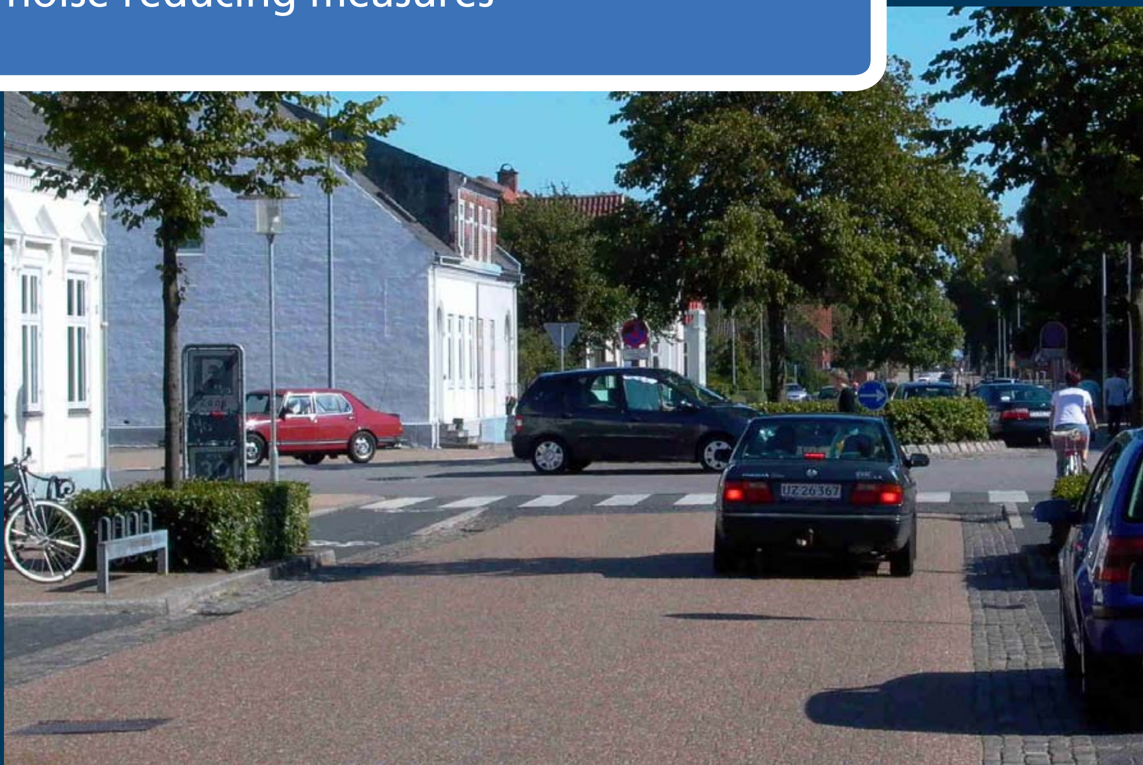
Traffic management and noise reducing pavements

- Recommendations on additional noise reducing measures



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Report 137
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Road Directorate
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Executive summary

This report is produced as Deliverable 12 - “Recommendations on Additional Noise Reducing Measures” - of the EU research project SILVIA. The report is the outcome of the work carried out by a working group in task 5.3 of working package 5 of the SILVIA project. The goal for task 5.3 is to investigate traffic management measures in order to highlight their capacity for noise control and to evaluate the possibilities and effects of combining traffic management measures with the use of noise reducing pavements especially in urban areas. The main goal of this document is to describe recommendations for road administrators with respect to additional noise reducing measures.

Traffic management measures such as environmentally adapted “through” roads, 30 km/h zones, road humps, roundabouts, restrictions on traffic in special periods, speed control etc are used on many urban roads in Europe. These measures are usually applied to improve traffic safety, typically by reducing the speed, and to “calm” residential areas from the environmental impact caused by the traffic in order to make the areas more pleasant to live in for the residents and more agreeable to shop and walk in for shoppers and other people. The term “traffic management” can be described as an application of different strategies and measures to change the flow of traffic on roads either to reduce the speed of vehicles passing by and/or to reduce the traffic volume itself. This will all have an effect on the environmental noise caused by vehicles.

The first part of the report is focused on analysing the relations between speed and noise. The effects of uneven driving pattern with accelerations and braking are included. This is analysed on the background of prediction models like the Nordic Method and the Harmonoise method developed in an EU project. The second part of the report is a comprehensive European literature survey to find and compile existing relevant knowledge on relations between traffic management and noise. On this background the final results and recommendations are developed.

Modelling noise

The use of new emission data for the Nordic Noise Prediction method shows that for urban driving at speeds in the range of 30 to 60 km/h a speed reduction of 10 km/h for light vehicles reduces the noise by up to 2 to 4 dB depending on the starting point. For heavy vehicles the reduction potential is 2 to 3 dB. For speed reductions of 10 km/h in the speed range from 110 to 60 km/h the noise reduction will be about 1 to 2 dB for roads with 10 % heavy vehicles

In some cases traffic management is used to reduce the amount of traffic on a road and/or to reduce the percentage of heavy vehicles. A 10 % reduction of traffic only leads to a 0.5 dB noise decrease, whereas a 50 % reduction decreases noise by 3 dB. On a road with 10 % heavy vehicles the noise will be reduced by 1 to 2 dB if all the heavy vehicles are removed.

The driving pattern also has an influence on noise levels, although uneven driving patterns usually do not dominate under normal driving conditions. At moderate accelerations the noise can increase by up to 2 dB (in comparison to constant driving speed) where such accelerations occur (which may be on rather limited locations) depending on the mix of vehicles. This is a little less than the reduction achieved by a speed reduction of 10 km/h. It is therefore important to design speed reduction measures in such a way as to avoid accelerations and decelerations as much as possible and to ensure that the accelerations do not occur at or near the position of dwellings or other noise-sensitive areas.

Traffic management examples
In the table underneath the results of the literature survey are summarised. The effect on noise is based on estimates of up to approximately 10% of heavy vehicles. The effect on noise of the different traffic management measures depend very much of the precise design and implementation of the measures as well as on how they are accepted by the drivers. Generally it can be concluded that reductions in average noise levels (L_{Aeq}) of up to 4 dB can normally be achieved but in special situations even higher reductions may be reached. But some speed reducing measures might increase noise like rumble areas and paving stones. Vertical deflections such as humps and cushions can reduce the average levels due to significant speed reductions but the maximum levels can increase due to body rattle noise produced as some vehicles (especially empty container lorries) negotiate the deflection. The actual reduction in the average level will depend critically on the percentage of heavy vehicles in the traffic stream.

Traffic management measure	**Potential noise reduction (L_{Aeq})**
Traffic calming / Environmentally adapted through roads	Up to 4 dB
30 km/h zone	Up to 2 dB
Roundabouts	Up to 4 dB
Round-top/circle-top road humps	Up to 2 dB
Flat-top humps	Up to 6 dB increase
Narrow speed cushions	Up to 1 dB increase
Night time restrictions on heavy vehicles	Up to 7 dB at night time
Speed limits combined with signs about noise disturbance	1 – 4 dB
Rumble strips of thermoplastic	Up to 4 dB noise increase
Rumble areas of paving stones	Up to 3 dB noise increase
Rumble wave devices	0 dB

The following general conclusions and recommendations in relation to noise can be drawn:

1. Speed reductions reduce noise.

2. However the noise from some heavy vehicles can in some cases increase due to increased gear shifting and body rattle noises.

3. In order to achieve a reduced speed it is normally not enough just to install speed limit signs. It is also necessary to redesign and rebuild the road so that the physical layout matches the intended speed.

4. Visual speed reducers are often effective in reducing noise.

5. It is important to achieve as smooth a driving pattern as possible.

6. It is important to minimise uneven driving patterns. This can be done by having appropriate distances between speed reducers.

7. It is important to achieve driving patterns where the vehicles are not brought to a complete stop as this generates more noise from decelerations and accelerations.

8. Speed reducers which displace the vehicles to the left or to the right are often effective in reducing noise especially in the case of heavy vehicles.

9. Speed reducers which change the vertical height of parts of a road (like some types of road humps) can in some cases be problematic in relation to noise, especially for heavy vehicles, where body rattle noises can produce large peaks in noise levels as these vehicles cross the vertical deflections.

10. The use of rumble areas, for example with paving stones, increases noise.

11. There are reports of cases with increased perceived annoyance even though the average noise level has decreased.

12. There are reports on increases in the perceived noise annoyance because of impulse-like noise, rattling in the bodywork or cargo of heavy vehicles, as well as short-time changes in the sound level and frequency caused by gear shifting or changing in engine revolutions due to acceleration or braking of a vehicle.

13. Speed reducers, which change the vertical height of parts of a road, may produce perceptible levels of vibrations in nearby houses. This depends on the type of ground condition and distance from the vertical deflection to the nearest house foundations. Serious annoyance has been reported especially where houses are close to road humps built on soft ground such as peat soils and alluvium deposits.

14. Speed reductions generally have a good effect on traffic safety.

In a Danish report it has been suggested that 5 dB should be added as a “penalty” to the actual noise level if impulsive noise or similar is occurring (for example where rumble areas/strips or paving stones are used) to compensate for the increased perceived annoyance. It must generally be concluded that more research is needed to investigate and quantify the effect of impulsive noise from road traffic, especially in relation to certain types of speed reducers. A general recommendation could be, on the background of the existing knowledge, to place speed reducers which change the vertical height of parts of a road and/or include rumble areas at a distance as long as possible from houses where people are living.

Traffic management and noise reducing pavements
It is obvious that it can be a good idea to combine traffic management measures and the use of noise reducing pavements in noise abatement schemes. Generally there does not seem to be any technical arguments for not combining these measures of noise abatement. However, it must be noted that porous pavements can be damaged on bends, junctions and roundabouts sites where forces at the tyre/road interface are relatively high. This must be taken into consideration when applying porous pavements on roads specially constructed to reduce speed. Speed reducers which displace the vehicles to the left or right may be problematic for the durability of porous pavements, because this will make the vehicles drive in curves for short distances. But other types of noise reducing pavements can be used in such cases.

In other parts of the SILVIA project the noise reducing effect of different pavement types are documented. On urban roads with speeds in the range from 40 to 60 km/h noise reductions of 1 to 4 dB can be achieved by using for example noise reducing thin layers or porous pavements. At higher speeds the noise reducing potential for these pavements may be up to 6 dB or even more. This noise reduction is of the same magnitude as or higher than the reduction which can normally be achieved by traffic management measures.

Noise reducing pavements and traffic management measures may influence the frequency distribution of road traffic noise in different ways, and this can have an influence on the total noise reduction. For simplification it can anyway be recommended to add (on a dB basis) the effect of the two types of noise reduction. It is therefore generally on urban roads possible to obtain noise reductions of 3 to 8 dB by combining the use of noise reducing pavements and traffic management measures. On highways with high speeds the potential for noise reduction may be up to 10 dB or even more.

Generally noise reducing pavements have a better reduction effect on noise from light vehicles than on noise from heavy vehicles. This means that if a traffic management measure such as an environmentally adopted street or a 30 km/h zone has an effect on reducing the percentage of heavy vehicles the beneficial effects of the noise reducing pavements will be increased.

Research needs
The literature has shown that noise reductions due to the introduction of traffic management schemes can result in both positive and negative responses from the inhabi-

tants. In some cases social surveys have shown a significantly reduced perceived annoyance and in other cases the perceived annoyance has increased even though the measured average noise levels have decreased. As the main goal of noise abatement is to improve the life quality for people there is a need for further research in this field. Research themes could be:

The effect of different designs of road humps and cushions on the perceived annoyance.
The effect of different types of rumble areas and strips on the perceived annoyance.
Development and optimization of traffic management schemes in order to reduce the perceived annoyance as much as possible.
Investigation and quantification of the effect on the perceived annoyance of impulsive noise from road traffic, especially in relation to certain types of speed reducers like humps and rumble areas.
The effect on the perceived annoyance when combining traffic management and noise reducing pavements in order to reduce noise.

Very few references have been retrieved where the use of advanced information technology and automatic traffic steering and management has been developed and investigated. Therefore there is also a need to focus on this field in research and development projects. In this research it will also be relevant to focus on projects where noise reducing pavements are included. There is a need to develop methods to build vehicle sensors into the surface of porous pavements without damaging the capacity of the porous pavement to lead rain water to the roadside.

There is also a need to further develop and test speed reducers such as rumblewave devices which can generate noise inside the vehicles but at the same time do not have any negative effect on the noise along the roads.

Contents

Preface

SILVIA is a collaborative RTD project supported by the European Commission under its Competitive and Sustainable Growth (GROWTH) programme. The project started in September 2002 and has a planned duration of three years. SILVIA aims at providing decision-makers with a tool allowing them to rationally plan traffic noise control measures. To this end, the work will aim at filling three major knowledge and technical gaps, namely by: setting up classification and conformity-of-production procedures of road pavements with respect to their influence on traffic noise, investigating and improving - based on existing data and laboratory and field testing - the functional and structural durability of low-noise pavement construction and maintenance techniques, and developing a full life-cycle cost/benefit analysis procedure for traffic noise abatement measures. As a result of the above the main final product of SILVIA will be a European Guidance Manual on the “Utilisation of Low-Noise Road Surfaces" integrating low-noise surfaces with other traffic noise control measures including vehicle and tyre noise regulation, traffic management and road and building noise protection equipment.

This report deals with the theme of integrating the use of traffic management as a tool to reduce noise in combination with noise reducing pavements. The report is deliverable no D12 of the SILVIA project. The report is the outcome of the work carried out by a working group in task 5.3 of working package 5 of the SILVIA project. The Danish Transport Research Institute is the Danish partner in the SILVIA project and they have subcontracted the work to the Danish Road Institute/Road Directorate. The working group had the following members:

- Hans Bendtsen, Danish Road Institute/Road Directorate (DRI), Denmark.
- Jürgen Haberl, Johan Litzka and Ernest Pucher, Vienna University of Technology (TUW), Austria.
- Ulf Sandberg, Transport Research Institute (VTI), Sweden.
- Greg Watts, Transportation Research Laboratory (TRL), United Kingdom.

Hans Bendtsen has been the task leader and the editor for the report. The members of the working group have reported on special issues. These reports have been integrated in this final report. A draft of the report has been discussed by all the partners of working package 5 before it was finalised.

Copenhagen, October 2004.

Forord

Denne rapport er produkt nr. 12 ” Anbefalinger af supplerende støjreducerende tiltag” i EU forskningsprojektet SILVIA. Formålet er at undersøge hvordan forskellige trafiktekniske metoder til at reducere trafikkens hastighed påvirker støjen. Det er desuden formålet at undersøge hvordan hastighedsreducerende tiltag specielt i boligområder kan kombineres med anvendelse af støjreducerende vejbelægninger. Hastighedsreducerende tiltag som miljøprioriterede gennemfarter, 30 km/t zoner, bump, rundkørsler, begrænsninger på trafikken i specielle tidsperioder, hastighedskontrol mv. anvendes i mange Europæiske byer. I første del er der specielt fokus på sammenhængen mellem kørsel med konstant fart og støjen hvilket belyses med den nordiske beregningsmetode for vejtrafik støj. Desuden analyseres støjen ved ujævn kørsel med opbremsninger og accelerationer som bl.a. belyses med anvendelse af Harmonoise beregningsmetoden. I anden del gennemføres et tværfagligt Europæisk litteraturstudie. På baggrund af disse undersøgelser udvikles praktiske anbefalinger for vej- og trafikplanlæggere.

1. Introduction and methods

1.1 Description and goals of SILVIA work package 5

Work Package 5 (WP5) of the SILVIA project [1.6] studies in detail the effects of combining noise reducing road surfaces with other noise reducing measures, not only focusing on vehicle noise sources but also on noise reduction under propagation by the use of noise barriers as well as on noise control through traffic management. The research in SILVIA WP5 is further sub-divided into four tasks.
The objectives of WP5 are:

- To describe noise reduction solutions taking into account the combination of pavement and tyre design (Task 5.1).
- To address noise reduction possibilities by assessing other vehicle noise sources (e.g. reducing power unit noise) (Task 5.1).
- To discuss the acoustical optimisation of local conditions (urban, semi-urban and rural roads, crossings, roundabouts, etc) (Task 5.2).
- To consider traffic management measures for noise control and the effect of these on mobility (Task 5.3) (this report).
- To estimate the noise reduction of low-noise pavements when combined with noise barriers and earth mounds, and when used on bridges (Task 5.4).

1.2 Aims of this report

Traffic management measures of different kinds are used on many urban roads. These measures are usually applied to improve traffic safety, typically by reducing the speed, and to “calm” residential areas for the environmental impact caused by the traffic in order to make the areas more pleasant to live in for the residents and more pleasant to shop and walk in for shoppers and other people. The main goal of task 5.3 is to investigate how noise-reducing pavements can be used together with traffic management measures to reduce noise, especially in urban areas. Recommendations for road administrators with respect to additional noise reducing measures will be described as input for the European Guidance Manual on the “Utilisation of Low-Noise Road Surfaces" which will be the main output of the SILVIA project.

In order to evaluate what the outcome of this task should be, it makes sense to take a look at the needs of the end users of the SILVIA project. The practical users like traffic- and road planners as well as road maintenance engineers need the following:

- Reliable and accurate information in the handbook/manual on how to combine noise-reducing pavements and traffic management.
- Information on how to reduce noise using traffic management.
- Integration with the use of noise reducing pavements.
- Best practice.
- Practical examples on how to combine noise-reducing pavements and traffic management.

These needs will be kept in mind while working with this task. The work in this task will primarily be based on existing research results.

1.3 Traffic management

The concept of traffic management can be seen as an overall description of different strategies and measures to change the flow of traffic either on one single road or on a network of roads. The goals are usually to reduce the speed and/or to reduce the traffic volume, but means to change the traffic composition are also included. The following concepts can be regarded as traffic management:

- Environmentally adapted through roads.
- Establishment of 30 km/h zones in residential areas.
- Construction of new by-pass roads.
- Restrictions on heavy traffic, mainly in residential areas or in the night time.
- Restrictions on traffic in special periods of the day or of the week.
- Speed reduction by the use of different measures on the road like bumps, areas with paving stones, rumble stripes, displacement of the driving lane and the like.
- Speed reduction enforced by the use of modern technology like variable traffic signs, speed radars, information technology in the vehicles, GPS and the like.
- The use of information technology and variable traffic signs to inform on optimum speed or alternatively to change the route immediately selected by the drivers.
- Green waves on roads with many intersections with traffic lights.
- Roundabouts instead of traditional intersections. Establishing zones or roads where special "silent" vehicle types has to be used (vans instead of lorries, electrical vehicles, hybrid vehicles).

As it can be seen from the above, different traffic management schemes can have an effect on parameters that have an influence on the noise from road traffic. The parameters that can be influenced and changed are the following:

- Traffic volume.
- Percentage of heavy vehicles.
- Distribution of traffic over the 24 hours of the day.
- Distribution of the traffic over the days of the week.
- Speed.
- Driving pattern.

In order to optimize noise reduction these different traffic management schemes can be combined with the use of noise reducing pavements and/or avoiding noisy pavements like paving stones and/or pavement with a very rough surface texture.

1.4 Methods

This report is basically based on comprehensive literature surveys (reports, papers and articles) to find and compile existing relevant knowledge on relations between traffic management and noise. This will include research results for special speed reducing systems and as an important feature also the effect of driving patterns. On this background the final results and recommendations are developed. This report is subdivided in some main sections:

- In chapter 2 some general relations between the traffic parameters, which can be influenced by traffic management (see section 1.3), and the effect on noise from road traffic are highlighted. This is done on the background of the Nordic prediction method for road traffic noise.
- The introduction of different traffic management schemes might also in some situations have an effect on the driving pattern of the vehicles. Many European prediction methods like the Nordic method are valid for situations where the vehicles are driving with constant speed and do not directly cover situations with uneven driving pattern. Therefore a special literature survey on the relations between uneven driving pattern and noise is included in chapter 3. The Harmonoise method developed in an EU project will be a part of this.
- Many types of traffic management schemes have been constructed in full scale around the world. Some of these schemes have been studied in research projects where the effects on traffic, speed and noise as well as other parameters, often traffic safety, have been measured and studied. Literature surveys on these research projects are carried out in chapters 4 to 7. For practical reasons the literature study on traffic management has been subdivided into 4 parts. The Nordic examples, where there is a special focus on environmentally adapted through roads and roundabouts, are presented in chapter 4. The British examples with special focus on road humps and cushions are presented in chapter 5. This is followed by Austrian experiences in Chapter 6. Other relevant examples are presented in chapter 7.
- Based on the literature survey, a catalogue on different traffic management measures will be drawn up in chapter 8. The effects on noise will be included in this catalogue, when it is possibly to gain information on this from relevant research projects. In some cases the noise effects can be calculated using the Nordic prediction method.
- The report is finalized by developing recommendations and drawing conclusions (chapter 9).

It is important to be able to compare the results found in the literature. For possible comparison of the effects of different noise reducing measures on traffic noise it is necessary to keep the following points in mind when analysing relevant literature:

- A precise description of the measure taken (including a photo or drawing of the measure).
- Types of pavement used if it is relevant for noise.
- The procedure and conditions (reflections, distance, terrain etc.) for noise measurements.
- The measured effect on traffic (speed, number and distribution between vehicle classes).
- The effect on noise (in relative and absolute dB).
- Noise reference.

A number of references form the background for this report. In order to make it easier for the reader to check the references, those relating to each chapter will be listed in a reference section at the end of the chapter.

As mentioned earlier the primary driving force for implementing different types of traffic management schemes is very often to improve traffic safety. Noise reduction is often a second order goal. Traffic management schemes will normally also effect factors such as air pollution, energy consumption, vibrations, visual aspects and total driving time.

It has been decided by the partners of SILVIA Task 5.3 that these other effects will not be taken into account in this project focusing on noise. To some extent these factors will be dealt with in working package 3 of the SILVIA project (Cost-Benefit Analysis of Noise Control Actions). It has also been decided not to include considerations on the possible effects on mobility and travel time. Information on other effects will be mentioned if available in the literature.

Noise can be measured (and predicted) in different ways. For administrative and planning purposes the daily average noise level ($L_{Aeq,24h}$) is normally used in many European countries, sometimes supplemented with the maximum noise level (L_{AmaxF}). The average noise level ($L_{Aeq,24h}$) can be subdivided in daytime and night time noise. With the introduction of the new EU directive on noise in 2002, noise mapping and planning according to the directive shall be carried out using L_{DEN} and L_{night}. L_{DEN} is calculated as the average daytime noise plus the evening noise with 5 dB added plus the nightime noise with 10 dB added. L_{night} is the average night time noise level ($L_{Aeqnight,8h}$).

The main goal in this report is to investigate the relative difference in noise levels obtained by implementing different types of traffic management schemes. In order to do so it is of little importance which types of noise levels are used, as long as the noise is given in the same standard in the “before” and the “after” situation. In this survey the noise given as average noise levels (L_{Aeq}) will be used if available.

