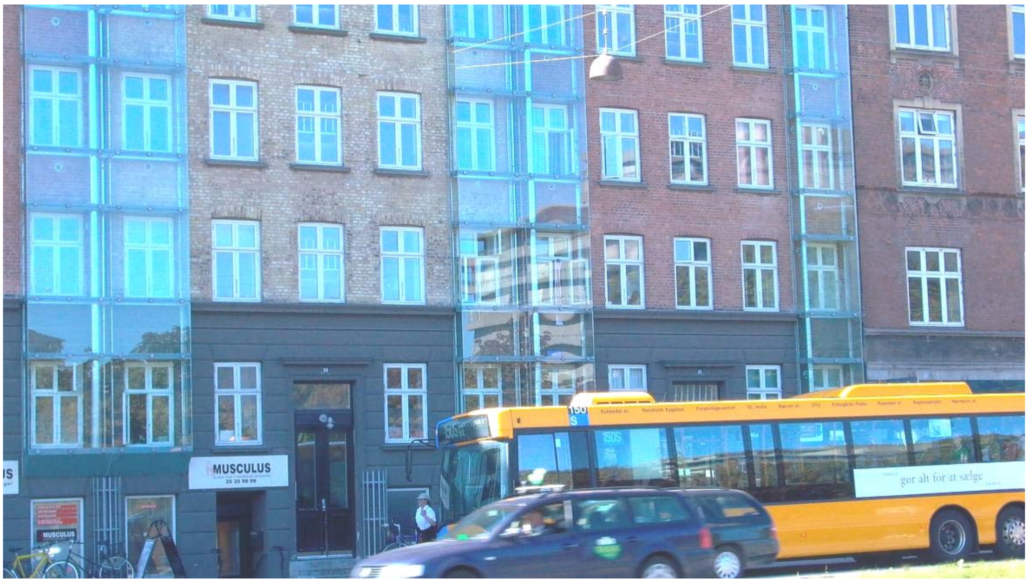

Figure 6.8. Glass covering has been mounted as noise insulation for bedrooms and living rooms at the façade of a multi-storey apartment building along a highway in Copenhagen, Denmark. Cleaner air from the backside of the building is used for ventilation between the glass covering and the existing windows. The noise abatement was financed as a part of an overall renewal of the building.

Figure 6.9. Noise reducing window constructed as a "noise shutter" that makes it possible to open the window. Placed in front of bedrooms and living rooms facing the highway (photo Allan Jensen, Rambøll).

Figure 6.10. Close up of "noise shutter" window where the extra noise insulating glass layer can be pulled to the right side in order to be able to open the "original window" (photo Allan Jensen, Rambøll).

Figure 6.11. Speed monitoring is normally used as a measure to improve traffic safety. If it has an effect on reducing the actual speed it can also have a noise reducing effect [10].

Figure 6.12. Reducing the speed where a highway passes noise sensitive areas could reduce the noise. A solution where the reduced speed limit is only effective in the evening and night period could be considered in order to reduce noise annoyance when people are sleeping. This measure is only effective at reducing noise only if the speed is actually reduced.

Another innovative idea that has been considered in Switzerland [29] is to build a concrete roof over the highway where it passes through noise sensitive and densely built-up urban areas. Then the "land" developed on top of the covered highway is sold as construction sites for urban development like dwellings and offices. The revenue from the 'new' land sales might finance or partly finance the noise abatement project.

7. New housing along exiting highways

In the mid 1980´s, noise was integrated in municipal land use planning in Denmark. In the planning process of new residential areas a land use plan has to be developed and approved by the local municipality. According to guidance from the Danish Environmental Protection Agency, noise has to be taken into consideration in land use planning and a guideline of noise at dwellings of 55 dB ($L_{Aeq,24h}$) and the recent introduction of L_{DEN} 58 dB has to be respected [23]. All urban land development and construction of new housing has followed these noise guidelines for more than 25 years. The noise abatement measures have been enforced by the municipalities and normally been paid for by the developer or contractor building new dwellings.

Figure 7.1. Earth embankment constructed at the same time as a new housing district to reduce the noise from an existing road at the houses and the gardens at Kvistgård, Denmark.

The measures that normally have been used to fulfil the noise criteria are the following:

- Long distance between roads and new buildings.
- Construction of noise barriers in some cases as an integrated part of the building design (see Figure 7.3 and 7.5).
- Earth embankments that might be constructed of surplus material from the construction site (see Figure 7.1).
- Using secondary buildings like garages, carports, bicycle sheds, laundry buildings etc as parts of noise barriers facing the road (see Figure 7.2).

- In built-up urban areas, it is sometimes allowed to use the building itself as a noise barrier in such a way that the building design has both a noisy and a silent side. In such cases, noise insulation has to be applied to provide an indoor noise level not to exceed 30 dB. The planning solution of the dwellings shall then be designed so the windows of living rooms and bedrooms faces the quieter side of the building and only ”secondary rooms” face the noisy side of the building (see Figure 7.4).

Figure 7.2. A new district of row houses constructed along an existing highway. A common car-port facility was constructed as a two storey high noise barrier.

Figure 7.3. New residential apartment building for elderly people where a transparent noise barrier has been integrated in the building design.

Figure 7.4. New three and four storey apartment buildings constructed close to a highway with high noise levels. At the façade facing the noise, the windows are small and highly noise insulated. The apartments are planned so that secondary rooms like bathrooms, corridors, storage rooms, etc are adjacent to the noisy façade. Bedrooms and living rooms are adjacent to the silent facade.

Figure 7.5. Brick noise barrier constructed as an integrated part of a new apartment building project.

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