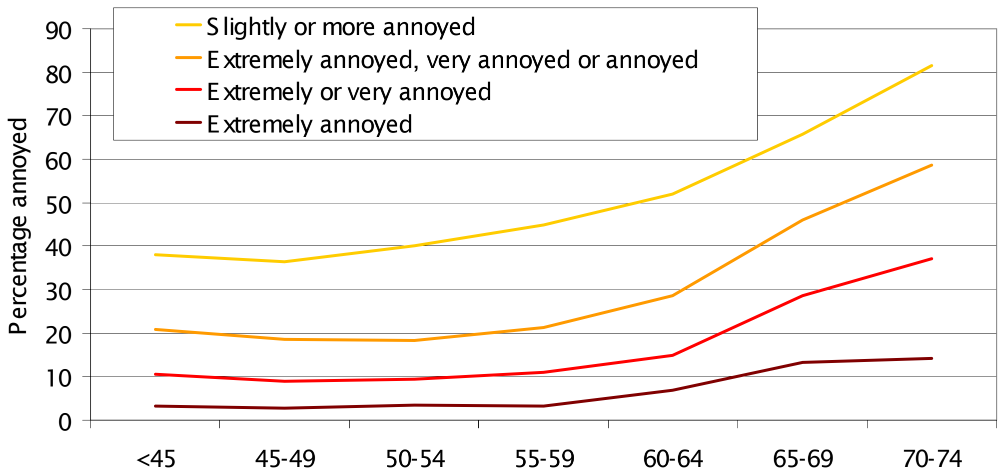


Figure 1.1 Relation between noise (LAeq,24h) and the perceived annoyance from a new Danish survey [1.1].

For traffic driving with a constant speed research has showed that there is a relatively good relation between the noise levels and the annoyance perceived by people living around the roads [1.1] (see Figure 1.1). In situations with uneven driving patterns this might not be the case. The changes in the "sound" of the noise caused by braking and acceleration or the short noise peaks when vehicles pass rumble strips or short sections with paving stones might cause increases in annoyance which are higher than what could be expected from the general relations between noise and annoyance [1.2]. Spectral changes may result in different noise reductions outside and inside houses.

It has been decided not to go into details with possible changes in spectra and changes in annoyance but just to mention these effects if there is available information on this.

1.5 Influence of different noise reducing measures – model of an average city

In order to be able to illustrate the effect of combining different traffic management measures with the use of noise reducing road surfaces the authors wish to refer to another SILVIA report, "Influence of different noise reducing measures – model of an average city" [1.3]. This report describes a model for predicting the noise situation for people living near urban roads. The calculation procedure within this model is valid for roads situated in an average European city where one 2.0 km long and even main street inside this city with five mayor intersections is regarded. It is possible to show the effect of various implemented noise reducing measures (heavy vehicle bans at night time, roundabouts, speed reduction measures, noise reducing surfaces,….) by comparing the initial noise situation with the noise after implementation of these different measures. The results of such comparisons may be illustrated as noise values (as $L_{A,eq}$ over 24 hours according to the Nordic prediction method for road traffic noise [1.4] or as L_{den} according to the EU noise directive 2002/49/EC [1.5]) or as the number of houses/dwellings/people in different noise classes. Finally by weighing the number of houses, dwellings or people affected by a certain sound pressure level with an annoyance factor, a so-called "noise load number" can be calculated.

1.6 References for chapter 1

[1.1] Larsen, Lars Ellebjerg; Bendtsen, Hans and Mikkelsen, Bo. Traffic noise annoyance. A survey in Aarhus, Odense and Randers. Danish Transport Research Institute (DTF), report 5, 2002. May be downloaded from www.dtf.dk

[1.2] Bendtsen, Hans; Larsen, Lars Ellebjerg. Støj ved bump på veje (Noise from road humps), report 2, 2001, Danish Transport Research Institute (DTF). English summary. May be downloaded from www.dtf.dk

[1.3] Haberl, Jürgen; Bendtsen, Hans: "Influence of different noise reducing measures – model of an average city," Report of the EU-project SILVIA (Sustainable Road Surfaces for Traffic Noise Control), GROWTH Project GRD2-2000-31801, Brussels, 2004.

[1.4] TemaNord 1966:525: "Road Traffic Noise – Nordic Prediction Method", Nordic Council of Ministers, Copenhagen, January 1996.

[1.5] EU 2002/49/EC: "Directive of the European Parliament and the Council relating to the Assessment and Management of Environmental Noise," European Commission, Brussels, June 2002.

[1.6] SILVIA homepage: www.trl.co.uk/silvia/

2. Speed and noise - general relations

Very often the main goal of introducing a traffic management scheme is to improve traffic safety; often the idea is to achieve this goal by reducing the speed of the traffic. At the same time the total volume of traffic might be influenced as well as the percentage of heavy vehicles. The current road traffic noise prediction models in Europe can be used to calculate the change of noise caused by changes in these traffic parameters as long as there is a situation, both before and after the implementation of traffic management, where the traffic is driving at a relatively constant speed. In this chapter the Nordic Prediction Method for road traffic noise [2.1] will be used to describe the noise consequences of traffic management under constant speed driving conditions.

In cases where roundabouts, humps and other chicanes are constructed along a road as a traffic management scheme the even driving pattern may be influenced significantly by introducing accelerations and breakings as the vehicles drive along a road. This may cause a change in noise levels, which can't be predicted by the use of ordinary prediction methods. In these situations there are two different ways to estimate the consequences for the road traffic noise:

1. To use specially developed prediction tools, which can be used for situations with uneven driving patterns. Such an approach will be investigated in chapter 3. An obstacle for doing so is that it is difficult to describe an uneven driving pattern in a simple way that can be measured on an actual road.

2. Another approach is to measure the noise before and after the introduction of traffic management measures. This method gives an expression of the relative changes of noise. In the literature studies of traffic management in chapters 4 to 7, results from such measurements will be included when they are available.

2.1 Influence of "normal" pavements

In the Nordic Prediction Method the reference pavement used is dense asphalt concrete with a maximum aggregate size of 11-12 mm or pavements with similar smooth surface textures. When a traffic management scheme is implemented on a road the pavement may be changed or renewed at the same time, especially in situations where the existing pavement is old and worn out with cracks, holes and ravelling.

Figure 2.1 shows the development in noise from a dense asphalt concrete on a highway. It can be seen that the noise increases approximately 1 dB in the first years after laying the pavement. The noise is then constant for many years until the pavement gets old with cracks and ravelling. In this last phase noise increases another decibel. This is a typical lifecycle for road pavements. From this example it can be seen that a noise decrease of 2- 3 dB might occur when an old pavement is replaced by a similar brand new pavement. This decrease in noise has the same order of magnitude as the decrease which can typically be expected from a speed reducing traffic management scheme. It is very important to have this in mind when evaluating the results of noise measurements before and after implementation of traffic management schemes in order to avoid wrong interpretations of measurement results.

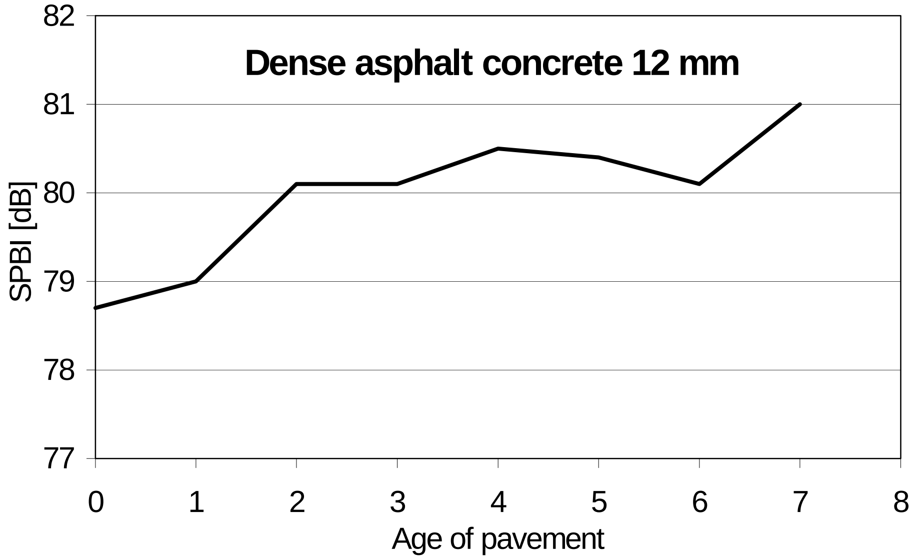


Figure 2.1 Noise from a dense asphalt concrete over the lifetime of the pavement [2.2] measured on a Danish highway (signed speed 80 km/h).

If the old pavement is replaced by a new type of pavement (which is not specially noise reducing) the noise may also change by +/- 2 dB. Such a change is also of the same magnitude as the effect on noise which can typically be expected from a traffic management scheme. So it is also very important to register if the pavement has been changed to another type, when results of noise measurements before and after implementation of traffic management schemes are evaluated.

It is necessary to distinguish between ordinary changes of pavements and introduction of special pavements like for example cobblestones that are a part of a traffic management project. The noise consequences of ordinary changes of pavements cannot be regarded as an effect of a traffic management scheme, whereas the use of special pavements is an affect to be accounted for.

2.2 Noise at constant speed

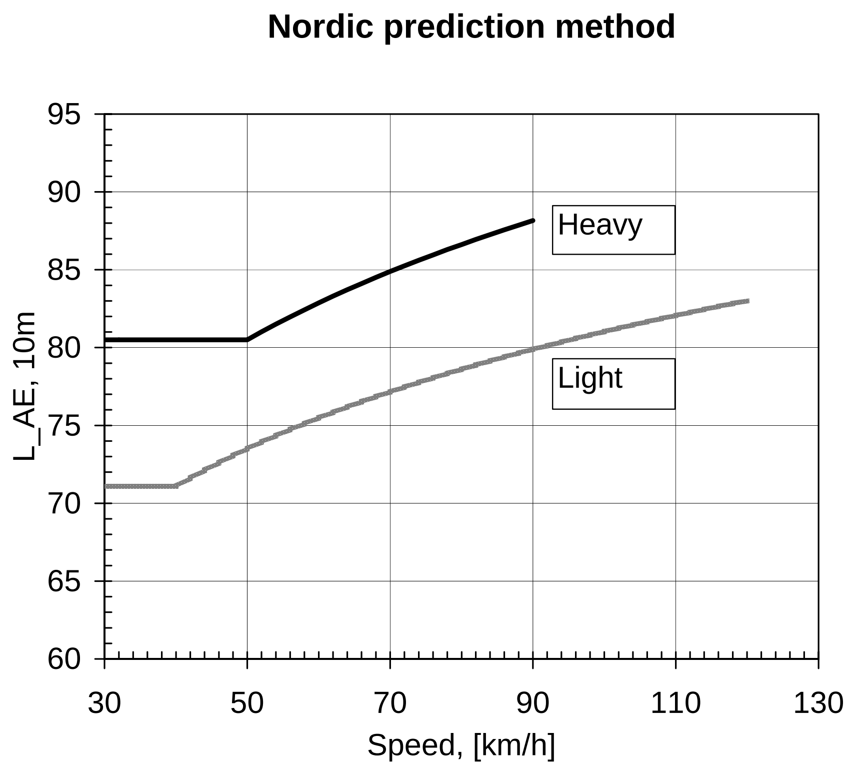


Figure 2.2 Noise emissions for light and heavy vehicles driving with constant speed in the Nordic Prediction Method for road traffic noise from 1996 [2.1] given as LAE for single vehicles at various speeds 10 meters from the centreline of a road.

The following formulas [2.1] give the relation between noise form single vehicles at a distance of 10 m to the centreline of a road (expressed as L_{AE} in dependence of the vehicle speed *v*):

$L_{AE}\ (light) = 73.5 + 25 \times \log (v/50)$	for $v \geq 40$ km/h	(1)
$L_{AE}\ (light) = 71.1$	for 30 km/h $< v <$ 40 km/h	(2)
$L_{AE}\ (heavy) = 80.5 + 30 \times \log (v/50)$	for $v \geq 50$ km/h	(3)
$L_{AE}\ (heavy) = 80.5$	for 30km/h $< v <$ 50 km/h	(4)

These formulas can be used to predict relative differences in noise before and after implementation of a traffic management scheme that has changed the average speed on a road.

As it can be seen on Figure 2.2, noise emissions are constant for light vehicles from 30 to 40 km/h. The reason for this may be that the drivers at low speeds select a low gear and make the engine run at a high number of revolutions. At higher speeds the noise increases with increasing speed. For heavy vehicles the noise is constant from 30 to 50 km, whereas it increases with increasing speed.

The average noise levels (L_{Aeq}) for a given time period (10 meter from the centreline of a road) can be calculated from the following formulas [2.1]:

$$L_{Aeq,T}\ (light) = L_{AE}\ (light) + 10 \text{ x } \log\ (N\ (light)/T) \quad (5)$$
$$L_{Aeq,T}\ (heavy) = L_{AE}\ (heavy) + 10 \text{ x } \log\ (N\ (heavy)/T) \quad (6)$$

N is the number of light or heavy vehicles respectively during the time period *T* in seconds. $L_{Aeq,24h}$ can be calculated using the average daily traffic and T = 86,400 seconds.

The total noise level for a road with both light and heavy vehicles can be predicted using the following formula [2.1]:

$$LAeq,T\ (mixed\ traffic) = 10 \text{ x } \log\ (10\ LAeq\ (light)/10 + 10\ LAeq\ (heavy)/10) \quad (7)$$

These formulas can also be used to calculate L_{DEN} by first calculating L_{day}, $L_{evening}$ and L_{night} separately with different time frames and adding them using the following formula [2.4]:

$$L_{DEN} = 10 \log\ (1/24 \text{ x } (12 \text{ x } 10^{Lday/10} + 4 \text{ x } 10^{Levening/10} + 8 \text{ x } 10^{Lnight/10})) \quad (8)$$

2.3 Practical examples

The following tables give some indications on which noise reductions to expect from changes in traffic (at constant speed) caused by implementing various traffic management schemes. The canges are predicted using the Nordic Prediction Method from 1996.

Table 2.1 shows the effect on noise when changing the speed of the traffic when the heavy traffic accounts for 10 % of the total traffic. It is assumed that the maximum speed of the heavy traffic is 90 km/h. This reduces the effect on noise of reducing speed over 90 km/h, because it is assumed that the heavy vehicles do not contribute to the noise reduction at these high speeds. According to this table the noise is reduced between 0 and 2 dB when the speed is reduced by 10 km/h.

Table 2.1 Noise reduction caused by a 10 km/h reduction in speed (10 % heavy traffic) predicted with the Nordic Prediction Method from 1996 [2.1, 2.5].

Change in speed	Noise reduction
From 110 to 100 km/h	0.7 dB
From 100 to 90 km/h	0.7 dB
From 90 to 80 km/h	1.3 dB
From 80 to 70 km/h	1.7 dB
From 70 to 60 km/h	1.8 dB
From 60 to 50 km/h	2.1 dB
From 50 to 40 km/h	1.4 dB
From 40 to 30 km/h	0 dB

Traffic management often also has an effect on the volume of traffic. Table 2.2 shows the noise reduction caused by a reduced traffic volume under the assumption that there are no changes in either speed or the percentage of heavy vehicles. The rule of thumb is here that a 50 % reduction in traffic reduces the noise by 3 dB. This table can also be used to illustrate the effect of introducing electrical vehicles. If it is assumed that the engine noise for electrical vehicles is negligible at lower speeds the introduction of an electrical vehicle can be handled as the removal of an ordinary vehicle. Thus, an introduction of 10 % electrical vehicles will at the most reduce the noise by around 0.5 dB.

Table 2.2 Noise reductions caused by reductions in the traffic volume predicted with the Nordic Prediction Method from 1996 [2.1, 2.5].

Reduction in traffic volume	Reduction in noise
10 %	0.5 dB
20 %	1.0 dB
30 %	1.6 dB
40 %	2.2 dB
50 %	3.0 dB
75 %	6.0 dB

Table 2.3 Noise reductions caused by reductions in the percentage of heavy traffic predicted with the Nordic Prediction Method from 1996 [2.1, 2.5].

Reduction in percentage of heavy vehicles	50 km/h	80 km/h
From 5 to 0 %	0.7 dB	1.0 dB
From 10 to 0 %	1.4 dB	1.9 dB
From 15 to 0 %	2.0 dB	2.6 dB

Sometimes there is a special focus on reducing the heavy traffic. Table 2.3 shows examples of the effect on noise of reducing the percentage of heavy vehicles. It is assumed that the traffic volume and the speed are unchanged.

These tables can be used to give a first estimate of the noise consequences, which can be expected from the implementation of a certain traffic management scheme. The formulas in section 2.2 can be used to give a more exact prediction of the expected consequences. In the following example the noise reduction caused by the rebuilding of a main road has been evaluated on this background.

In the Danish city of Århus one of the main arterial roads (Dronning Margrethes Vej) has been rebuild as the result of the implementation of a traffic management scheme [2.5]. The road was used as a north going connection from the harbour with a high amount of heavy vehicles. As a part of the urban traffic plan for Århus another arterial road was enlarged to carry the heavy traffic from the harbour. Afterwards Dronning Margrethes Vej has been rebuild in order to improve traffic safety and the local environment. The 12 m wide road was narrowed with only one driving lane in each direction combined with construction of bicycle lanes and a wide central reserve with green vegetation. In order to remove the heavy traffic, signs forbidding lorries to use the road were set up, and an electronic route guidance for the lorries to alternative routes was established. Only busses and trucks with errands in the local area are allowed. After the reconstruction the traffic volume was reduced by 12 % and the heavy traffic by 60 %. The mean driving speed was reduced from 57 to 50 km/h. It has been estimated that the noise was reduced by 3 dB because of these changes [2.5].

2.4 New emission data

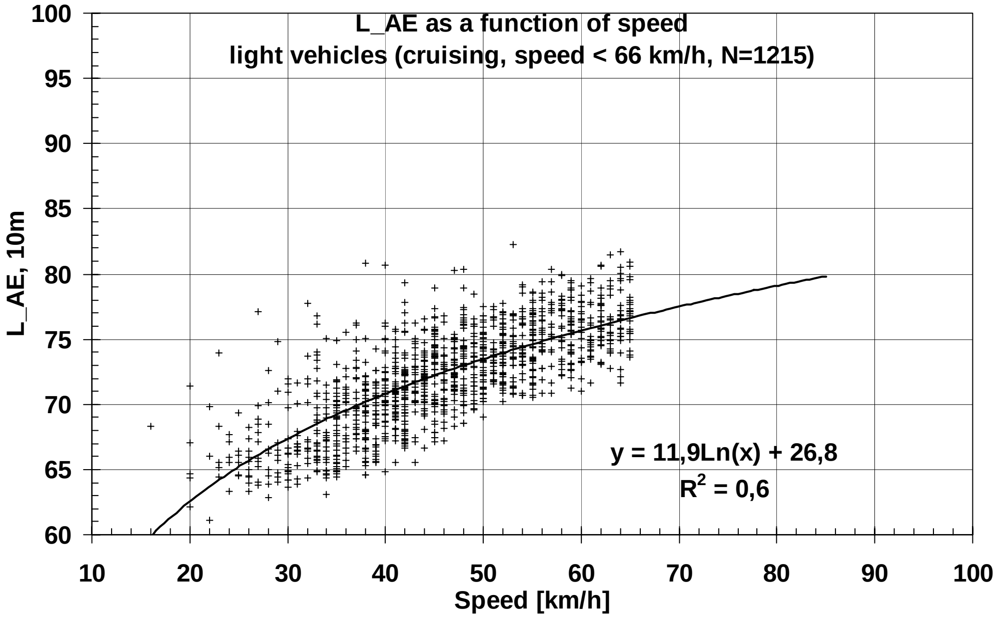


Figure 2.3 Noise emissions for light vehicles less than 3½ tons at low speeds measured on Danish roads with constant speed in 1999-2000 as LAE 10 m from the centre line of the road [2.3].

As can be seen in section 2.3 the noise is constant at low speeds according to the current Nordic Prediction Method from 1996. This method is based on emission measurements performed on Nordic roads in the beginning of the 1990s. A new detailed measurement campaign was carried out in Denmark in 1999 and 2000 [2.3] in order to establish noise emissions for the next generation of the Nordic Prediction Method (called NORD2000), which is still not implemented for practical use. The results of these measurements for low speed traffic under 65 km/h are showed in figure 2.3 and 2.4. A logarithmic regression line is estimated. There is a spread in the data around these regression lines, but for light as well as heavy vehicles there is a clear tendency that the noise is reduced when the speed is reduced even at very low speeds. An explanation can be that the EU regulation on noise emissions basically has an effect on the engine noise, which is dominating at these rather low speeds.

At low speeds the noise emission is very dependent on the selection of gear and the revolutions of the engine. This is part of the explanation for the relatively big spread in the emission data at low speeds. The drivers' selection of gear and revolutions is very dependent on the layout of the actual road, on which the vehicle is driving. The best way to evaluate the noise consequences of traffic management at low speeds is therefore to perform qualified noise measurements and not to rely on generalised prediction methods.

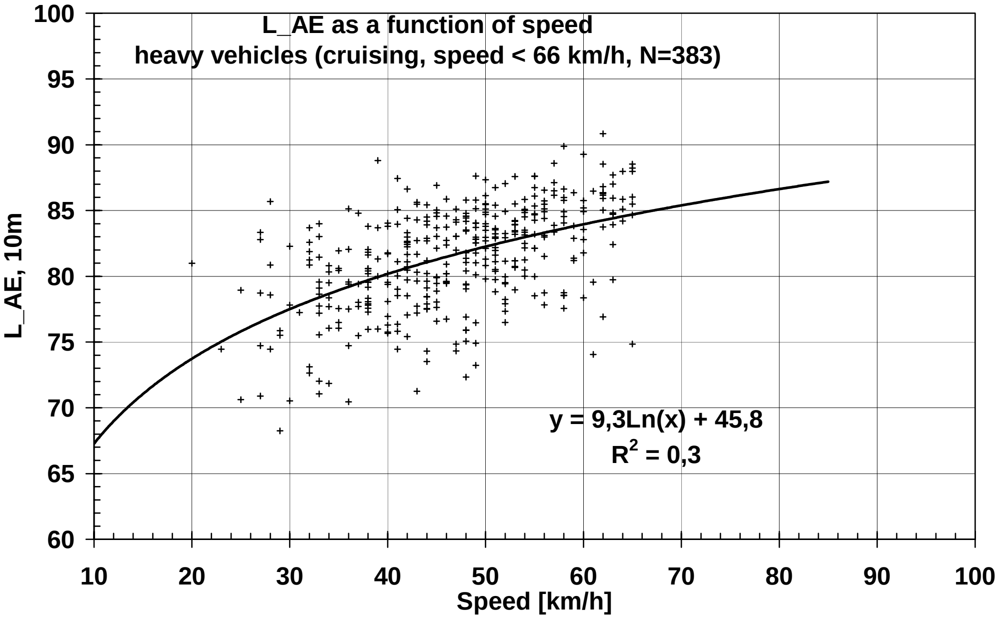


Figure 2.4 Noise emissions for heavy vehicles over 3½ tons at low speeds measured on Danish roads with constant speed in 1999-2000 as L_{AE} 10 m from the centre line of the road [2.3].

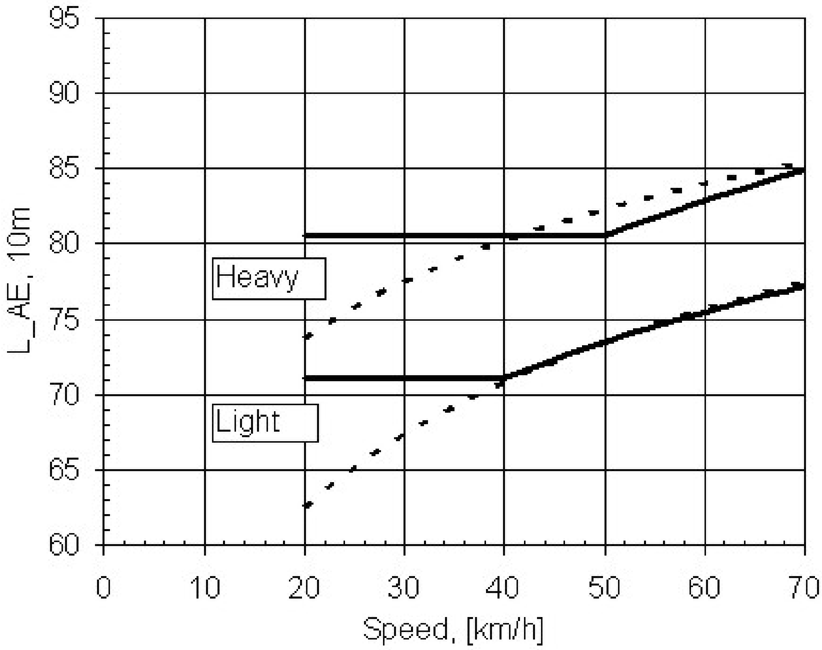


Figure 2.5 Comparison between the emission data in the current Nordic prediction method (full lines) and new emissions measured in 1999-2000 (dotted lines) for low constant speeds.

Figure 2.5 shows a comparison of the emissions in the current Nordic prediction method and the new emission data measured in 1999-2000. For light vehicles the two data sets are the same for speeds above 40 km/h. At lower speeds the noise decreases according to the new data. For heavy vehicles the tendencies are roughly the same.

Table 2.4 shows the effect on noise when changing the speed of the traffic for light and heavy vehicles separately based on the new emission data from Figure 2.3 and 2.4. Because of the significant tendency in the data from 1999-2000 for the decrease of noise at low speeds between 30 and 50 km/h it has been decided by the working group to include this tendency in the conclusions in chapter 9 for speeds over 30 km/h. Practically this will be done by using the logarithmic relation between speed and noise in the current Nordic prediction method (formulas *1* and *3*) also for this low speed interval instead of the constant noise levels that are included in the method (formulas *2* and *4*).

Table 2.4 Noise reduction caused by a 10 km/h reduction in speed according to new Danish noise emission measurements from 1999-2000 (driving with constant speed) [2.3].

Change in speed	**Noise reduction light vehicles**	**Noise reduction heavy vehicles**
From 60 to 50 km/h	2.1 dB	1.7 dB
From 50 to 40 km/h	2.7 dB	2.1 dB
From 40 to 30 km/h	3.7 dB	2.7 dB

2.5 References for chapter 2

[2.1] Road Traffic Noise – Nordic Prediction Method, TemaNord 1996:525, Nordic Council of Ministers 1996, Copenhagen, Danmark.

[2.2] Bendtsen, Hans; Larsen, Lars Ellebjerg; Greibe, Poul. Udvikling af støjreducerende vejbelægninger til bygader. Statusrapport efter 3 års målinger. (Development of noise reducing road surfaces for urban roads. Status report after 3 years of measurements. In Danish with extensive English summary). Report 4, 2002. Danish Transport Research Institute. May be downloaded from www.dtf.dk.

[2.3] Andersen, Bent. Støjudesndelse fra biler på vejnettet (Noise Emission from Vehicles in ordinary Traffic..In Danish with English summary), report 2, 2003, Danish Transport Research Institute, Kgs. Lyngby, Danmark, 2003. May be downloaded from www.dtf.dk.

[2.4] Directive 2002/49/EU of the European Parliament and of the Council of 25th of June 2002 relating to the assessment and management of environmental noise.

[2.5] Bendtsen, Hans et.al. Vejtrafik og støj – en grundbog (Road traffic noise – a textbook). The Danish Road Directorate. Report 146, 1998. May be downloaded from www.vd.dk.

3. Influence of uneven driving pattern on noise

3.1 The HARMONOISE model

In the previous chapter, the speed influence on noise emission was presented; mainly based on the Nordic Prediction Model from 1996 and new Nordic data that will be part of the new Nordic Model “Nord2000”. The Nordic model, however, does not provide any means of looking at the influence of uneven driving patterns, such as frequent accelerations and decelerations. Fortunately, the EU project HARMONOISE, partly running in parallel to SILVIA, has developed a “source model” that includes such considerations. It is important to note that this model is based on measured data according to state-of-the-art.

The HARMONOISE source model currently has the following features of importance to this report [3.1]:

- Each vehicle category is represented by two point sources, each having a specified sound power having contributions from tyre/road and propulsion noise. Thus the latter two sources are treated separately in each occasion.
- As a minimum 3 vehicle categories are used: Passenger cars, medium heavy and heavy vehicles. Additional categories are defined but optional. The "average" medium heavy vehicle is assumed to have two axles and the "average" heavy vehicle is assumed to have 4 axles although corrections to other number of axles can be made.
- All default data refer to a reference condition which is constant speed, an air temperature of 20 ˚C and a "virtual reference" surface which is selected as being the average of a DAC 0/11 and an SMA 0/11. Deviations from these conditions are corrected for.
- Default data for tyre/road noise is given by the equation:

$$L_{WR}(f) = a_R(f) + b_R(f)\lg\left[\frac{v}{v_{ref}}\right]$$

- All coefficients are given in 1/3 octave bands 25-10000 Hz. 80% of the tyre/road sound power is assigned a point source at 0,01 m and 20% is assigned a point source at 0,3 m (passenger cars) or 0,75 m (heavy vehicles).
- Default data for propulsion noise is given by the equation:

$$L_{WP}(f) = a_P(f) + b_P(f)\left[\frac{v - v_{ref}}{v_{ref}}\right]$$

- All coefficients are given in 1/3 octave bands 25-10000 Hz. 20% of the propulsion noise sound power is assigned a point source at 0,01 m and 80% is assigned a point source at 0.3 m (passenger cars) or 0.75 m (heavy vehicles).

The HARMONOISE model thus makes it possible to calculate noise changes in third octave bands. The coefficients for various vehicle categories and frequencies would be too complicated and too comprehensive to report here [3.13].

The above equations are valid for free flow traffic at constant or near constant speed. For interrupted flow traffic there is a correction for accelerations and decelerations; see below. For traffic at crossings without traffic lights there is no correction; such calculations should be carried out like the case with an uninterrupted traffic flow, although persisting changes in speed have to be taken into account. Interrupted flow also influences tyre/road noise. However, no correction to tyre/road noise is proposed for tyre slip occurring at such conditions. Measurements indicate that substantial slip (> 5%) only occurs under such extreme conditions that there will be negligible influence on L_{den} calculations. Nevertheless, it may influence L_{Amax} calculations.
Correction for acceleration/deceleration at interrupted flow traffic such as at light-controlled intersections is made only to propulsion noise and is given by:

$$\Delta Lacc = Ca \quad for\ -2\ m/s^2 < a < 2\ m/s^2$$

where:
a = the acceleration (a>0)/deceleration (a<0) in m/s^2
C = 4.4 for light vehicles and 5.6 for heavy vehicles.

For heavy vehicles having 3 axles or more, when applying engine brake, the unsigned value of the acceleration *a* shall be used. Such will often be the case under steep and long downhill conditions. Provided data for the speed changes of vehicles are available, the HARMONOISE model makes it possible to calculate the effect this has on noise. Table 3.1 presents examples of the influence on noise emission from vehicles (tyre/road and propulsion noise) of uneven driving pattern. The results cover a speed of 50 km/h before accelerating/decelerating. Effects are lower at higher speeds due to increased rolling noise component.

Table 3.1 The influence on noise emission from vehicles (tyre/road and propulsion noise) of uneven driving pattern (acceleration/deceleration). The noise influence is presented in relation to a reference case of constant speed of 50 km/h based on the Harmonoise Model [3.1].

Acceleration/deceleration	Vehicle type	Noise influence	Note
1 m/s^2	Light	1.7 dB	Moderate acceleration
2 m/s^2	Light	4.5 dB	High acceleration
0.5 m/s^2	Heavies	+ 2.1dB	Moderate acceleration
1 m/s^2	Heavies	+ 4.5 dB	High acceleration
- 1 m/s^2	Light	- 0.8 dB	Slow deceleration
- 2 m/s^2	Light	- 1.2 dB	High deceleration
- 1.5 m/s^2	Heavies, 2 axles	- 4.5 dB	Moderate deceleration
- 1.5 m/s^2	Heavies, 3 axles	+ 4,5 dB	Moderate deceleration

It can be noted that a speed-reducing measure causing a speed reduction of 10 km/h, but which results in accelerations according to the “moderate case” in Table 3.1, will increase propulsion noise at the location of accelerations by 1.7 to 2.1 dB, depending on the mix of vehicles. Since the speed reduction from 50 to 40 km/h will cause an overall noise decrease of 2.1-2.7 dB according to Table 2.4, and HARMONOISE would predict approximately 3.0 dB of noise reduction for a constant speed decrease from 50 to 40, the net effect on noise may well be a marginal noise decrease; i.e. where such accelerations occur (which may be a rather limited location).

It is therefore, important to design such speed reduction cases in a way which avoids the highest accelerations to occur at or near the position of dwellings or other noise-sensitive areas.

3.2 The RoTraNoMo model

The RoTraNoMo project [3.2] has the purpose to develop a vehicle noise model in great detail taking all relevant driving conditions into account. It will be much more detailed than any other model available. When this is written, no information about the details of the model is available.

3.3 The RWTÜV modified model

The RWTÜV model was developed for the German Environmental Protection Agency (Umweltbundesamt) by TÜV Automotive in Aachen Germany. The model was further improved within a project run 2002-2003 by TÜV Automotive and TRL (Transportation Research Laboratory in United Kingdom), funded by the European Commission. The model somewhat resembles that of HARMONOISE, except that it does not use frequency spectra; it operates just on A-weighted overall levels. A brief description can be found in [3.3].

Like the HARMONOISE model it distinguishes between tyre/road noise and propulsion noise. Tyre/road noise is modelled in a similar way as HARMONOISE. The emission factors for propulsion noise L_{prop} are:

$$L_{prop} \text{ (at no load)} = k_1 * (n - n_{idle})/(s - n_{idle}) + k_0,$$

$$L_{prop} \text{ (at wide open throttle)} = w_1 * (n - n_{idle})/(s - n\ n_{idle}) + w_0$$

where: k_1, k_0, w_1 and w_0 are noise emission factors
- n = engine speed
- n_{idle} = the engine speed when the engine is idling
- s = engine speed at which the engine develops its maximum power

The noise emission factors are listed in Table 3.2 [3.3]. It is unclear how cases where the engine load is between “full” (=wide open throttle) and “low” are handled.

Table 3.2 Example of noise emission factors in the RWTÜV modified model. Registration year 1996 means that the vehicles considered are those which meet the present EU noise limits which have been applied since 1996 [3.3].

Vehicle layer	**Registration year**	**Low load**		**Full load**	
		K_1	k_0	w_1	w_0
Car, petrol, <1.4 l	From 1996	29	49	22.6	56
Car, petrol, 1.4 l – 2 l	From 1996	30	50	22.6	58
Car, petrol, > 2 l	From 1996	31	50	22.6	59
Car, petrol, > 2 l, high perf.	From 1996	31	52	35	58
Car, diesel, < 2 l	From 1996	30	51	23.5	58
Car, diesel, > 2 l	From 1996	30	51	23.5	58
Car, diesel, > 2 l, high perf.	From 1996	31	52	35	58
Light duty vehicle, petrol	From 1996	17.3	55.6	10.8	63.4
Light duty vehicle, diesel	From 1996	17.3	55.6	10.8	63.8

If, for example, a car of the third category above is checked, the noise increase from low to full load (will correspond to acceleration from 0 to about 2 m/s^2) at an engine speed of 3000 rpm (s assumed to be 5000 and n_{idle} 800 rpm) is 4.6 dB. This is quite similar to what HARMONOISE would predict (se table 3.1). Figure 3.1 gives an example of noise emission versus engine speed according to RWTÜV.

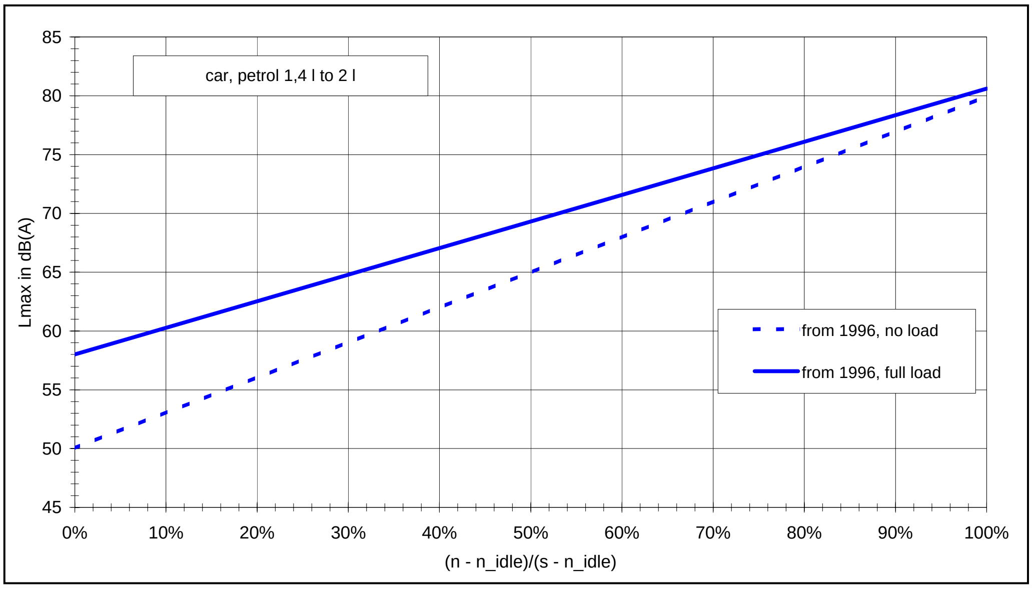


Figure 3.1 Increase in noise emission from a "no load" condition (constant speed) to a "full load" condition (maximum acceleration for this car). Data from [3.3].

3.4 The VENOM model

In a cooperation project, the Swedish National Road and Transport Research Institute (VTI) and the Technical University of Gdansk (TUG) in Poland have developed a noise emission model called VENOM (**VE**hicle **NO**ise **M**odel). This was originally based on a model developed for a project studying the effect of driving according to the principles of "EcoDriving" [3.4].

The objective of the ongoing VENOM project is to develop a model by means of which one can predict the influence of vehicle noise emission of various driving conditions, as well as of various vehicles and characteristics of such vehicles. The model is built-up of results of extensive noise measurements on a number of typical light vehicles. Measured data are compiled in a data bank, which will then be used as an input to calculation procedures utilizing certain driving cycles of vehicles, in order to calculate noise emission as some average level and/or maximum levels over a certain driving distance. The driving cycles are intended to be possible to modify by the user to represent different driving patterns or driving behaviour.

The model is intended for use as a tool for calculation of noise emission effects of various changes in for example vehicles, traffic restrictions or driver behaviour.

The project is being finalized; thus, at the time of writing only preliminary and limited data can be shown. A special technique developed at the Technical University of Gdansk was used in order to convert the measured data to approximating equations. Separate equations were developed for various driving conditions; i.e., coast-by, constant speed, deceleration, acceleration and braking. When applicable, the equations were created separately for each gear. The following types of equations were found to fit the results well and were used:

Coast-by: $L_{CB} = A_{CB}*Ln(V) + B_{CB}$

Constant speed: $L_{CS(1)} = A_{CS(1)}*V+B_{CS(1)}$ *for the 1st gear*

$L_{CS(i)} = A_{CS(i)}+Ln(V)+B_{CS(i)}$ *for the 2nd -5th gear*

Deceleration: $L_{DC(i)} = A_{DC(i)}*V^2+B_{DC(i)}*V+C_{DC(i)}$

Acceleration: $L_{AC(i)} = A_{CB}*Ln(V) + B_{CB}+ (C_{AC(i)}*V^2+D_{AC(i)}*V+E_{AC(i)})*a^2 + +(F_{AC(i)}*V^2+G_{AC(i)}*V+H_{AC(i)})*a$

Braking: $L_{BR} = A_{CB}*Ln(V) + B_{CB}+ (C_{BR}*V^3+D_{BR}*V^2+E_{BR}*V+F_{BR})*a^2+ +(G_{BR}*V^3+H_{BR}*V^2+I_{BR}*V+J_{BR})*a$

Where:

L = Maximum A-weighted sound level during a pass-by
V = Vehicle speed corresponding to the recorded sound level
a = Acceleration (can be both negative and positive)
i = Gear number
A, B, C, D, E, F, G, H, I, J are constants
Ln is the natural logarithm

Figures 3.2-3.4 present examples showing the fit between the model based on the equations and actually measured data for a passenger car with moderate performance (Volvo S40, with an 1.8 litre engine). The figures represent constant speed driving (mainly tyre/road noise), ("normal") acceleration and ("normal") deceleration, using different gears and at different speeds.

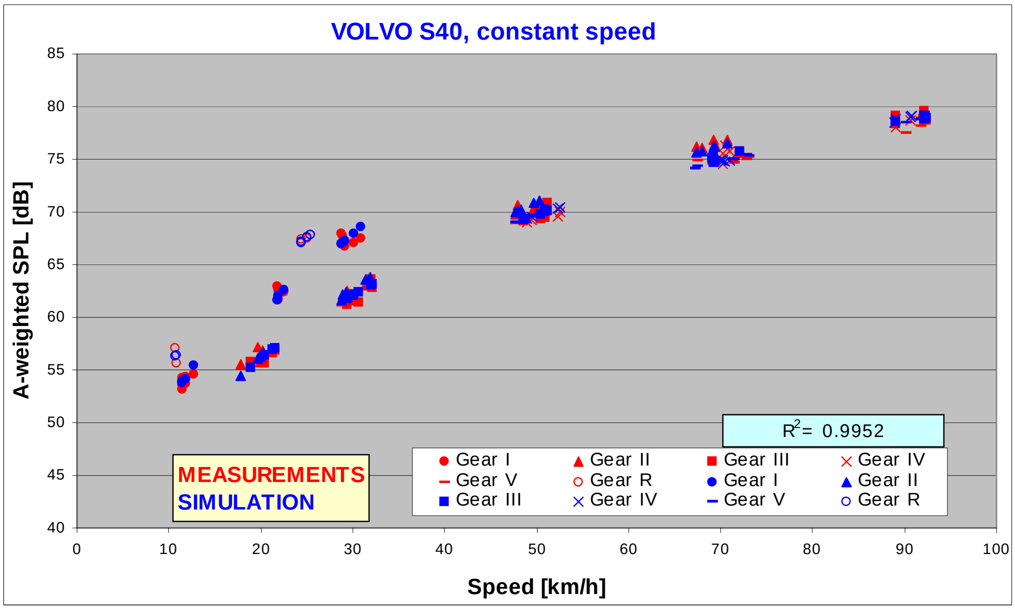


Figure 3.2 Simulated sound levels (blue symbols) compared to actually measured ones (red symbols). Constant speed driving for the Volvo S40 passenger car. From [3.4].

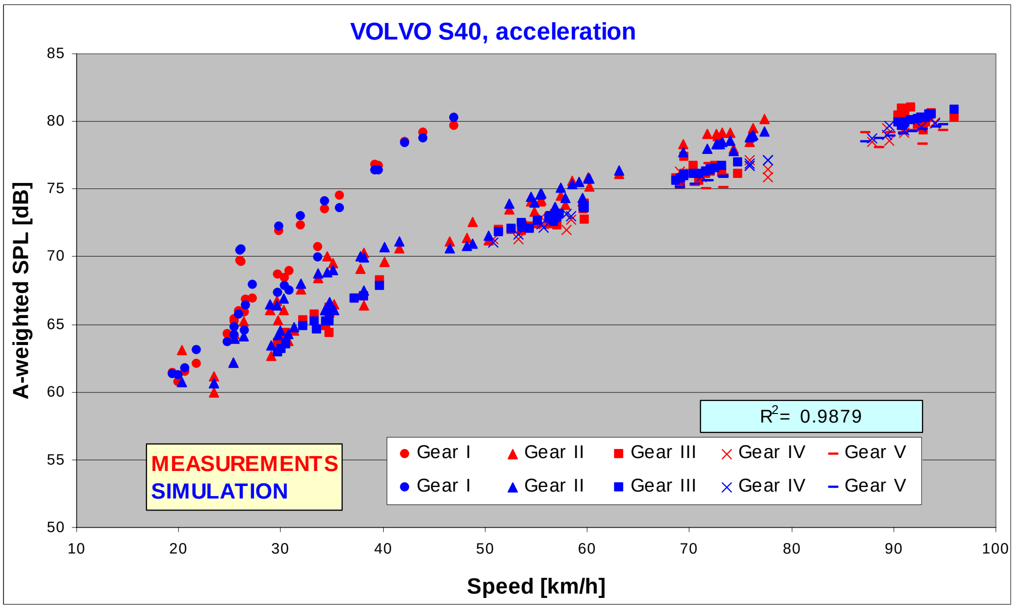


Figure 3.3 Simulated sound levels (blue symbols) compared to actually measured ones (red symbols). Acceleration mode for the Volvo S40 passenger car. From [3.4].

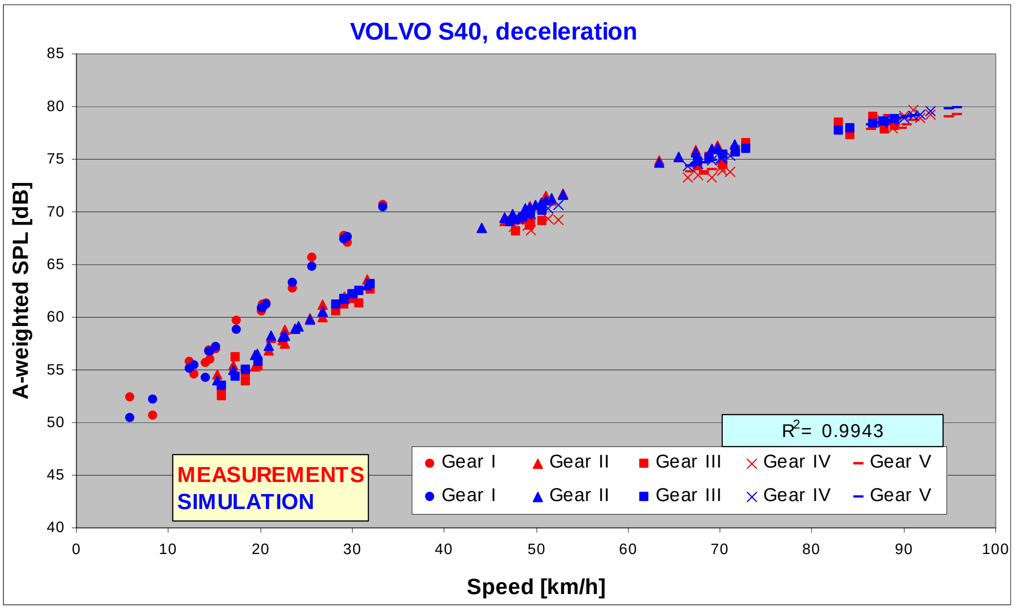


Figure 3.4 Simulated sound levels (blue symbols) compared to actually measured ones (red symbols). Deceleration mode for the Volvo S40 passenger car. From [3.4].

The EcoDriving report [3.4] further presents noise emissions for various types of driving, such as constant speed, acceleration, deceleration (using engine braking) and deceleration (using wheel brakes). All diagrams cannot be shown here. Instead there will be some examples of early application of this model on the following pages.

3.5 Early case studies using the VENOM/EcoDriving model

3.5.1 Introduction

The VENOM model is not yet finalized. However, the data from the EcoDriving project, which is part of the final VENOM model have already been used in some case studies. These case studies were low-budget studies, which meant that validating noise measurements could not be afforded.

3.5.2 The EcoDriving project

The general idea of EcoDriving is to reduce exhaust emissions (in particular carbon dioxide) and fuel consumption without sacrificing travelling time, at least not to a significant extent. Compared to "normal" driving, EcoDriving assumes that driving behaviour is changed according to the following principles (instructions for the driver):

- When starting from standstill, use the first gear as short time as possible, and change to the second gear as soon as the car has started to move.
- In the acceleration phase, accelerate rather fast, preferably on the second gear, until you have reached your target speed. In many cases, one can change from the second to the fourth gear without using the third gear, in particular in urban driving where the posted speed is 50 km/h.
- Try to engage the "final" gear (4^{th} or 5^{th}) as soon as possible in order to minimize the engine speed.

- When decelerating, use engine braking as much as possible (i.e. release the accelerator pedal), and avoid using the brakes until it is really necessary.
- Look at the traffic and the road/street environment in front of you in order to start deceleration as soon as possible when it is obvious or likely that your car has to reduce its speed or to stop. Engine braking can then be applied to a greater extent which.
- If possible, avoid stopping the car when it is not necessary; instead drive it smoother.
- If possible, choose a driving lane where you can run the best according to EcoDriving principles.
- If possible, keep a distance to the nearest vehicle in front of you that makes it easier for you to "run your own race", i.e. to drive according to the EcoDriving principles.
- If the car has a constant-speed device, do not use it when driving in hilly areas.
- If your driving takes you over a hill, accept that the car reduces its speed somewhat when driving uphill, do not attempt to maintain a constant speed. Once the crest has been reached, accelerate downhill to gain some of the speed you lost when going uphill.

It was concluded that the effects on vehicle noise emission of practising EcoDriving as compared to "normal" driving are very small. The equivalent noise levels seem to be reduced by a few tenths of a decibel, which is insignificant for noise exposures in practical situations, while the maximum noise levels may be reduced somewhat more, possibly by 0 - 2 dB. The latter will, however, affect only a very limited number of noise recipients along a street or road. It was, therefore, concluded that EcoDriving may be introduced to a large extent in traffic without any substantial effect on noise emission. If any, the effect will be favourable.

3.5.3 Speed-reducing hump in Katrineholm

In the Swedish town of Katrineholm; in a centre location one street was rebuilt as part of a traffic calming project. Part of this effort was the building of a road hump at a pedestrian crossing having a paving stone surface on the flat top portion of the hump. The EcoDriving model was used to calculate the effect that the changed conditions would have on the noise emission, as expressed by various measures. The basis was a measurement (supplemented with an expert judgement where data was insufficient) of the driving speed and gear selection as a function of position along the street section. The traffic there was mainly light traffic; thus the calculations were made for only cars. Figure 3.5 shows the speed and the associated noise as a function of position along the street. The data presented contain a correction for the road surface effect due to the use of the ramps at the beginning and end of the hump as well as the paving stones on top of the hump, as estimated from earlier experience and by expert judgement. These corrections can be seen as the transients in the noise curve as well as an increase of the noise by 3 dB on top of the hump. The figure clearly shows the noise reduction caused by the speed reduction, but also the somewhat compensating action by the transients and the paving stones. Table 3.3 shows the corresponding maximum and equivalent levels for the "before” and “after" situations.

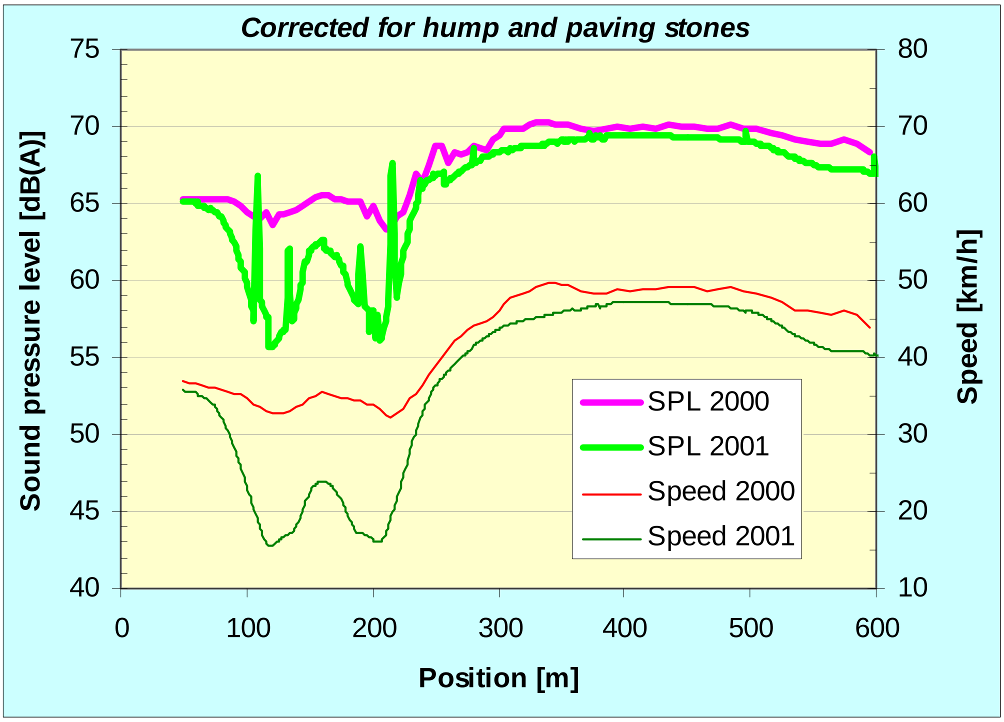


Figure 3.5 Effect of a street hump: values for 2000 represent the case before the hump was built, values for 2001 represent the case after it was built. Vehicle speed and the associated A-weighted Sound Pressure Level (SPL) as a function of position along the street are plotted for an "average car". A correction for the road surface effect due to the use of the ramps at the beginning and end of the hump as well as the paving stones on top of the hump have been made. From [3.5].

The final noise differences were concluded to be insignificant except at the intersections; and in the latter case equivalent noise was reduced but maximum noise was increased. Thus it is difficult to say whether there was an improvement or impairment of the acoustic environment.

Table 3.3 Results of the noise calculations using the EcoDriving model. The equivalent levels are intended to represent an average noise level along the entire 600 m long street section considered. From [3.5].

Parameter	**Unit**	**Year 2000 (no hump)**			**Year 2001 (with hump)**		
		At street humps	**After street humps**	**Entire section**	**At street humps**	**After street humps**	**Entire section**
Equivalent sound level	dB	64.7	69.2	67.9	60.5	68.3	67.0
Maximum sound level	dB	65.6	70.3	70.3	67.7	69.7	69.7

3.5.4 Effect of introduction of a roundabout in Uppsala

In Uppsala in Sweden, the effect of building a roundabout in an intersection was calculated, using a similar procedure as for the previous project. The intersection was built as part of traffic calming efforts along a street. This intersection had no stoplights before the roundabout was built. Thus the comparison concerns a 4-way intersection

(2-lane streets) with no other traffic control than right-of-way for the major street, as compared to the same intersection after introducing a roundabout in it (with right-of-way for all vehicles already driving in the roundabout).

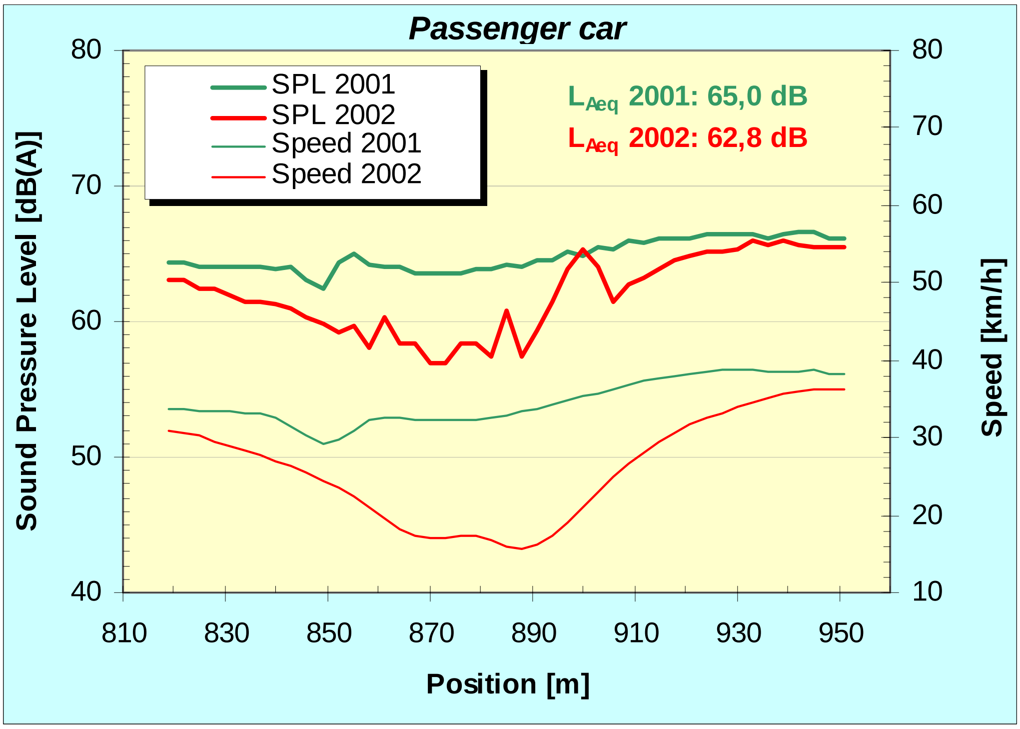


Figure 3.6 Effect of a roundabout: values for 2001 represent the case before the roundabout was built, values for 2002 represent the case after it was built. Vehicle speed and the associated A-weighted Sound Pressure Level (SPL) as a function of position along the street are plotted for an "average car". The data presented contain a correction for the side force effect on tyre/road noise due to the radius of the roundabout. The roundabout is located approximately at 870-890 m. The LAeq levels are calculated over the entire test section shown in the figure. From [3.6].

Figure 3.6 shows the results of the calculations [3.6]. Data for 2001 are for the conventional intersection (the "before" situation), whereas data for 2002 are for the roundabout case (the "after" situation). It was assumed in both cases that the vehicles arrived at the intersection one by one in such a way as not needing any full stop. This may be justified by the moderate traffic volume in this case. If they would have had to stop, the noise differences would have been reduced. In order to compensate for the increase in tyre/road noise due to driving with high side forces a correction for the noise levels in the roundabout of 3 dB was first made. This correction was based on estimations of the side forces (from speed and roundabout radius, side forces can be calculated) and using data collected by TUG for noise influence of side forces [3.7].

The results show that a roundabout causes a local decrease of speeds, which results in a reduced noise emission. The total effect is a reduction of equivalent sound level of around 2 dB along a 100 m street section with the intersection in the middle. However, the maximum noise level over the considered street section is not reduced significantly.

3.6 Noise emission at street intersections and roundabouts

An MSc Thesis recently published at Chalmers University of Technology, reports studies by calculations using the new Nord2000 model as well as by measurements at various locations in relation to intersections the noise emission of various vehicle categories at or near intersections [3.8]. The intersections included three signal-controlled and three roundabout-controlled intersections in the city of Borås in Sweden.

The results showed that the Nord2000 model overestimated the noise levels adjacent to the intersections, if using as the speed the posted speed (which was 50 km/h). The reason for the overestimations was believed to be the difference between the actual speed and the posted speed. However, in Nord2000, it is intended that the actual speeds shall be used whenever they are available. It was found that the noise levels were in general lower close to the intersections as compared to further away from them. This result is in line with what was shown in the previous subchapter. It was further noted that the roundabouts generate somewhat lower equivalent noise levels than the light-controlled intersections.

3.7 Effects of traffic calming measures on street in Västerås

An early experiment with traffic calming measures was conducted in the Swedish city Västerås in 1982-84 [3.9]. Speed humps of various constructions were tried but the ones studied for noise influence were depressions in the street. Noise levels and frequency spectra were measured at four positions along the street at different distances from the humps.

Close to a hump, noise expressed as both L_{10} and L_{50} (L_{50} is the noise level exceeded 50 % of the time; corresponding for L_{10}) was reduced by 1-2 dB. A short distance in front of and after the humps, the L_{50} levels was also reduced by 0-3 dB; however, the L_{10} levels were affected inconsistently. Between two humps (not affected by them), noise levels L_{10} and L_{50} were measured almost exactly the same before and after the hump was introduced. The noise reductions measured at or near the hump were explained by corresponding speed reductions. The average speed over the entire street section was reduced from 50 to 40 km/h; at the humps the speeds were reduced more. However, the overall noise effects were small; even so at and near the humps.

This example refers to measurements and thus vehicles about 20 years old when this is written. Nevertheless, the relative effects; i.e., the changes in noise levels due to the driving pattern changes should be essentially relevant also today; considering that the vehicles on such a street are mainly passenger cars and that these have undergone only small changes in exterior noise levels over the years [3.10].

3.8 Subjective study of noise effects comparing intersections and roundabouts

An interesting study which compared the subjective responses to noise exposures from a light-controlled intersection versus a roundabout was published in [3.11]. The study was part of the European project SVEN.

One part of the SVEN project was to expose a jury to noise recorded at a light-controlled intersection and to noise recorded at a roundabout; both in Paris and to ask the jury to estimate the annoyance. The noise levels were adjusted in order that the equivalent noise level of both events was the same.

The results are shown in Figure 3.7. It is quite evident that people prefer the sound from the roundabout. It is probable that this is because the roundabout causes somewhat more smoothly flowing traffic with less intruding acceleration events.

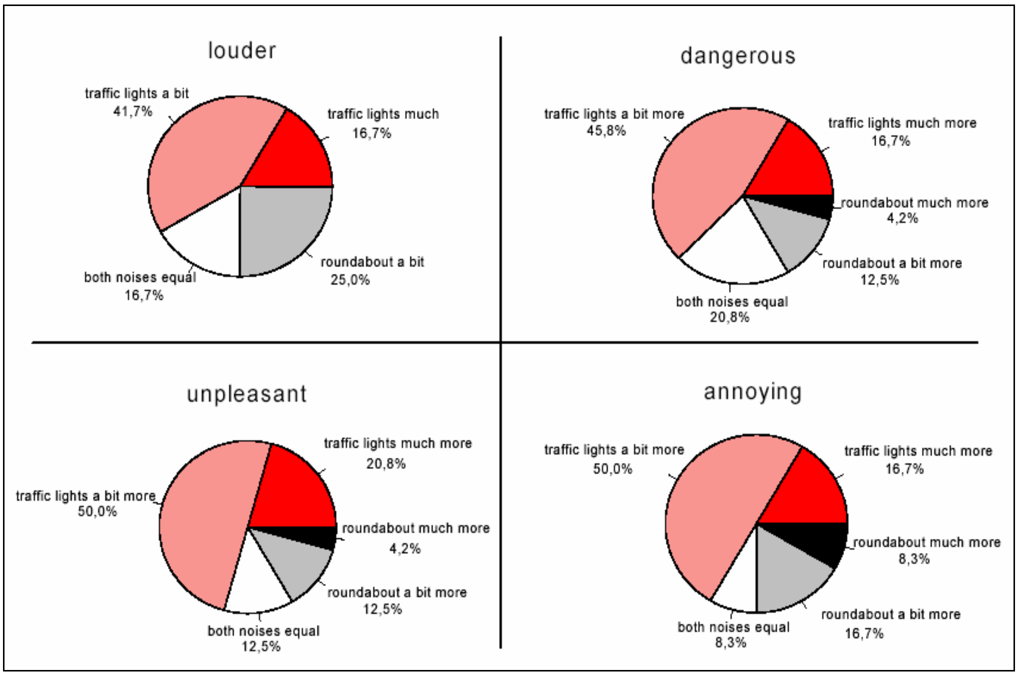


Figure 3.7 Subjective estimation of the sound from a light-controlled intersection and a roundabout in Paris. The sound was recorded and replayed to a jury with volume adjustment to create the same equivalent levels from both places. From [3.11].

3.9 Typical driving patterns

In the studies reported above, actual driving patterns are of great interest and are mostly needed as input. Examples of such driving patterns for a medium passenger car are presented in Figures 3.8-3.9 below. The first of the two figures show results measured for a residential street and the second for a major urban street [3.12]. It can be seen that the vehicles are driving with constant speed or very moderate accelerations most of the time. This indicates that on normal strait roads there are no reasons to take accelerations/decelerations into consideration when predicting noise.

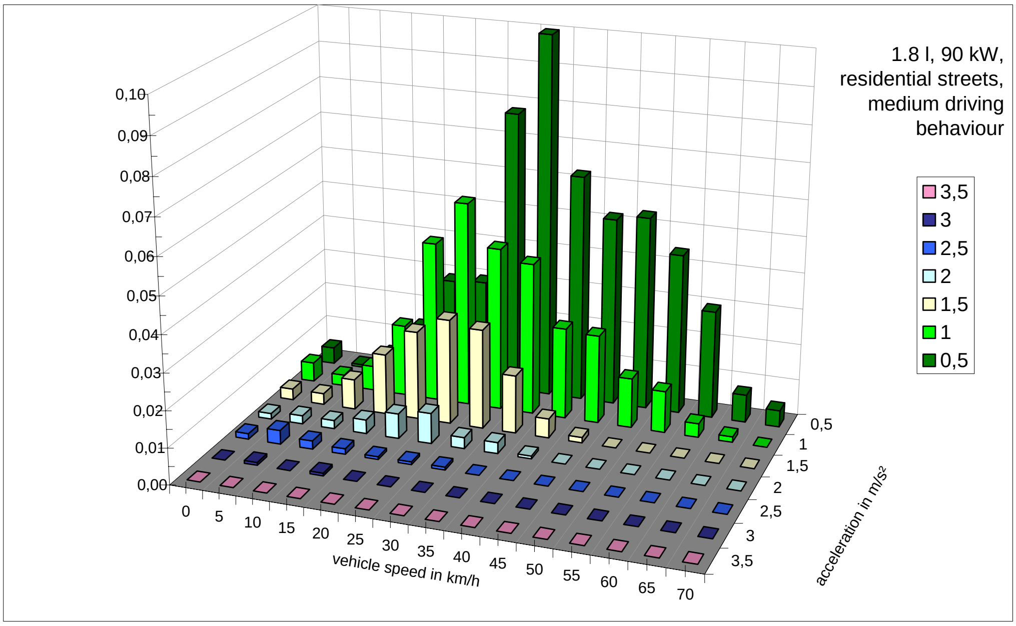


Figure 3.8 Typical driving patterns for a passenger car with a 90 kW engine on residential streets. Data from [3.12] collected in Aachen, Germany. The vertical axle is the proportion of full time (100 %) that is spent in a certain combination of speed and acceleration.

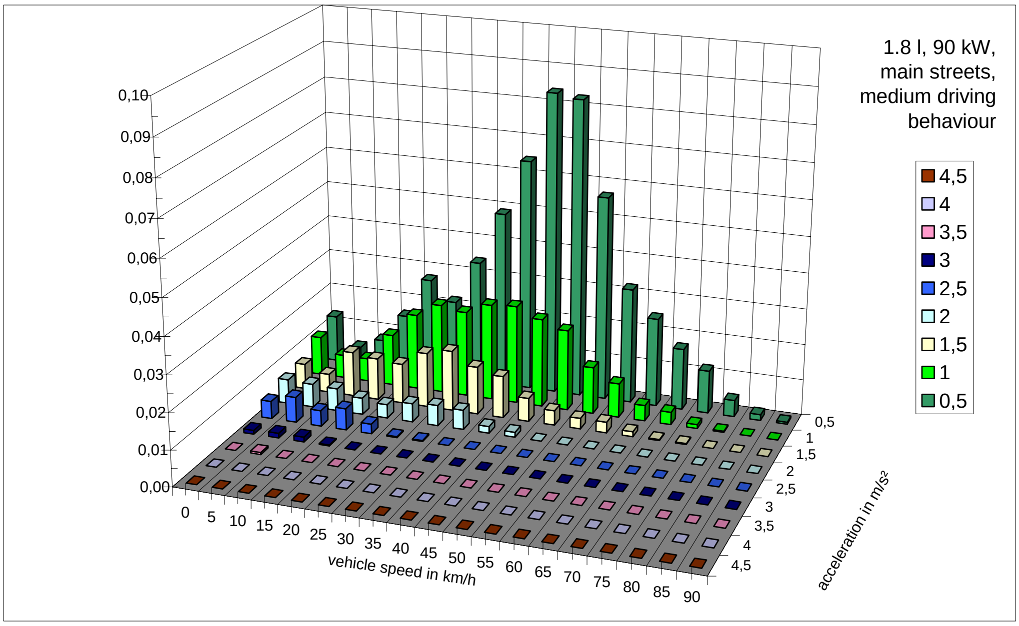


Figure 3.9 Typical driving patterns for a passenger car with a 90 kW engine on urban main streets. Data from [3.12] collected in Aachen, Germany. The vertical axle is the proportion of full time (100 %) that is spent in a certain combination of speed and acceleration.

3.10 References for chapter 3

[3.1] Jonasson, Hans; Sandberg, Ulf; van Blokland, Gijsjan; Ejsmont, Jerzy; Watts, Greg; Luminari, Marcello (2004): "Source modelling of road vehicles". Draft Technical Report HAR11TR-020614-SP09v8, Deliverable 9 of the HARMONOISE project, SP, Borås, Sweden.

[3.2] RoTraNoMo (2004): RoTraNoMo (G3RD-CT-2002-00801) is a Project supported by the European Commission‘s DG Research.

[3.3] Morgan, P A; Nelson, P M; Steven, H (2003): "Integrated Assessment of Noise Reduction Measures in the Road Transport Sector". Project report PR SE/652/03, TRL Limited, Crowthorne, United Kingdom.

[3.4] Sandberg, Ulf; Ejsmont, Jerzy A.; Ronowski, Grzegorz (2002): "EcoDriving - Effects on Vehicle Noise Emission". VTI Meddelande 920, Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden.

[3.5] Thulin, Hans; Forward, Sonja; Karlsson, Bo; Sandberg, Ulf (2002): "Demoprojekt Region Mälardalen - Resultat från undersökningar i 5 tätorter år 2000/2001" (in Swedish), VTI Meddelande 930, Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden.

[3.6] Thulin, Hans; Forward, Sonja; Karlsson, Bo; Sandberg, Ulf (2003): "Åtgärder på det kommunala vägnätet i fem tätorter - Demonstrationsprojekt i Vägverket Region Mälardalen år 2000/2001" (in Swedish), VTI Meddelande 949, Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden.

[3.7] Sandberg, Ulf; Ejsmont, Jerzy A. (2002): "Tyre/Road Noise Reference Book". Informex, SE-59040 Kisa, Sweden (www.informex.info).

[3.8] Bredenfeldt, Henrik; Nilsson, Andreas (2004): "Traffic Noise in Crossings and Roundabouts". Report E04-12 (MSc Thesis), Chalmers University of Technology, Dept of Applied Acoustics, Gothenburg, Sweden.

[3.9] Anon. (1985): "Effekter av olika fartdämpare på genomfartsgator" (in Swedish). Project report from Trafikbyrån, Trafiksäkerhetsverket, Borlänge, Sweden.

[3.10] Sandberg, Ulf (2001): "The Effect of Regulations on Road Vehicle Noise – Final report by the I-INCE Working Party on Noise Emissions of Road Vehicles". Noise/News International, June 2001.

[3.11] Notbohm, Gert; Schwarze, Sieglinde (2002): ”Evaluation of sound quality of urban traffic noise by psycho-physiological methods”. Proc of Transport Noise and Vibration, 4-6 June 2002, St Petersburg, Russia.

[3.12] Steven, Heinz (1998): "Investigations on Improving the Method of Noise Measurement for Powered Vehicles". FIGE Report No. 105 06 068, RWTÜV Fahrzeug GmbH, Ginsterweg 5, D-52146 Würselen, Germany.

[3.13] Harmonoise homepage www.harmonoise.nl.

4. Nordic experiences

In order to find the relevant Nordic literature, the library at the Danish Road Institute has preformed systematic literature searches. The Nordic partners in the SILVIA project has contributed with relevant references together with staff members from the Danish Road Directorate and from private consulting companies.

Table 4.1 Evaluated Nordic literature.

Authors	Institution	Year of publication, country	Title	Traffic management measure
Borges, Stanly, Herrstedt and Fjeldsted	Road Directorate	1987, Denmark	Effect evaluation of environmentally adapted through roads in Vinderup	Environmentally adapted through roads
Bendtsen	Road Directorate	1987, Denmark	Effect evaluation of environmentally adapted through roads. Environmental effects. Noise, air pollution, vibrations and energy consumption, Vinderup	Noise and annoyance studies of environmentally adapted through roads
Herrstedt et.al.	Road Directorate	1993; Denmark	An improved traffic environment – A catalogue of ideas	Catalogue of measures to reduce speed in urban areas
Greibe, Nielson and Herrstedt,	Road Directorate, EU DUMAS project	1999, Denmark,	Speed management in urban areas	A handbook on planning of speed management
Bendtsen and Larsen	Danish Transport Research Institute	2001, Denmark	Noise from road humps	Road humps as speed reducers
Bendtsen and Høj	Road Directorate	1990, Denmark	Rumble areas and noise	Rumble areas as speed reducers
Bendtsen and Jakobsen	Road Directorate	1990, Denmark	Driving pattern and noise in urban areas	Noise at intersections and on arterial urban roads
Bendtsen	Road Directorate	1988, Denmark	Noise from profiled road strips	Road side rumble strips improving traffic safety
Hydén, Odelid and Várhelyi	University of Lund	1995, Sweden	The effect of a general speed reduction in urban areas	Roundabouts
Storeheien and Skaalvik	SINTEF Group	1987, Norway	Traffic noise from roundabout	Roundabout
Jonasson and Ström	Swedish National Testing and Research Institute	1999, Sweden	Road traffic noise at low speeds	Literature on low speeds in urban areas and effects on emissions and noise
Thulin, Foeward, Karlsson and Sandberg	Swedish National Road and Transport Research Institute	2002, Sweden	Demonstration project Region Mälardalen	Speed reducing measures on streets in towns, effects on noise, traffic safety and acceptance by people
Pettersen	National Road Administration	Norway, 1995	Preliminary information about environmental streets and noise	Speed reductions on streets and noise consequences

4.1 Environmentally adapted through roads

In many built up areas arterial roads with a relative high traffic volume and heavy vehicles passes through urban areas where shops and other public facilities are located along the arterial road. This results in conflicts between the fast road traffic and the people of the city. The object of making an environmentally adapted through road is primarily, by the means of various physical measures, to reduce the speed of the cars, and at the same time improving the urban environment for the light road users and the people living along the main roads.

Figure 4.1 Examples of the design of the environmentally adapted through roads in Vinderup, Skærbæk and Ugerløse.

As a full scale research project environmentally adapted through roads were constructed in 3 Danish villages in the 1980s [4.1]. These were Vinderup, Skærbæk and Ugerløse with 1.000 to 4.000 inhabitants. The traffic on the through roads were around 3-4.000 vehicles per day. It was the objective to reduce the speed, not the amount of traffic. The 1.0 to 1.6 km long through roads were rebuilt through the cities by the use of measures like:

- Town gates at the entrances to the cities to mark the beginning of the road section with speed reductions.
- Biking lanes.
- Improvement of the footpaths.
- Zebra crossings for pedestrians.
- Displacement of the road lanes.
- Islands in the middle of the road.
- Space for parking marked with white stripes and islands along the road.
- Use of other pavement types or pavement with other colours at shorter road sections.

- Use of roundabouts.
- Redesign of intersections.

The design of the through roads was also improved by new lights, trees and bushes and the use of a special strategy for the use of traffic signs. Examples of the rebuild roads can be seen in Figure 4.1. Road humps were not used in these environmentally adapted through roads.

A comprehensive measurement program was developed and many factors were measured before and after the reconstruction of the roads [4.1]. Among these factors were speed, noise and the perceived annoyance of the noise [4.2]. The speed and the noise were measured at three to four locations along the roads. The measurement points (A, B, C and D in Table 4.2) for speed and the measurement points for noise (I, II and III in Table 4.3) were not exactly the same.

Table 4.2 Speed and speed reduction measured in the 3 villages at tree or four locations (A, B, C and D) along the environmentally adapted through roads [4.2].

Village	**Speed before in km/h**				**Speed after in km/h**				**Speed reduction in km/h**			
	A	B	C	D	A	B	C	D	A	B	C	D
Vinderup	51	42	42	64	42	43	38	55	9	-1	4	9
Skærbæk	68	53	52	59	58	48	48	49	10	5	4	10
Ugerløse	44	53	60	-	37	45	52		7	8	8	-

The construction of the environmentally adapted through roads in the three villages resulted in a reduction of the speed along the main roads by around 4-9 km/h (Table 4.2). The detailed speed measurements also shoved that especially the very fast cars disappeared from the roads [4.1]. At the same time the noise was generally reduced by 1-3 dB (Table 4.3).

Table 4.3 Noise as $L_{Aeq,24h}$ and noise reduction measured in the 3 villages at tree locations (I, II and III) along the environmentally adapted through roads [4.2].

Village	**Noise before in dB**			**Noise after in dB**			**Noise reduction in dB**		
	I	II	III	I	II	III	I	II	III
Vinderup	66	68	66	63	67	67	3	1	-1
Skærbæk	63.6	65.6	62.2	61.4	63.6	61.9	2	2	0
Ugerløse	65.2	66.1	65.4	61.4	64.3	63.5	4	2	2

Questionnaires were send to all households in the villages both before and after the construction of the environmentally adapted through roads. A question on annoyance by noise was included in the questionnaires. The reply rates were around 50 %. The results from the people living in the villages can be seen in Table 4.4. The replies include both people living along the main roads and people living in the districts behind the roads. The question on noise was the following: “How often are members of the family annoyed by noise from the main street when they are at home?” It can be seen that the amount of people who often end sometimes are annoyed by noise from the main road is significantly reduced after the construction of the environmentally adapted through roads. At the same time the amount of people who never or seldom are annoyed is increased.

The general conclusion on these surveys is that the environmentally adapted through roads reduce speed as well as noise and that people also feel less annoyed by noise. On the background on these Danish and some international experiences a catalogue of ideas on improved traffic environment has been published [4.3] together with a report on speed management in urban areas [4.4] that can be used as a framework for the planning and evaluation of speed management schemes.

Table 4.4 Answer to the question “How often are members of the family annoyed by noise from the main street when they are at home?” before and after the construction of environmentally adapted through roads in the 3 villages [4.2].

Village	**Often**		**Once in a while**		**Seldom or never**	
	Before in %	After in %	Before in %	After in %	Before in %	After in %
Vinderup	25	8	23	10	50	62
Skærbæk	16	6	27	11	55	83
Ugerløse	34	12	25	15	38	71

The general conclusion on these surveys is that the environmentally adapted through roads reduce speed as well as noise and that people also feels less annoyed by noise. On the background on these Danish and some international experiences a catalogue of ideas on improved traffic environment has been published [4.3] together with a report on speed management in urban areas [4.4] that can be used as a framework for the planning and evaluation of speed management schemes.

4.2 Road humps

The noise has been measured [4.5] from a series of road humps constructed to reduce speed and improve traffic safety on arterial streets with through traffic in urban areas. The background was cases where neighbours have complained about the noise generated by the vehicles passing the humps. The following hypotheses were investigated using an interdisciplinary approach:

1. On roads with humps the noise is generally reduced because of speed reductions.
2. There is a slight increase in the noise just before and after the humps, because vehicles - especially trucks - brake and accelerate as they pass the humps.

Table 4.5 Arterial urban road sections with humps [4.5] included in the survey. The "speed before" was measured before the construction of humps.

Road section	Length of section	Number of humps	Average distance between humps	Speed before	Speed by hump
Road-30	255 m	2	127 m	Unknown	33 km/h
Road-40-1	400 m	4	120 m	Unknown	32 km/h
Road-40-2	631 m	4	147 m	Unknown	33 km/h
Road-40-3	361 m	3	123 m	52 km/h	38 km/h
Road-50-1	872 m	4	249 m	52 km/h	47 km/h
Road-50-2	1563 m	6	274 m	61 km/h	50 km/h
Road-50-3	2219 m	9	252 m	59 km/h	52 km/h
Road-60	1037 m	4	281 m	66 km/h	55 km/h

Eight road sections with 2 to 9 humps have been selected for the project (see Table 4.5). The introduction of humps has reduced the speed by 5 to 14 km/h. Roads with 4 different speed classes are included (30 to 60 km/h). The results are shown separately for these 4 classes. All the humps are designed as so called "circle humps" where the cross section of the hump in the direction of the road describes a section of the surface of a circle. All the humps more or less fulfil the official Danish requirements for design of humps ensuring a smooth passage for vehicles driving with the recommended speed. The humps are representative for newer Danish humps.

It has been an important goal to ensure equal conditions on the selected road sections. The pavements of the road sections and the humps are dense asphalt concrete or surfaces with a similar surface structure. The noise is measured in free field conditions. There are no reflections from buildings or fences. The measurements have been normalised to a road surface temperature of 20 degrees Celsius. The only variable parameters defining the noise are believed to be differences in speed and driving pattern on the 8 road sections. It has not been possible to carry out a before-and-after study because the road humps were already constructed when the project was started. Instead 3 different measuring positions have been selected on each road section:

1. A position just in the middle of a road hump, to represent the noise generated by vehicles passing the humps (termed "hump").
2. A position 10 m before/after the same hump, to represent the noise generated by vehicles braking before or accelerating after the hump (termed "10 m before").
3. A position situated in the middle of a road segment between two humps, to represent the noise generated by vehicles cruising at more or less constant speed (termed "middle").

Figure 4.2 One of the so called "circle humps" included in the survey [4.5].

An expression of the noise (termed "before") covering the situation before construction of the humps has been predicted from the measurements in position 3 (middle) corrected to the speed before the humps were constructed. The Statistical Pass By Method was used. The noise (SEL) has been predicted for a mixed traffic with 80 % passenger cars, 10 % vans, 9 % trucks with two axles and 1 % trucks with more than two axles. Driving patterns have been registered using a measuring vehicle following randomly chosen vehicles. The average driving patterns for passenger cars are shown in Figure 4.3. There is a tendency towards smoother driving pattern when the design speed of the road increases.

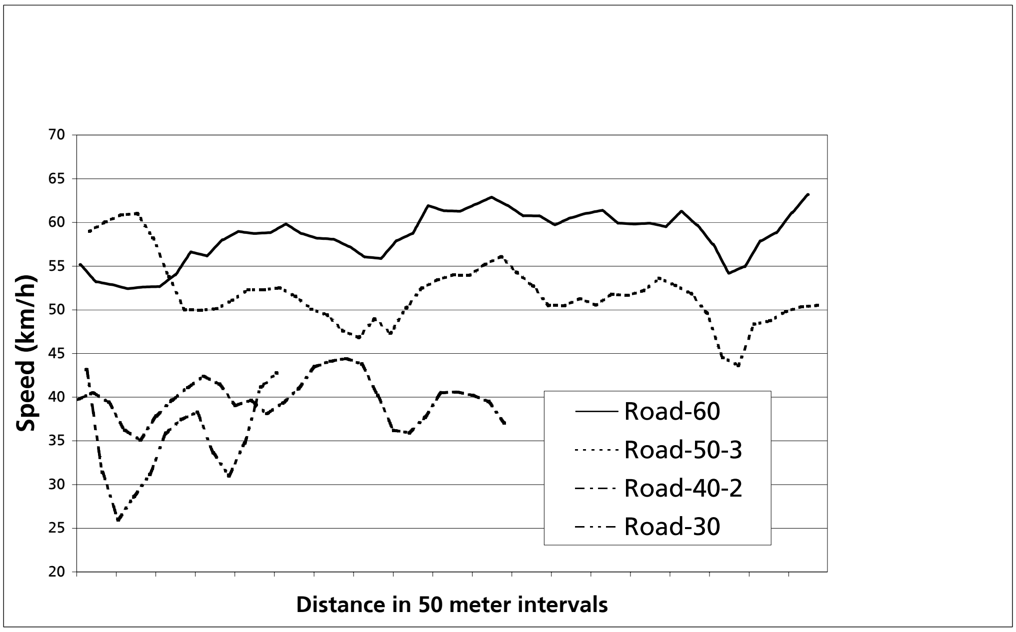


Figure 4.3 Measured average driving patterns for passenger cars on the 4 different road types [4.5].

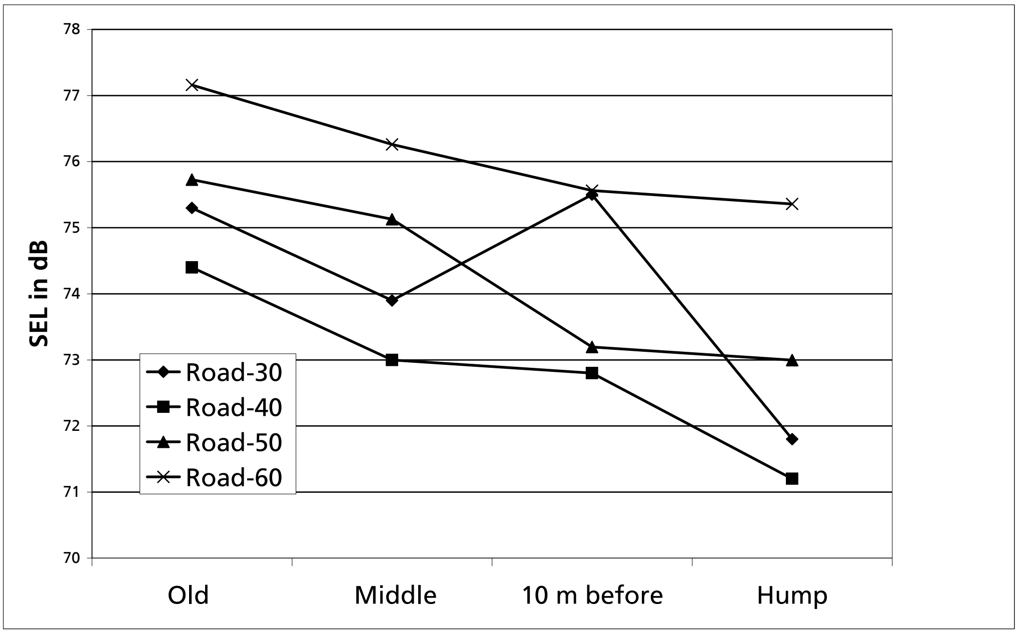


Figure 4.4 The noise measured as SEL for mixed traffic (80/10/9/1). The levels "before" the humps were constructed have been predicted [4.5].

The main results can be seen in Figure 4.4. The speed (se Table 4.5) and the noise have been reduced after the introduction of humps. In the "middle" section the reduction was around 1 dB. By the humps the highest reductions of 2 to 4 dB are seen. By the low speed roads (30 and 40 km/h) the noise tends to be 2 to 4 dB higher, 10 meters from the humps than directly by the humps. This must be caused by acceleration. The same tendencies are seen for all 4 vehicle categories. Looking at L_{AFmax} the same picture is seen.

A questionnaire was designed to study the reaction to noise by the people living next to the roads. All households situated in the first row along the roads included in the study have been handed a questionnaire. The households have been divided into two subgroups:

1. People living close to the road humps at a maximum distance of 20-30 m from a hump.
2. People living at a greater distance from the road humps.

The general reply rate was 78 %. The results can be seen in Table 4.6. The general tendency shows a higher number of annoyed persons close to the road humps than in between the humps. By the 30 km/h road the result is opposite. Traffic volume and the $L_{Aeq,24h}$ are not the same on the different road categories. This is likely to be the reason for the big variation in degree of annoyance.

The first hypothesis is confirmed, as the noise (SEL) is generally reduced by 1 to 4 dB after construction of humps. The second hypothesis is also confirmed, as the noise is 0 to 4 dB higher 10 m before the humps than by the humps. Even though the noise is reduced people living very close to the humps tend to be more annoyed than people living between humps.

Table 4.6 The main results of a questionnaire survey on annoyance near road humps. Percentage of people answering yes to the question: "If you hear road traffic noise, is it annoying when you are inside your home with the windows closed?". The answers have been summarised for all roads in each of the 4 speed categories [4.5].

Speed category	Annoyed or very annoyed		Very annoyed	
	Near hump	Far from hump	Near hump	Far from hump
30 km/h	25 %	58 %	8 %	9 %
40 km/h	20 %	11 %	5 %	0 %
50 km/h	69 %	53 %	32 %	7 %
60 km/h	43 %	13 %	14 %	0 %

4.3 Rumble areas

Figure 4.5 Example from Lyngby of a rumble area where profiled thermo plastic strips (10 cm wide 0.8 cm high) has been applied on the road surface.

Rumble areas and rumble strips have been used in some traffic management schemes. A rumble area is typically a name for a change in the road surface over a short distance. A rumble area is typically consisting of stripes cut down into the road surface, profiled thermo plastic strips on the pavement surface or an area with paving stones. When a rumble area is run over by the tyre of a car a loud tyre/road interaction noise is generated and noise from the suspension system of the vehicle is also generated. The sudden increase of noise is supposed to sharpen the attention of the driver. Rumble areas are normally used for different purposes:

1. As a pre-warning for example at the approach to a road section with low speed.
2. As a speed reducing measure.

When the tyre of a vehicle passes over the rumble area an increase in the noise level occurs and this can be heard in the surrounding environment and may result in increased annoyance in nearby residential areas. This has been the reason for complaints from people living close to rumble areas. There are cases where newly established rumble areas has been removed by the road authorities because of complaints. This was the background for a Danish research project where noise from different types of rumble areas [4.6] was measured.

The study is based on reference measurements. In every case two series of L_{Aeq} noise measurements have been carried out. One measurement at the rumble area and one measurement at a reference position with the same type of asphalt pavement as by the rumble area. The distance between the rumble area and the reference position was selected so the noise from the rumble area was not affecting the measurements at the reference position. The conditions at the two measurement positions were identical regarding background noise and reflections from buildings. The noise measured at the rumble area has been adjusted to the same speed and the same volume of traffic as by the reference position. Therefore the measurements reflect the extra noise generated at the rumble areas. The dimensions of the different rumble strips can be seen in Table 4.7. As can be seen in Figure 4.5 a rumble area typically consists of 4 to 10 strips placed after one another.

Table 4.7 Noise increases measured at different types of rumble areas [4.6].

Type of rumble area	Dimensions of rumble stripes	Location	Reference speed km/h	Noise increase in dB
Paving stones	7 m long section	Allerød	60	1.6
Paving stones	15 m long section	Tåstrup	50	2.1
Narrow thermo-plastic strips	10 cm wide 0.8 cm high	Lyngby	50	2.1
Wide thermo-plastic strips	100 cm wide 0.5 cm high	Ugerløse	50	2.7
Stripes cut down in the pavement	15 cm wide 1 cm deep	Vinderup	80	3.7

For the roads with a reference speed of 50-60 km/h the rumble areas increases the noise 2-3 dB. For the road with a reference speed of 80 km/h the increase is 4 dB.

The noise from the rumble areas is pulsating. Impulse noise is generally more annoying than more continuous noise. Therefore the impulse noise, expressed as an equivalent noise level, has to be adjusted in order to compare it with continues noise with regard to annoyance. It is a recommendation in Danish environmental administration to ad 5 dB to impulsive noise from industries. In [4.6] it is suggested to use the same correction for impulsive noise from road traffic passing rumble areas. With this correction the noise increases 7-9 dB in the surroundings of rumble areas. No studies of the perceived annoyance from rumble areas that might qualify the 5 dB correction has been conducted as a part of the research project described in [4.6].

In order to highlight the effect of rumble areas on drivers a series of indicative measurements has been conducted inside a passenger car driving over a rumble area constructed of paving stones and a normal pavement [4.6]. The increase of the maximum noise was measured at 9 to 15 dB depended on the driving speed (see Table 4:8). This indicates that rumble areas can have a significant effect on increasing noise inside cars in short time periods. The increase of the external noise along the road was for this type of rumble area measured to 2 dB.

Table 4.8 Maximum noise measured inside a Opel Kadett driving with different constant speeds on a rumble area constructed of paving stones and a normal pavement [4.6].

Speed in km/h	L_{Amax} on rumble area in dB	L_{Amax} on normal pavement in dB	Increase in noise in dB
30	76	64	12
40	81	66	15
50	80	67	13
60	80	71	9

4.4 Intersections and urban roads

In 1989 a series of noise measurements were carried out on arterial roads with a high traffic flow in Copenhagen [4.7]. The goals were to investigate the noise from road traffic driving with speeds less than 50 km/h. The noise was measured as L_{Aeq} and the results were normalised to a traffic flow of 2000 vehicles per hour. The noise was measured in the rush hours and in the middle of the day. There was no significant difference between the normalised noise level in these two different periods of the day on these roads where the traffic was near to the capacity of the roads.

On two of the roads (Bredgade and Jagtvej) the traffic was driving with no tendencies of traffic congestion (relatively smooth driving pattern). On one road (Sølvgade) there was a special bus lane and one road (Strandvejen) traffic calming had been introduced as an environmentally adapted throughroad using biking lanes, zebra crossings for the pedestrians, islands in the middle of the road, parking and displacement of the road lanes.

The normalized noise level in the middle of the day and the average speeds can be seen in Table 4.9. The speed limit for all 4 arterial roads was 50 km/h. It can be seen that on all roads the average speed is lower. The special construction of two of the roads has an influence on the speed and the driving pattern and therefore also on the noise. The highest noise level was found on Sølvgade where there is a separate bus lane which means that the busses do not delay the other vehicles so they can drive more flowingly. The noise is 1-2 dB higher than on the two roads with smooth driving. The lowest noise level is found on the road with traffic calming where the speed is also lower than on the other roads. Here the noise level is 1-2 dB lower than on the two roads with smooth driving.

Table 4.9 Normalised noise level as L_{Aeq} in dB for 2000 vehicles pr hour in the middle of the day [4.7].

Road	Type of road	Noise as L_{Aeq} in dB	Speed in km/h
Bredgade	Relatively smooth driving pattern	73.1	35.3
Jagtvej	Relatively smooth driving pattern	73.9	45.1
Sølvgade	Separate bus lane	75.3	39.4
Strandvejen	Traffic calming	72.0	34.0

Noise measurements were also performed at an intersection with traffic lights and at a nearby measurement position where the traffic was driving with an even driving pattern not influenced by the traffic lights at the intersection. These measurements indicated a 1 dB higher noise level at the intersection, which can be explained by an uneven driving pattern with accelerations.

4.5 Road side rumble stripes

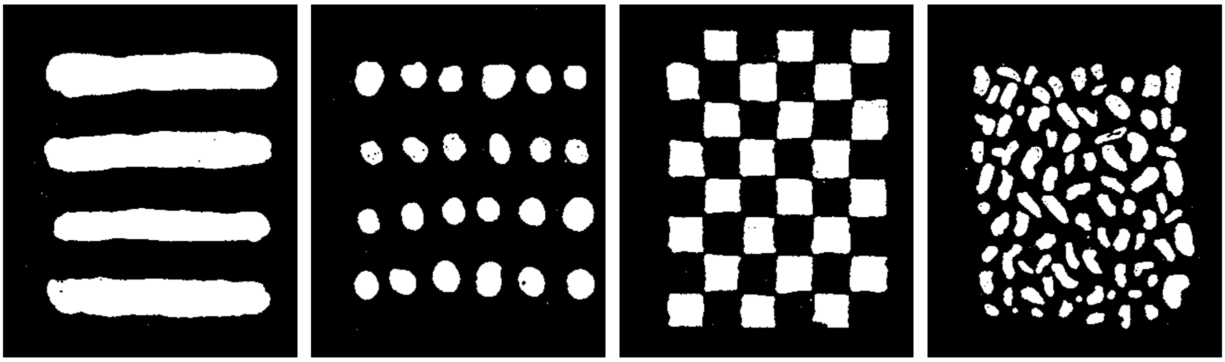
Profiled white stripes are sometimes used to mark the side of a road. In the later years, this kind of road markings are also as experiments used to mark the middle of roads. Profiled road stripes have a good effect in reflecting light at night time. At the same time extra noise is generated inside vehicles driving on the profiled stripes. This can wake up sleepy drivers before they drive to the road side and therefore prevent accidents. Generally profiled road stripes are considered to have a positive effect on traffic safety [4.8].

The noise generated from this kind of road marking has been investigated in a Danish project. On a main road with a speed limit of 80 km/h 11 different versions of profiled road stripes were laid on the pavement at the road side. A passenger car (Opel Kadett) with a constant speed of 80 km/h was driven 5 times over these different stripes and the noise at the road side as well as inside the car was measured as the $L_{Apeak,max}$ level. The measurements were reproducible even though the peak noise level was used. As a reference the noise was measured when the passenger car was driving on a pavement with hot rolled aggregate which was evaluated to be around 1 dB noisier than dense asphalt concrete. The profiled road stripes were one year old and in a good condition when the measurements were performed.

Four different types of profiled road stripes were included in the project (see Figure 4.6):

1. “Longflex” is characterised by thick stripes of thermo-plastic (thickness 3-5 mm) with distance of 5 to 8 cm.
2. “Spotflex” is characterised by lines of thermo-plastic dots (thickness 3-6 mm) with a distance of 5 to 13 cm between the lines.
3. “Chequered” is like a chessboard with thermo-plastic squares (thickness 3-6 mm) with a size of 4.5 X 4.5 cm or more.

4. “Evenly distributed” is characterised by small dots of thermo-plastic evenly distributed over the area of the profiled road stripe.



Longflex | Spotflex | Chequered | Evenly distributed

Figure 4.6 Drawings of the four different types of profiled road stripes, consisting of a profiled thermoplastic material with reflecting beads, which are placed on the top of the road pavement. Figures from [4.8].

As can be seen from Table 4.10, there is no obvious connection between the relative increase of the maximum outdoor noise level when passing over a profiled road stripe and the relative increase of the maximum noise level inside the vehicle. For Longflex no 1 the increase in the indoor noise level is only half the increase in the outdoor noise level whereas it is the opposite for Chequered no 2.

From Table 4.10 it can also be seen that the Evenly Distributed profiled stripe are the best to use regarding outdoor noise, and secondly the Chequered profiled stripes. Both the Longflex and the Spotflex types generate more noise. Based on the measurements the following general tendencies can be seen for profiled road stripes. The increase in noise level can be lowered if:

- The distance between the individual stripes is increased.
- The width of the individual stripes is decreased.
- The thickness of the individual stripes is reduced.

Guidelines for noise are often set up as the noise level over a long period like 24 hours ($L_{Aeq,24h}$). The $L_{Aeq,24h}$ level will probably increase if profiled road stripes are used on a given road. The increase depends on the number of vehicles that are actually driving on the profiled road stripes and thus for a short time increases the noise level. This might be found at a 24-hour measurement, but it will probably only result in an increase of the noise level by around 0.1 to 0.5 dB. A minimal increase of the noise level like this will however probably not reflect the increase in annoyance perceived by people living along the road because of the randomly occurring pulsating noise peaks, which might be up to 10 dB above the most commonly appearing peaks of noise.

Table 4.10 Noise reductions ($L_{Apeak,max}$) measured along the road side and inside the test car for the different profiled road stripes relative to a pavement with hot rolled aggregate [4.8].

Type of profiled road stripe	Increase of noise outside along the road side in dB	Increase of noise inside the car in dB
Longflex 1	10.4	4.5
Longflex 2	7.6	5.0
Longflex 3	3.7	4.5
Spotflex 1	5.3	2.5
Spotflex 2	7.0	5.0
Spotflex 3	4.3	2.5
Chequered 1	4.1	5.0
Chequered 2	3.3	8.5
Chequered 3	3.3	2.5
Evenly Distributed 1	0.1	0.5

As mentioned in section 4.3 it is a recommendation in Danish environmental administration to ad 5 dB to impulsive noise from industries. Such a 5 dB addition might be used when evaluating the noise from a road with profiled road stripes. Whether or not to use this 5 dB addition must depend on how frequently vehicles are driving on the profiled road stripes and possibly also on what time of the day this typically occurs. Questionnaires of noise annoyance could be used to evaluate when the 5 dB addition should be used.

4.6 Effect of roundabouts in Växjö

In 1991 21 roundabouts were constructed at intersections on arterial roads in Växjö in Sweden as part of a project to reduce traffic speed, thereby increasing traffic safety [4.9]. The roundabouts were all constructed with only one lane for traffic, and so that heavy vehicles could drive across the elevated central area. Prior to and after establishing the roundabouts, speed was measured at and between intersections, and noise was measured at three intersections, which are judged to be representative in regards to speed and urbanity. The noise was measured for at least 24 hours before and after establishing roundabouts instead of intersections.

Average speed was reduced by 11-18 km/h at intersections provided with roundabouts, and almost all speeding was eliminated. Speed was also reduced on road sections between roundabouts, if the distance between these did not exceed approximately 300 m. The shorter the distance between roundabouts, the greater the speed reduction is.

Noise levels at the three intersections are reduced by 1.6, 3.9, and 4.2 dB after establishing the roundabouts as compared to the situation before. These reductions cannot fully be explained by the speed reductions of 11-18 km/h, and it thus seems likely that there is some reduction due to smoother accelerations or other factors regarding driving pattern. Besides the noise reductions measured at the roundabouts, the noise along the sections between the roundabouts must also have been reduced due to the reduced speed.

This project points to roundabouts as a suitable means of traffic calming, which also allows for a reduction of traffic noise. The effect on traffic safety was also positive, whereas the initiative leads to an increase in air pollution of about five percent.

4.7 Norwegian study of a roundabout

Noise has been measured at an intersection (without traffic lights) before and after it in 1986 was reconstructed to a roundabout. In both situations the speed limit was 50 km/h [4.10]. The total traffic volume as well as the percentage of heavy vehicles has not been affected. Before the reconstruction there was 3 year old dense asphalt concrete with 12 and 16 mm aggregate on the roads and after the construction the pavement was dense asphalt concrete with 16 mm aggregate which was only 3 month old when the noise measurements were carried out. The different pavement types and ages in the before and the after situation may have a marginal influence on the noise in the two situations [4.10]

The noise before and after the reconstruction was measured as L_{Aeq} levels in 30 minutes periods at 7 roadside positions at different distances from the intersection /roundabout. There is no change in the traffic volume from the before to the after situation reflected in the noise measurements so the changes in noise must be caused by a reduction of speed and maybe a change in driving pattern. In the before situation the traffic on the east-west going road had to obey a full stop sign where as tdriving pattern. Speed measurements showed that the speed was reduced by 20 % for the vehicles passing through the roundabout, the variations in speed have been reduced and the driving pattern has become more even. The results can be seen in Table 4.11. It can be seen that close to the roundabout the noise has been reduced by around 2 dB. At long distances no noise reduction has been measured.

Table 4.11 Noise reductions measured before and after construction of a roundabout at measurement positions with different distances to the roundabout [4.10].

Measurement position	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Distance to roundabout in m	10	10	20	20	50	50	100
Noise reduction in dB	1.8	1.9	1.0	1.6	0.1	2.5	-0.6

4.8 Low speeds in urban areas

A literature study has been conducted in Sweden on the effects of 30 km/h schemes in urban areas on emissions and noise [4.11]. The report [4.11] has a brief presentation of different Nordic and international results. In the noise part there is a lot of focus on the Nordic road noise prediction method which is already described in details in chapter 2 of this report. Some of the other results presented date back to the 1980s and must therefore be considered rather old seen in perspective of the ongoing EU regulation on noise emissions from new vehicles. There are also results from some of the Nordic projects which are already described in details in the above sections. Based on the study the following general conclusions are drawn:

- All surveys have proven that for free floating traffic under a speed of 50 km/h, the noise will be reduced if the speed is reduced.
- The reduction is significantly greater for passenger cars than for heavy vehicles.
- The reduction for passenger cars depends on the driving pattern.
- The reduction is higher for the maximum noise level than for the equivalent noise level (L_{Aeq}).
- It is important to design speed reducing measures so that as even driving pattern as possible is achieved.
- Single speed reducing measures with big individual distances are not good.
- If the speed is reduced from 50 to 30 km/h, a reduction of the equivalent noise level (L_{Aeq}) of 3-4 dB can be achieved and for the maximum noise level up to 7 dB reduction.

4.9 Swedish demonstration project

Demonstration projects have been carried out in 5 Swedish towns.

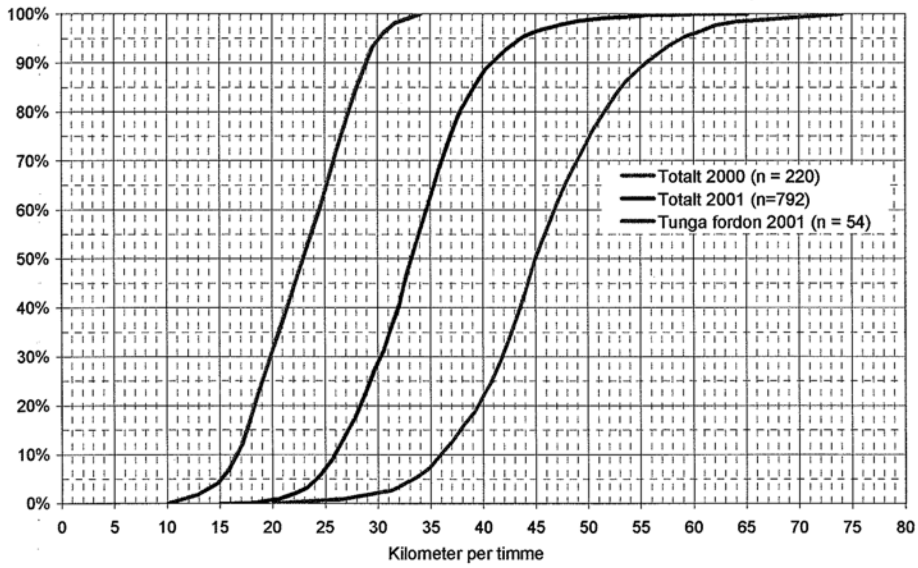


Figure 4.7 The accumulating speed distribution at Salsgatan in Flen. Left cure heavy vehicles after reconstruction, middle curve all vehicle types after reconstruction and right curve all vehicle types before reconstruction [4.13].

Physical measures were used in order to reduce speeds and improve traffic safety. These measures were:

- Raising the level of the pavement at intersections.
- Use of paving stones at some intersections.
- Roundabouts.
- Construction of pinch points and chicanes along the streets to narrow and/or displace the driving lane.
- Use of zebra crossings for pedestrians.

- Use of different surfaces like paving stones in order to strengthen the perception by the drivers that the space of the streets has been reduced.

Table 4.12 General speed reductions achieved in the Swedish project [4.13].

Town	**Enköping**	**Flen**	**Katrine-holm**	**Västerås**	**Örebro Street 1**	**Örebro Street 2**
Speed before in km/h	45	45	37	56	35	42
Speed after in km/h	30	33	17	46	30	31
Speed reduction in km/h	15	12	20	10	5	11

Comprehensive studies were carried out before and after the reconstruction of the streets. The sites were filmed on video and this was used to determine the speed distribution of vehicles. The driving pattern was studied using a pursuit vehicle to determine the speed reducing effect of the measures along the streets. Surveys were conducted in order to determine the opinions of the road users on the measures. Due to practical reasons and budget restrictions noise measurements were not carried out. Instead the Nordic prediction method (see chapter 2) and a special model developed by VTI (see chapter 3) were used to make estimates of the effects on noise. For the road sections with paving stones a standard noise increase of 3 dB was used.

The speed and the driving patterns were measured by analysing the video films of the traffic. An example of the speed distribution before and after the reconstruction of Salsgatan in Flen can be seen in Figure 4. 7. As can be seen in Table 4.12 general speed reductions of 5 to 20 km/h have been achieved. In one town (Katrineholm) the noise was predicted before and after the reconstruction of a road where raised level of the road surface was used at intersections. The general equivalent noise level (L_{Aeq}) was reduced by 2 dB because of the reductions in speed. But at the same time it was evaluated that the maximum noise at the intersections was increased by 2 dB, whish is explained by rattling and other sounds from some of the heavy vehicles passing the raised levels of the road surface.

4.10 Environmental urban streets in Norway

The Norwegian experiences with environmental streets and noise has been summarised in [4.14].

Schweigaardsgata

One example is Schweigaardsgata in Oslo which on a 350 m long section has been rebuild to an environmental street. The entrance to the street has been marked by narrowing the road, the driving lanes have been narrowed, a roundabout has been constructed and the speed limit was reduced to 40 km/h. This is combined with visual improvements of the road environment by plantation and new street lightening. Drainage asphalt has also been applied to the road as well as to the pedestrian lanes. Before and after the reconstruction the driving pattern has been measured with a pursuit vehicle. The noise of this pursuit vehicle was also measured at the roadside.

The speed has been reduced at the entrance and the end of the environmental street but no changes in the average speed was observed at the middle of the road section which is explained by a rather low speed (around 34 km/h) already before the reconstruction. The maximum speeds have anyway been reduced by 10-15 km/h. The general equivalent noise level (L_{Aeq}) was unchanged but the maximum level (L_{Amax}) was reduced by 1-3 dB which is believed to reduce the perceived annoyance by the people living along the road [4.15]. No studies of annoyance were conducted in this project! Results about the possible effect of the noise reducing drainage asphalt are not reported.

Rakkestad
In the second example a 600 m long section of the main street in Rakkestad has been reconstructed to an environmental street [4.14]. A roundabout was used as a gate in the northern end and displacement of the driving lanes was used as a gate in the southern end. At three intersections and pedestrian crossings the level of the pavement was raised and paving stones were used on the raised areas. The speed limit was reduced from 50 to 30 km/h. The noise was measured at three positions along the road before and after the reconstruction. These positions were not near the areas with paving stones. A noise reduction of 1.0 to 1.5 dB was measured. A questionnaire survey has been conducted. People were asked if they felt a change in noise and vibrations after the reconstruction. The result indicated that people felt that noise and vibrations had increased. This increased annoyance is explained by increased noise at the ramps leading to the areas with a raised level of the pavement as well as by increased noise by the areas with paving stones.

In another project (Os in Hedmark) paving stones made of local granite was used on raised levels at intersections and pedestrian crossings. The noise level was increased by 3 dB (L_{Aeq}) by the paving stones [4.14]. A questionnaire showed that people thought that noise had increased. Also in a project in Åros paving stones were used on a 70 m long road section. 1 m wide areas of paving stones across the road were laid with a distance of 12 m like a rumble area (se section 4.3). This raised the equivalent noise level by 2 dB (L_{Aeq}) and the maximum noise level by 4 to 6 dB (LAmax) [4.14].

4.11 References for chapter 4

[4.1] Borges, Per; Stanly, Peter; Herrstedt, Lene and Fjeldsted, Peter. Effektvurdering af miljøprioriteret gennemfart I Vinderup (Effect evaluation of environmentally adapted through roads in Vinderup). In Danish. Road Directorate/Road Data Laboratory Denmark. Report 52, 1987.

[4.2] Bendtsen, Hans. Effekt af miljøprioriteret gennemfart. Forureningseffekterne. Støj, luftforurening, vibrationer og energiforbrug Vinderup (Effect evaluation of environmentally adapted through roads. Environmental effects. Noise, air pollution, vibrations and energy consumption, Vinderup). In Danish with English summary. In Danish. Road Directorate/Road Data Laboratory Denmark. Report 49, 1987.

[4.3] Herrstedt, Lene et. al. Bedre trafikmiljø – Et idekatalog (An improved traffic environment – A catalogue of ideas) In Danish. Road Directorate in Denmark, Report 106, 1993.

[4.4] Greibe, Poul; Nielson, Puk and Herrstedt, Lene. Speed management in urban areas. A framework for the planning and evaluation process. EU DUMAS project. Road Directorate in Denmark, Report 168, 1999. May be downloaded from www.vd.dk.

[4.5] Bendtsen, Hans; Larsen Lars Ellebjerg. Støj ved bump på veje (Noise from road humps). In Danish with English summary. Danish Transport Research Institute. Report 2, 2001. May be downloaded from www.dtf.dk.

[4.6] Bendtsen, Hans; Høj, Jakob. Rumlefelter og støj (Rumble areas and noise) in Danish with an English summary. Road Directorate/Road Data Laboratory Denmark. Report 89, 1990.

[4.7] Bendtsen, Hans; Jakobsen, Torben. Kørselsmønster I byer og vejtrafikstøj (Driving pattern and noise in urban areas). In Danish. Road Directorate/Road Data Laboratory Denmark. Note 4, 1990.

[4.8] Bendtsen, Hans. Støj fra profilerede vejstriber (Noise from profiled road stribes). Road Directorate/Road Data Laboratory Denmark. Note 25, 1988.

[4.9] Hydén, C., Odelid, K. and Várhelyi, A. (1995): *Effekten av generell hastighetsdämpning i tätort* (The effect of a general speed reduction in urban areas, summary in English), University of Lund, Department of Traffic Planning and Engineering, Bulletin 131, Lund, 1995.

[4.10] Storeheien, S. Å.; Skaalvik, K. Trafikkstøy fra rundkjøring (Traffic noise from roundabout). ELAB SINTEFF-Gruppen. STF44 A87149.

[4.11] Jonasson, Hans; Tomas Ström. Gatutrafikbuller vid låga hastigheder (Road traffic noise at low speeds). Swedish National Testing and Research Institute. SP report 1999:11.

[4.12] Hedström, Ragnar. Miljöeffekter av 30 km/h i Tätort – med avsende på avgasutsläpp och buller (Environmental effects of 30 km/h in urban areas – with respect to emissions and noise) (In Swedish with English summary). Swedish National Road and Transport Research Institute. VTI meddelande 869, 1999.

[4.13] Thulin, Hans; Forwars, Sonja; Karlson, Bo; Sandberg, Ulf. Demoprojekt Region Mälardalen (Demonstration project Region Mälardalen) (In Swedish with English summary). Swedish National Road and Transport Research Institute. VTI meddelande 930, 2002.

[4.14] Pettersen, Odd K. Ø. Foreløbig information om miljøgate og støy (Preliminary information about environmental streets and noise). National Road Administration, Norway. Marts 1995.

[4.15] Berge, Truls. Schweigaardsgata – analyse av kjøreadferd før og etter ombygging til miljøgate (Schweigaardsgata – analyses of driving pattern before and after reconstruction to environmental street). SINTEF, DELAB, Norway report STF40 A92072.

5. British experiences

Based on largely TRL studies over many years this chapter will examine the influences of traffic control measures on noise levels. These studies can be divided into:

1. Vehicle based studies where conditions were carefully controlled on a test track and pass-by noise of individual vehicles were measured at a number of test speeds.
2. Traffic and vehicle based studies at the road side where traffic calming measures have been introduced and measurement of noise and often the speed of selected vehicles have been measured before and after installation.

The enclosed studies can be seen in Table 5.1

Table 5.1 Evaluated literature from United Kingdom.

Authors	Institution	Year of publication, country	Title	Traffic management measure
Abbott, Phillips and Layfield	Transport Research Laboratory	1995, UK	Vehicle and traffic noise surveys alongside speed control cushions in York	Speed cushions
Abbott, Watts and Harris	TRL Transport Research Laboratory	2000, UK	Traffic calming in Gloucester – influence on noise and ground-borne vibration	Traffic calming
Department of Transport	Department of Transport	1996, UK	Road humps and ground-borne vibrations	Road humps
Harris, Stait, Abbott and Watts	Transport Research Laboratory	1999, UK	Traffic calming: Vehicle generated ground-borne vibration alongside sinusoidal, round-top and flat-top humps.	Traffic calming and humps
Watts, Harris and Layfield	Transport Research Laboratory	1997, UK	Traffic calming: Vehicle generated ground-borne vibration alongside speed control cushions and road humps	Traffic calming and humps
Watts, Stait, Godfrey , Chinn and Layfield	Transport Research Laboratory	2002, UK	Development of a novel traffic calming surface 'Rippleprint'	Speed reduction by rumble surface
Watts and King	Transport Research Laboratory	2004, UK	Prediction of ground-borne vibration generated by heavy vehicles crossing a rumble-wave device	Speed reduction by rumble surface
Wheeler, Abbott, Godfrey, Lawrence and Phillips	Transport Research Laboratory	1996, UK	Traffic calming on major roads: the A49 trunk road at Craven Arms, Shropshire	Traffic calming
Wheeler, Abbott, Godfrey, Phillips and Stait	Transport Research Laboratory	1997, UK	Traffic calming on major roads: the A47 trunk road at Thorney, Cambridgeshire	Traffic calming

Equipment set up
Typically a microphone is placed a few metres from the traffic calming device to record peak values, and in some cases vibration is measured using a geophone attached to the track surface or nearest house façade. Figure 5.1 shows a typical set up for a roadside study. Vehicle speeds are measured using a radar speed meter so the crossing speed over the traffic calming device can be measured.

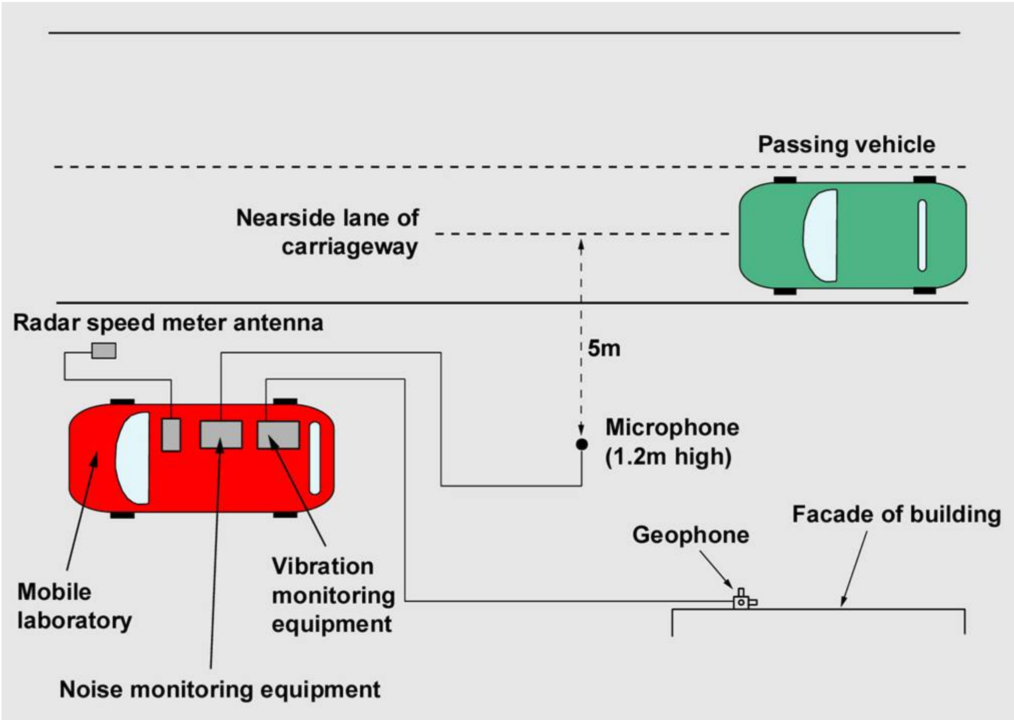


Figure 5.1 Site layout for noise and vibration measurements [5.2].

Traffic calming devices examined
The traffic calming measures examined have included road humps, speed cushions and junction tables. Figure 5.2 shows typical examples of these devices.

Road humps are typically 3-4m long and rise to a maximum of 100mm. Speed cushions are of similar proportions except there are gaps to allow heavy vehicles to pass through without vertically deflecting the wheels. Light vehicles of smaller width cannot straddle these cushions and at least one set of wheels are deflected. Junction tables are flat raised areas which cover the area of the junction. There are ramps of the order of 100m high on the junction approaches.

A further example of a traffic calming device that has been trialled is a rumblewave device. This consists of a sinusoidal surface which is designed to alert drivers without forcing them to slow down. To achieve the desired effect the peak to peak amplitude is only 6-7mm with a wavelength of 0.35m. This produces considerable noise and vibration in passing vehicles but the exterior noise is little affected. Figure 5.3 shows views of such a rumblewave device.

(a) Road hump

(b) Speed cushion

(c) Junction table

Figure 5.2 Examples of traffic calming measures examined [5.2].

(a) 20m long pad on a suburban road subject to a speed limit of 48 km/h (30mile/h)

(b) Test track trials using a motorcycle

Figure 5.3 Rumble wave device at a road site and on the test track at TRL [5.6].

5.1 Test track studies

5.1.1 Humps and cushions

Noise

A variety of large commercial vehicles were used in the trials, selected from types found to be susceptible to body noise. The vehicles traversed two types of road hump (round and flat top), and a variety of speed cushions. For comparison purposes level road surfaces, and a 600 mm long ramp 25mm high and a 1.2m wide trench 40mm deep representing a poorly maintained surface, were used in taking measurements of maximum vehicle noise. Both types of hump were 75mm high: the flat top ones had a

1:12 on/off ramp gradient and a 6m plateau length. The length of the round top hump was 3700 mm. The speed cushions ranged from 60mm to 80mm in height, 1950 to 3500 mm long and 1500 to 1900mm in width. The cushion on/off ramp gradients were generally 1:8 and side ramp gradients were generally 1:4 [5.1].

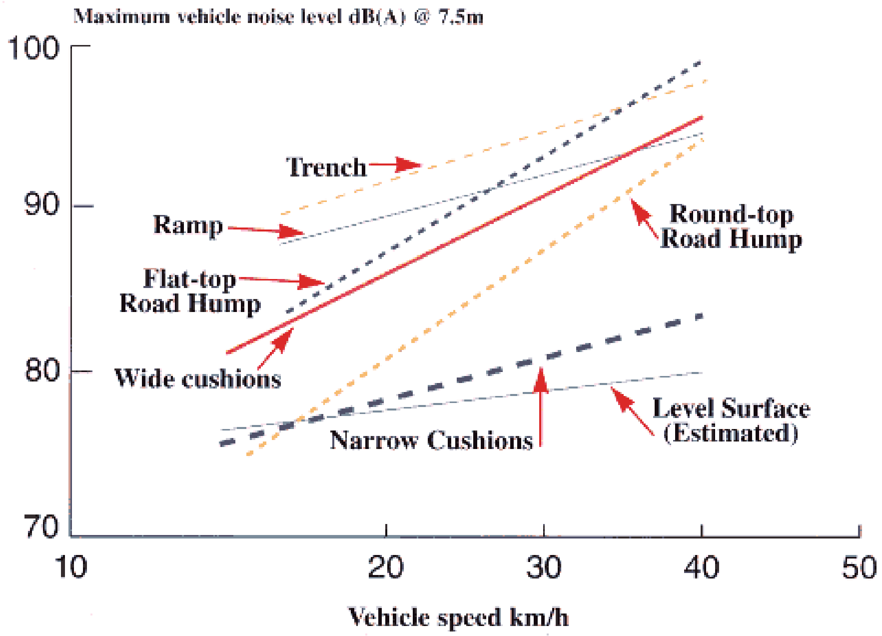


Figure 5.4 Comparing average noise levels for commercial vehicles alongside different profiles [5.3].

Figure 5.4 shows how the average maximum noise level for large commercial vehicles varies with speed for different road profiles. The commercial vehicles tested included four 2-axle rigid trucks, a 3-axle rigid tipper and an articulated vehicle with a 2-axle trailer with empty container. Relating the noise to the likely speed of a large commercial vehicle passing over the different road profiles showed that for wide cushions (assumed speed 24km/h) and flat top road humps (assumed speed 18km/h) there was a substantial increase over a level surface of 7.9dB and 6.3dB, respectively.

For the narrow cushions (assumed speed 34km/h) there was an increase of about 2 dB. However, for round top road humps (assumed speed of 18km/h) there was a reduction in vehicle noise of about 2 dB. This led to a better acoustic performance than for other speed control measures, particularly as the proportion of large commercial vehicles increased. If, however, the speed of large commercial vehicles increases above the assumed speed, then as can be seen from Figure 5.4, the effect on maximum vehicle noise levels and the subsequent change in acoustic performance with round top road humps would be significant. This may result in an increase rather than a decrease in vehicle noise. Such situations might occur where large commercial vehicle are present outside normal working hours, when traffic flow is light and drivers feel they can drive faster than normal.

Figure 5.4 also illustrates that the highest maximum noise levels from large commercial vehicles were generated when travelling over the profiles simulating poorly maintained surfaces, e.g. the "trench" and the "ramp".

Single- and double-decker buses were also tested. Measurements showed that the effect of installing speed cushions would be to increase the individual vehicle noise levels by less than 1 dB. For round and flat top humps, because speeds would be lower than for speed cushions, there would be a reduction in vehicle noise of about 3dB.

Figure 5.5 shows an example of the peak noise that can be produced as an empty 38 tonne articulated lorry passed over a flat topped road hump. Such rapid increases in noise are likely to cause particular annoyance to residents (see section 5.3 where social survey results are summarised).

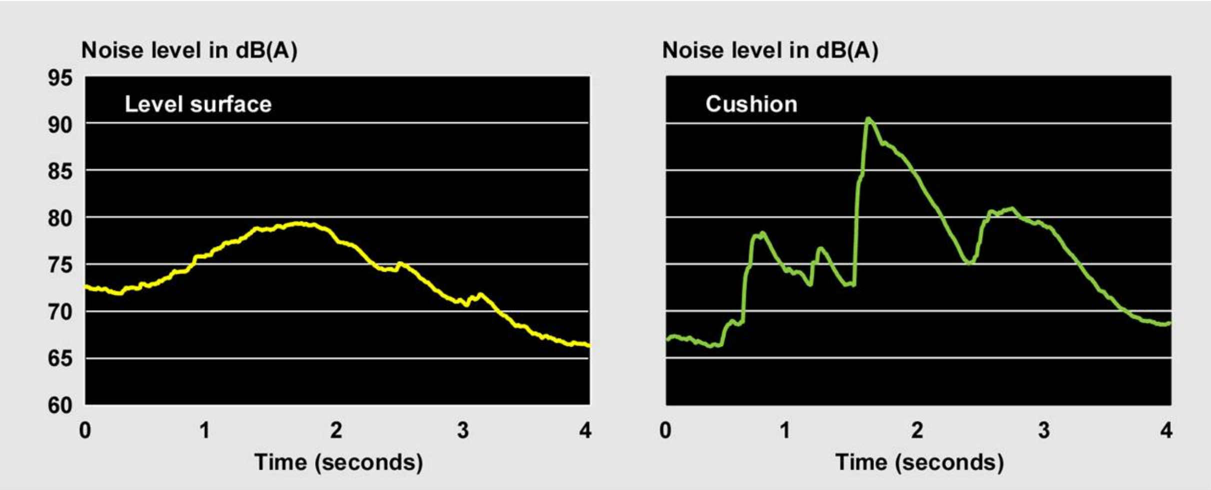


Figure 5.5 Comparison of time histories of A-weighted levels as an empty truck passes over a level surface and a 75mm high flat top hump [5.2].

The effects on overall traffic noise of introducing these traffic calming measures onto an urban road were estimated using the results from the track experiment and a simple L_{Aeq} model [5.1]. Examples of the flat top hump and speed cushion are shown in Figure 5.2. This analysis clearly indicated that changes in traffic noise levels are related to the proportion of large commercial vehicles in the flow and the type of road hump, e.g. round top/flat top, or speed cushion. Figure 5.6 shows the estimated change in traffic noise levels according to the type of installation.

A range of traffic scenarios are included with increasing proportion of large commercial vehicles in the traffic stream. The assumed crossing speeds for each vehicle category are also shown together with the corresponding speeds prior to installation e.g. level road. The estimated change in traffic noise levels shown in Figure 5.6 also assumes that the total traffic flow before and after installation remains unchanged. It can be seen that the narrower cushions (1500mm - 1600mm) have a better acoustic performance than wider cushions (1880mm - 1900mm) as the proportion of large commercial vehicles in the traffic stream increases. The performance of round top humps is notable in that traffic noise levels start to increase only after the proportion of large commercial vehicles exceeds about 20%.

More recent studies have examined the effects of round and flat topped humps with sinusoidal sides [5.4]. It was concluded that for commercial vehicles the maximum noise levels were slightly lower for the sinusoidal designs than for the standard equivalent. It was found that flat topped humps produced the highest levels as found in the previous study.

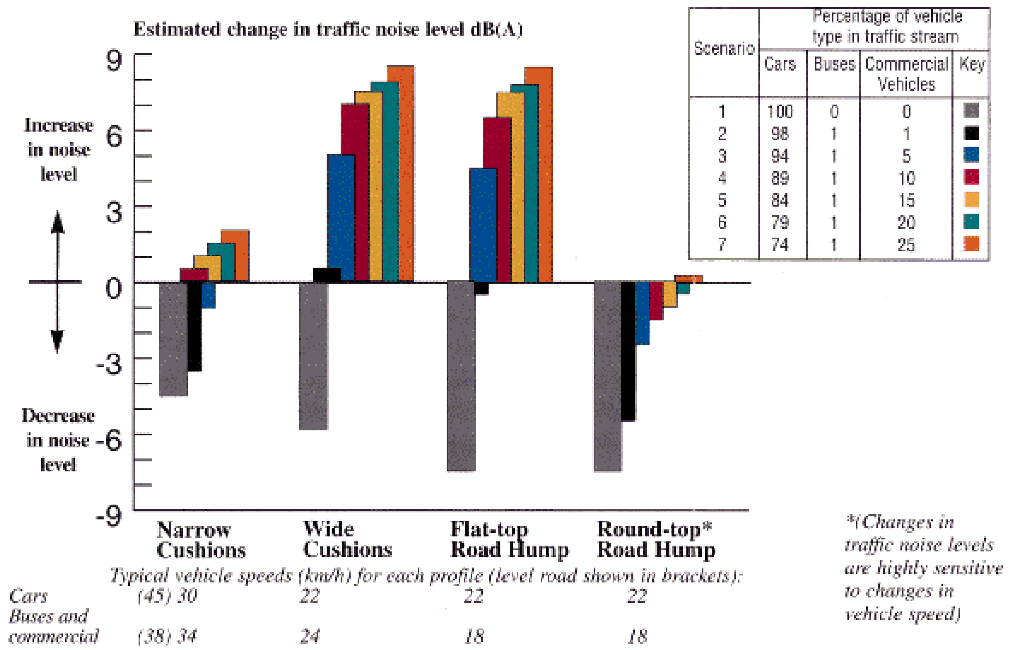


Figure 5.6 Predicted changes in traffic noise level L_{Aeq} after installing different types of speed control measures for a range of traffic scenarios [5.3].

Vibration

In a separate track experiment [5.5] vibration measurements were taken at the track-side when a range of vehicles were driven over 4 speed cushions and 2 road humps of various dimensions. The descriptions of the devices tested are as follows:

- Cushions: Length ranged from 2 to 3.5m, width from 1.5m to 1.9m and height from 64 to 74mm.
- Humps: Lengths from 0.9 to 7.8m and heights from 64 to 74 mm. Both flat topped and rounded profiles were tested.

Eleven vehicle types were used, selected from three categories: light vehicle; buses and large commercial vehicles. The vehicles ranged from a passenger car, through single and double-decker buses and a midi bus, to rigid and articulated goods vehicles. The two rigid vehicles had gross vehicle weights (GVW) of 7.5t and 17t, and the articulated vehicles had GVW of 32.5t and 38t. The 38t vehicle was fitted with steel leaf suspension, and the 32.5t vehicle with air suspension. Generally the commercial vehicles were tested in both loaded and unloaded conditions.

As with previous studies, it was found that there was a tendency for vibrations to increase with increases in speed. For a given crossing speed the 74mm high hump of length 0.9m (“thump”) generated the highest levels of vibration recorded during the study. The long flat top road hump also had high vibration levels relative to the other road hump types, though much lower than the "thump". The narrowest cushions gave results similar to each other, causing the least generation of vibration.

The side ramp gradients of the wider speed cushions also appeared to influence the level of vibration generated. The steeper the ramp, the higher the vehicles will ride over the cushion, and the greater the vibration.

Based on typical crossing speeds, for the various road hump types the longer wider cushions with the steepest side ramps (1:3) gave the highest maximum and mean vibration levels for commercial vehicles, followed by the long flap top hump. The round top hump gave the lowest maximum and mean vibration levels for commercial vehicles. Vehicles with GVW over 7.5t were found to generate the highest levels of ground-borne vibration.

For buses, the flat top road hump gave the highest maximum and mean vibration levels. The round top hump was next highest. The short (2m) length, 1.9m wide speed cushion with 1:4 side ramp gradients gave the lowest maximum and mean vibration levels.

British Standard 7385: Part 2 provides guide threshold values of vibration exposure which may give rise to minor cosmetic damage to buildings. The threshold relates to very minor damage such as the formation of hairline cracks on plaster finishes or in mortar joints and the speed of existing cracks. These values were used to calculate minimum distances which it would be desirable for road humps to be sited from dwellings, according to soil types. Predictions have also been made of minimum distances within which sustained vibration exposure may cause superficial hairline cracks that might often go unnoticed. At lower levels of vibration exposure the minimum distances required to avoid ground-borne vibration that would be perceptible or might give rise to complaint. These latter minimum distances were predicted based on a review of literature available. It was found that even very minor hairline cracking should not occur unless the road humps are placed less than 4m from a dwelling for even the softest soil. It is highly unlikely that any road hump or cushion will result in structural damage occurring to neighbouring buildings.

Predictions were also made for the range of distances between a hump or cushion which would lead to perceptible vibrations. For this purpose a peak particle velocity of 0.3 mm/s was used as the threshold value. It can be seen that on soft ground such as alluvium, peat and London Clay a separation distance of over 10m is required to avoid disturbance. The wide cushion produced the highest levels of vibration while the round hump produced the lowest. Such predictions have been used for guidance in the positioning of humps and cushions in urban areas [5.3].

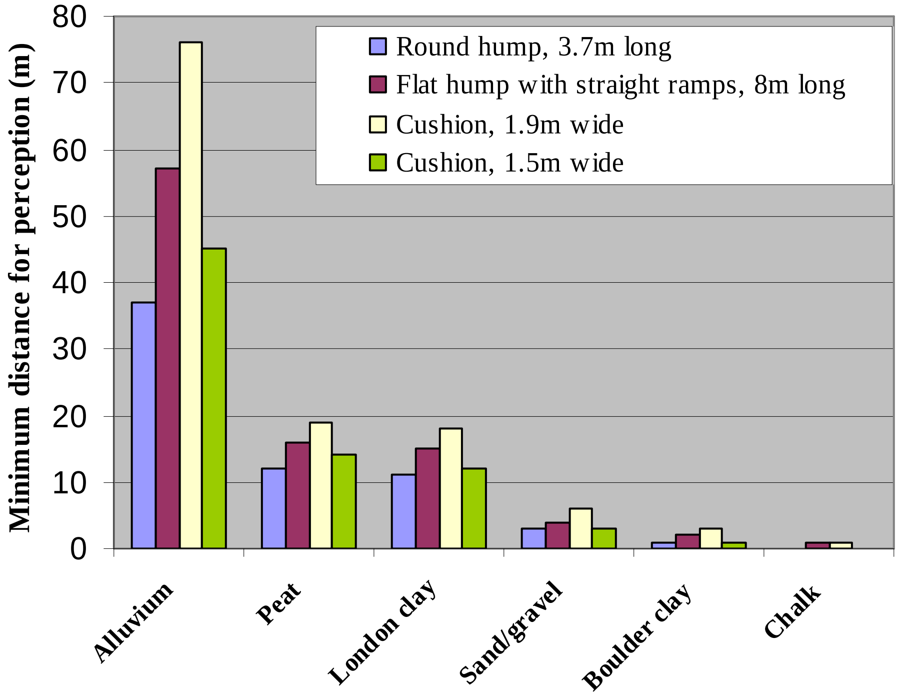


Figure 5.7 Minimum distances on various ground to avoid perceptible vibration [5.5].

5.2 Rumblewave devices

Noise

A more recent study has examined the noise produced by the rumblewave device which can be seen in Figure 5.3. The results are compared with more typical driver alerting devices such as rumble strips and imprinted surfaces e.g. with a herringbone pattern [5.6]. Figure 5.8 shows the maximum A-weighted level at 30m for these various options using a Ford Mondeo test vehicle. Similar results were obtained with a smaller vehicle (Vauxhall Corsa).

It can be seen that for the rumblewave surfaces (3A and 3D) having a peak to peak amplitude of 6 and 4 mm respectively there is very little change in exterior noise level when compared with the level test track surface. However for the imprinted pattern (3E) and the rumble strips (3F) there is clearly an increase of the order of 2- 3dB. Inside the vehicle there was found to be a significant increase in noise of over 5dB at 56 to 64 km/h (35 to 40 mile/h) and vibration levels were also significantly raised.

It was concluded form a range of tests carried out on light and heavy vehicles that the rumblewave driver alerting devices had potential to alert car and van drivers without causing significant increases in exterior noise. The device is commercially available in the UK and is known as “Rippleprint”.

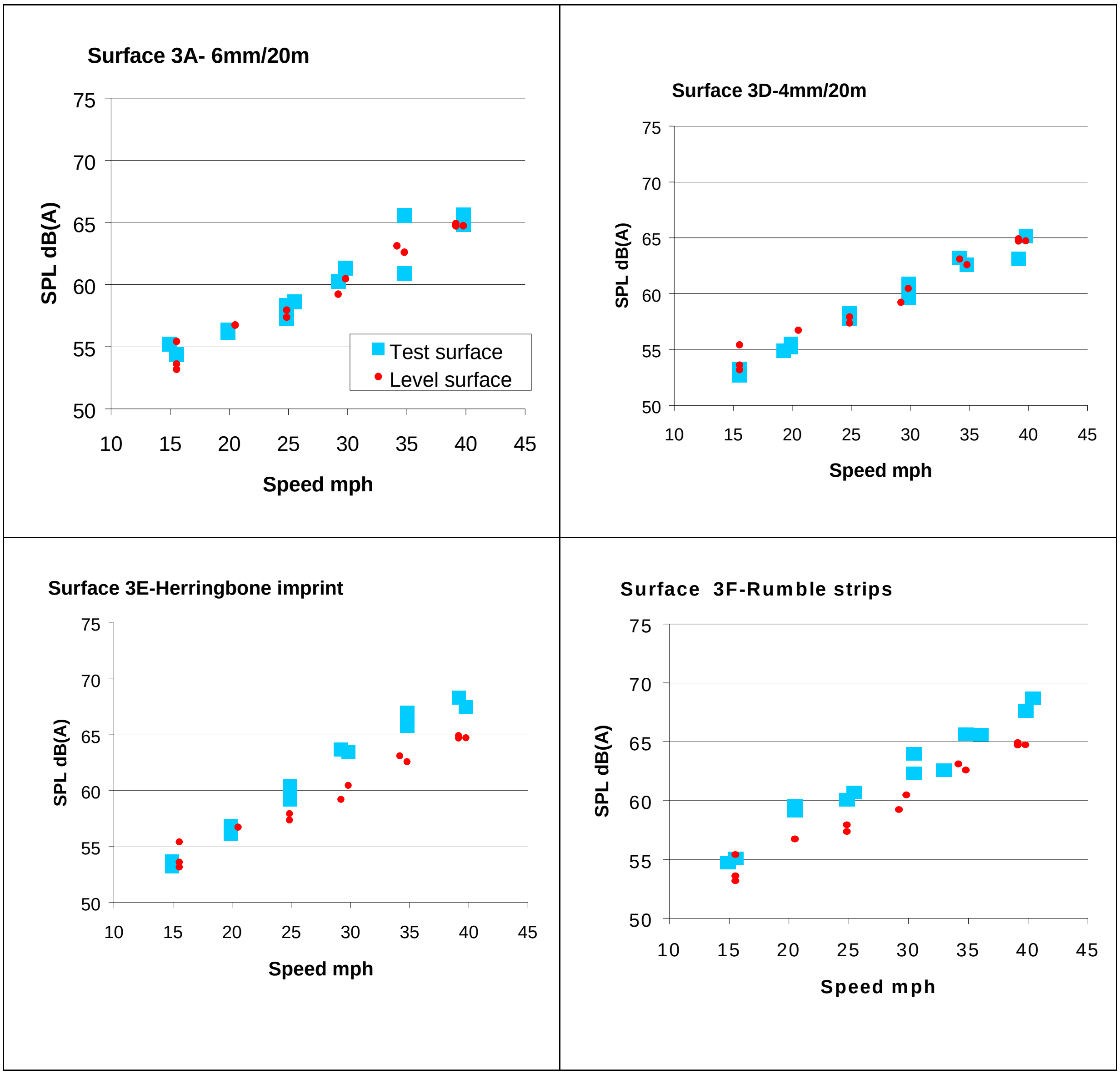


Figure 5.8 Maximum A-weighted sound pressure levels at 30m produced by a Ford Mondeo saloon car crossing rumblewave and rumble strip devices [5.11].

Vibration

Rumblewave devices have been installed at nearly 100 sites in the UK and it has been found that at a small number of these ground-borne vibrations have been noticed. To develop advice on appropriate design to avoid these problems a series of measurements were conducted. This involved measurements on the TRL test track and at a number of homes adjacent to the device [5.7].

The maximum likely vibration amplitude close to a typical rumblewave pad was established by driving two heavy vehicles over the devices at speeds from 25 to 55 km/h on the TRL test track. Results from vibration measurements at four sites were used to determine the amplification from the amplitude in the ground near the foundations of a building to the corresponding amplitude on upper floors. These factors were then incorporated into the prediction equation for different ground conditions. It was recommended that rumblewave devices should not be placed closer than 25m from the nearest house façade. This advice may need to be revised on the basis of further experience with the device under a greater range of conditions than those studied. On soft ground such as peat and alluvial and ground of uncertain nature (in filled ground) greater separation distances will be required.

5.3 Roadside studies

5.3.1 Studies in York and Slough

Measurements were made, in 1993, at a site in Slough Berkshire, where 75mm high round top asphalt humps had been installed along a residential road. A second group of noise measurements were made in York, also in 1993, on residential roads which formed part of a wider trial of the performance of speed cushions. Measurements were also made in 1993 and 1994 at another speed cushion site in York, Gale Lane, which was not part of the wider speed cushion trial [5.1]. The speed cushion designs and layouts on the roads in York were varied: 60 to 80mm in height; 1650 to 1900mm in width, and on/off ramp gradients 1:3.5 to 1:8. Materials used were blocks, red asphalt, and moulded reconstituted rubber.

In Slough, "before" and "after" measurements were made of the maximum vehicle noise levels and the overall traffic noise levels, at and between the road humps. Similar measurements were made at and between the speed cushions in York at Gale Lane. At the other cushion sites in York, only "after" measurements of maximum vehicle noise levels were made.

The studies showed that, where the vehicle flow predominantly consists of light vehicles, with an insignificant proportion of large commercial vehicles, day-time traffic noise levels can be reduced by the introduction of traffic calming measures such as road humps. Day-time traffic noise levels were reduced by about 3 dB alongside the road humps in Slough and by about 4 dB alongside the speed cushions at Gale Lane at York.

The results for night-time traffic noise levels were less clear cut. Night-time traffic noise levels alongside the road humps at the site in Slough were about 2 dB higher than in the same period during the before survey, but were about 2 dB lower alongside the speed cushions at Gale Lane. Night-time changes in traffic noise levels are more susceptible to the influence of noise from non-traffic sources or noise from distant heavier trafficked roads. A change in the wind direction in the before and after periods, could explain the increase in noise levels, if distant sources are influential.

Although changes in overall vehicle noise levels are important when considering noise annoyance to residents, an additional factor which may also be important is the variation in noise level. The studies in York showed that, on roads with speed cushions, noise variation was highly correlated to difference between the mean speed over the cushions and the mean speed midway between the cushions. The results indicated that the closer the spacing between the cushions, the lower were both the speed difference and the noise variation, with a 50m spacing producing a very low variation in speed and noise.

5.3.2 Gloucester study

TRL have also carried out noise and ground-borne vibration surveys alongside traffic calming schemes in the City of Gloucester in the UK as part of the ‘Safer City’ initiative [5.2] financed by the Charging and Local Transport Division (CLT) of the Department of Environment Transport and the Regions (DETR) to investigate the environmental impact of urban traffic management and safety schemes. Examples of the measures introduced are shown in Figure 5.2.

In years 1997/8 measurements of vehicle and traffic noise together with ground-borne vibration were taken at selected sites in the Longlevens area before and after the installation of the traffic calming scheme. Previous work has shown that the level of noise from roads is directly proportional to the volume and speed of the traffic and the proportion of heavy vehicles. It was anticipated that reductions in traffic flow and mean vehicle speeds resulting from the traffic calming measures would cause decreases in overall traffic noise levels. However, earlier studies have shown that the presence of vertical deflections can cause changes in the level or character of the noise from some vehicles. This is most likely to occur as a result of changes in driver behaviour, or because of the excitation of sources of heavy vehicle body rattle noise.

Measurements of vehicle noise were taken at various roadside positions before and after the installation of the traffic calming scheme. The purpose of this was to assess the change in maximum noise levels generated by vehicles passing through different points of the scheme. The traffic calming features studied were:

- Speed cushions: nominal 75mm high, 3.5m long, 1.6m wide, with on/off ramp gradients of 1:10 and side ramp gradients of 1:4.
- Junction tables: nominal 75mm high with ramp gradients of 1:13.5, length varying from 21m to 39m. The crossing points at the kerbs were flush with the raised plateau with tactile surfaces provided to assist visually impaired pedestrians.
- Flat-top road hump: nominal 75mm high with ramp gradients of 1:13.5 with the length varying from 4m to 12m. Tactile surfaces on the pedestrian approaches were provided at locations where the humps were likely to be used as crossing places.

In addition measurements were also taken at a level site between cushions for comparison.

Noise measurements

The Statistical Pass-by (SPB) method was used to measure vehicle noise before and after the installation of traffic calming measures. At each site a microphone was located 1.2m above the road surface and 5m from the centre of the nearside lane. The microphone was connected to a noise analyser configured to record the maximum A-weighted sound level during individual vehicle pass-bys. Vehicles were selected for measurement if they were judged to be sufficiently separated in the traffic stream so that other vehicles did not influence their noise characteristics. Where possible during the after survey, tape recordings of noise from selected heavy vehicles were taken directly alongside the feature, and alongside a level section of road a short distance in front of the feature. It was intended that the analysis of the recordings would show any change in the level or character of the noise from individual heavy vehicles as they passed over the features compared to that alongside the level surface.

It was concluded that for light vehicles the maximum A-weighted level adjacent to these traffic calming measures was reduced by between 5 and 7 dB following the introduction of these devices. It was noted that the noise reduction between the cushions was lower at 2.7 dB. However, for heavy vehicles there was no significant change in maximum levels, reflecting the problem with body rattle noise as some vehicles cross these devices. It was found that for an unloaded articulated tipper truck the noise level was over 11 dB higher than at the adjacent level surface.

Overall exposure to traffic noise was monitored outside residential properties before and after the installation of the traffic calming measures. Daytime traffic noise exposure ($L_{A10,18h}$) was reduced at all of the monitoring sites following the installation of the traffic calming measures and ranged from 2.8 to 5.8 dB.

In addition the number of individual noise events exceeding a selected noise level threshold in each hour together with the maximum noise level in each hour was also recorded. It was intended that these results would give some indication of the effect of the traffic calming measures on the generation of noisy events of short duration. A video camera was also set up whilst noise measurements were made of vehicles passing over a speed cushion. At the site alongside a speed cushion the number of noisy events exceeding 80 dB in a 24 hour period reduced from 32 to 21 following the installation of the cushion. The cushion was successful in reducing the number of buses accelerating through the site but some of the noisiest events in the after period were caused by body rattle noise which is impulsive in nature and has therefore the potential to cause greater nuisance.

Vibration measurements

Measurements of ground-borne vibration were also taken at properties close to selected traffic calming features to determine the levels generated by passing vehicles. Surveys were carried out before and after the installation of a junction table and during the after survey alongside a cushion and the hump. Vibration was detected using geophone transducers which generate signals proportional to particle velocity. The geophones were positioned near to foundation level of the nearest house at the facade nearest to the road. The distance between the measurement position and the road was approximately 9 m at the junction table and approximately 14 m at sites the hump and cushion sites.

It was concluded that the average level of ground-borne vibration at the junction table did not increase significantly. However, the maximum level recorded increased in the after period. For the hump and cushion sites no before data were available but it was found that several of the events recorded adjacent to the cushion may well have been perceptible in the nearest house and alongside the hump at least one event could have been perceptible.

5.3.3 Rural trunk road, Craven Arms

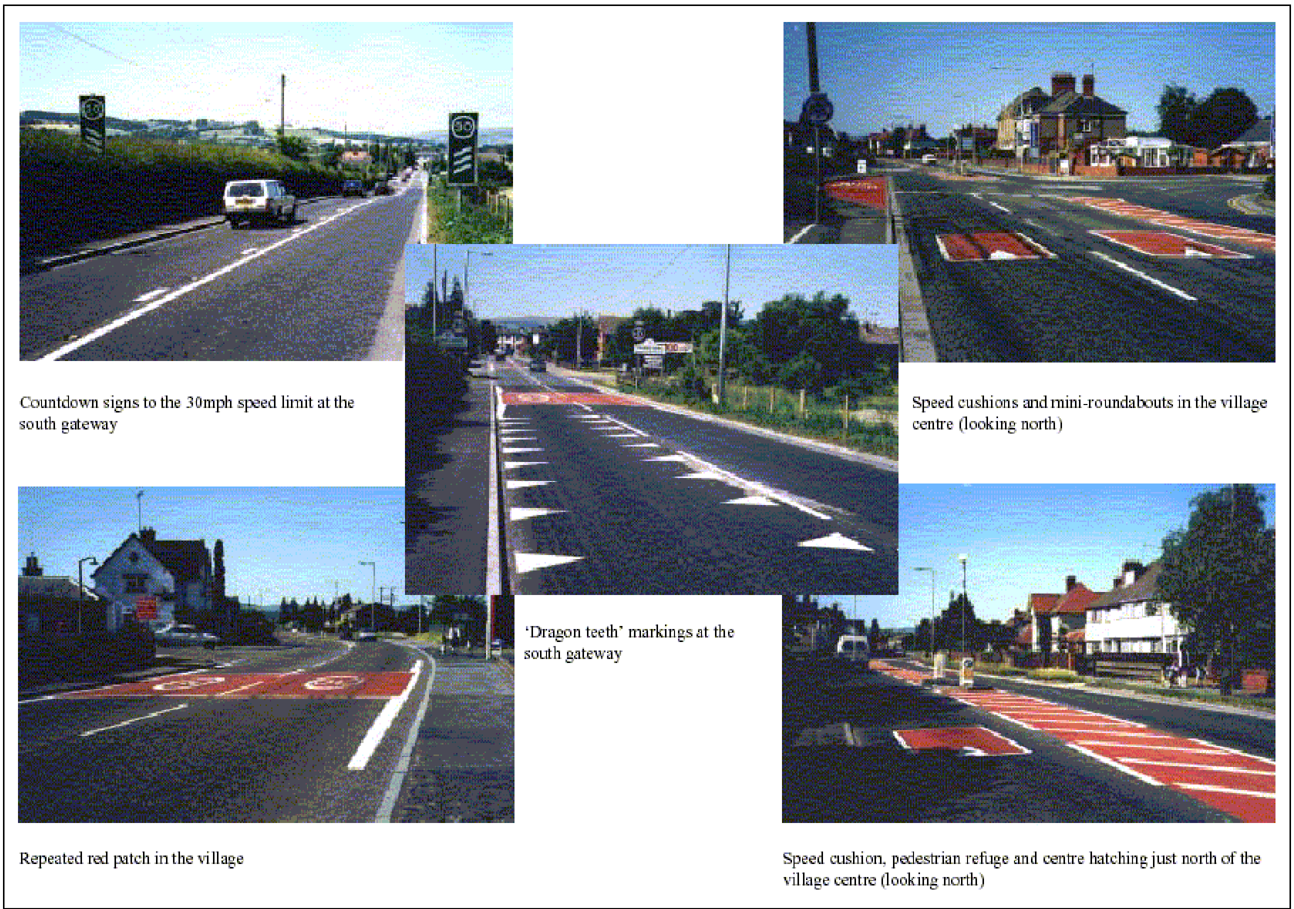
Measurements of changes in traffic and vehicle noise have also been made before and after the installation of traffic calming schemes on three rural trunk roads. These were the A49 at Craven Arms in Shropshire, the A47 at Thorney in Cambridgeshire and the A1079 at Hayton in east Yorkshire. These roads carry average two-way flows of 9.000 to 17.000 with 15 to 20% heavy vehicles.

Figure 5.9 shows the traffic calming features installed at Craven Arms. On each main road approach “countdown” markers signs and “dragon teeth” markings were installed in advance of the gateway feature [5.8]. The gateways comprised 48 km/h (30 mile/h) speed limit signing mounted above large village nameplates each side of the carriageway, together with an area of bright red surfacing with white edge markings and a painted “30” roundel. The speed limit before the scheme was introduced was 40 mile/h. In the village, the red patches and associated markings at the gateways were repeated at intervals in the outskirts of the village, and mini roundabouts were installed at four junctions around the centre of the village. In the centre a number of speed cushions (either single or in pairs all of width 1500 mm), also coloured red, were installed between the mini-roundabouts. Centre hatching on a red background and pedestrian refuges completed the scheme, which had a high visual impact.

It was found that mean and 85 percentile speeds fell by 13 to 14 km/h at the gateways, by 5 to 10 km/h in the outer parts of the village and by more than 16 km/h in the village centre, where the mini-roundabouts and speed cushions were installed. It was found that traffic flows had not changed significantly.

Vehicle noise levels were measure adjacent to and between the speed cushions, at one of the gateways, and at a site within the village away from any physical calming measures. The reduction in speed at and between the cushions resulted in reductions in maximum noise levels for both light and heavy vehicles of between 5 and 10 dB. Slightly smaller reductions were recorded at the gateways. The reduction in noise level was 9.5 dB for light vehicles at the cushion sites (close to the mini-roundabout), corresponding to a speed reduction of 24 km/h. Generally, the noise emission levels for both light and heavy vehicles travelling over the cushions were similar to those travelling between the cushions when normalised for speed. However, where there was a mini-roundabout immediately prior to the site, noise emission levels from heavy vehicles were about 3 dB higher than those recorded where cushions were more isolated.

Daytime traffic noise levels $L_{A10,18h}$, fell by 2dB at the site away from any calming measure and by 4 dB adjacent to a single cushion. In contrast night-time $L_{A10,6h}$ levels were generally unchanged maybe because of extraneous noise during quieter night-time periods.



Countdown signs to the 30mph speed limit at the south gateway

Speed cushions and mini-roundabouts in the village centre (looking north)

'Dragon teeth' markings at the south gateway

Repeated red patch in the village

Speed cushion, pedestrian refuge and centre hatching just north of the village centre (looking north)

Figure 5.9 Traffic calming features at Craven Arms [5.12].

A social survey was carried out with about 200 local residents. They correctly perceived that vehicle speeds had reduced but about half the respondents thought noise had actually *increased*.

5.3.4 Rural trunk road, Thorney

Figure 5.10 shows examples of the traffic calming features installed at Thorney. At this site the speed limit was unchanged at 48 km/h (30 mile/h) [5.9]. On each main road approach, prominent signing warning of traffic scheme was installed in advance of the gateway. This comprised a raised imprinted brick-pattern contrasting surface within a slight narrowing of the road achieved using chicanes. In the village, two mini-roundabouts were installed, one within a part-time 32 km/h (20 mile/h) speed limit associated with a school. One of the mini-roundabouts was later removed following complaints of noise from nearby residents. Near the school entrance a Zebra crossing was installed and a speed camera was introduced near the village centre. Following the introduction of these measures there were large reductions in average speed throughout the village. Mean and 85 percentile speeds fell by 14 km/h at the gateways and within the 32 km/h limit the reductions were up to 19 km/h. Traffic flows were found to be unchanged. Same question as above on driving pattern – no information.

Noise levels were measured at a number of points including one gateway, within the 32 km/h speed limit and in the village centre. The reductions in speed at the traffic calming measures resulted in reductions in maximum vehicle noise levels at all three sites., excepts for heavy vehicles in the village centre where noise levels were unchanged. The greatest changes occurred at the gateways where a reduction of 6 dB was recorded for light vehicles and a reduction of 4 dB for heavy vehicles.

Both daytime $L_{A10,18h}$ and night-time $L_{A10,6h}$ traffic noise levels fell by 3 to 5 dB except in the village centre where there was little change. It was considered that the presence of a nearby signalised junction near the village centre may have reduced the observed effect.

A social survey was also carried out with about 200 residents of Thorney soon after installation. Two-thirds correctly perceived that vehicles speeds had reduced but three-quarters thought noise had increased. Most respondents blamed the surface treatment at the gateways and the Zebra crossings and the mini-roundabout where additional noise from body-rattle, braking and acceleration would have been generated on some occasions. In fact 60% were concerned about the mini-roundabout and nearly 6% reported that they had been kept awake at night by the additional noise produced.

It is likely that the maximum noise levels and the number of very noisy events may have increased following the scheme due to increased body rattle noise. There is some evidence that dissatisfaction is conditioned by these very noisy events rather than the average level.

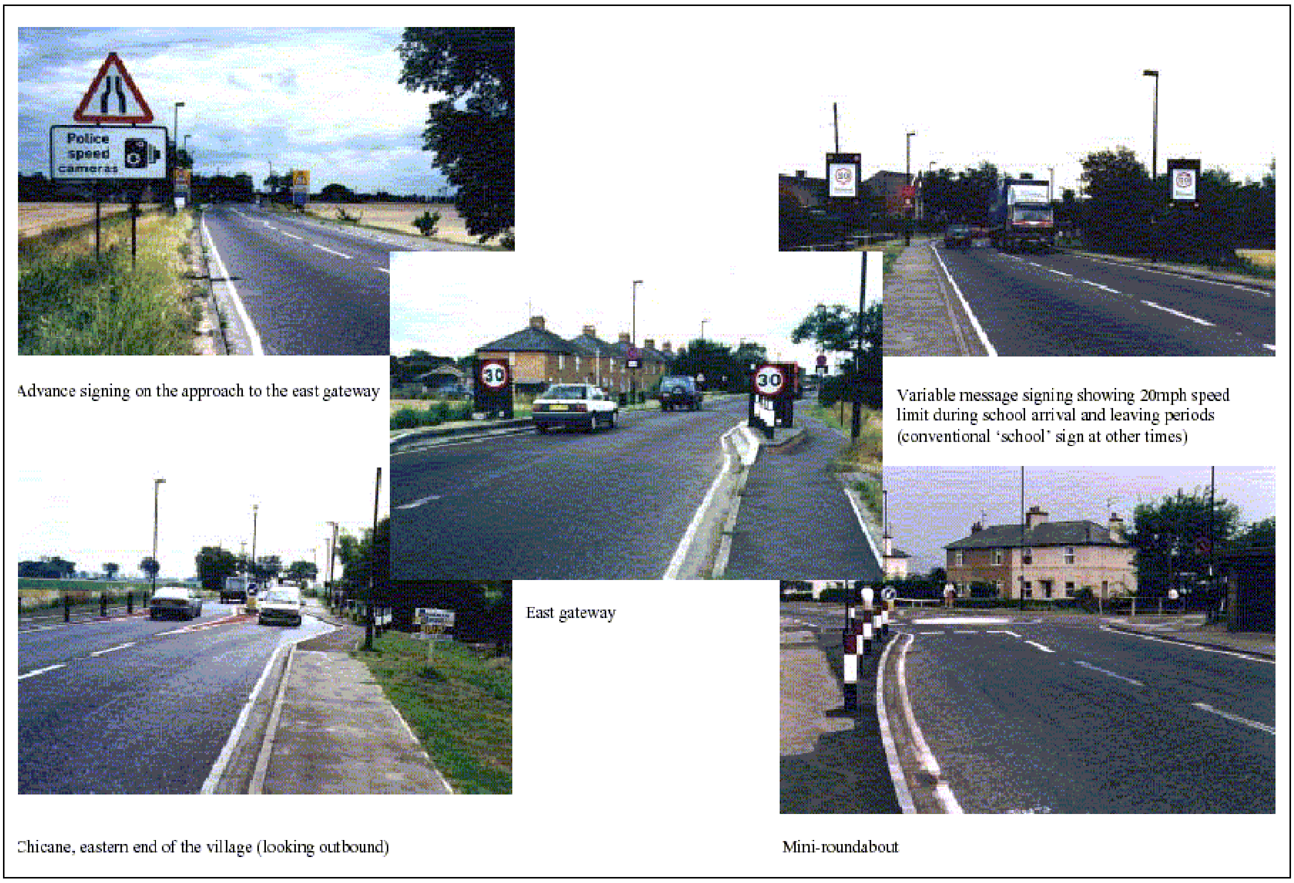
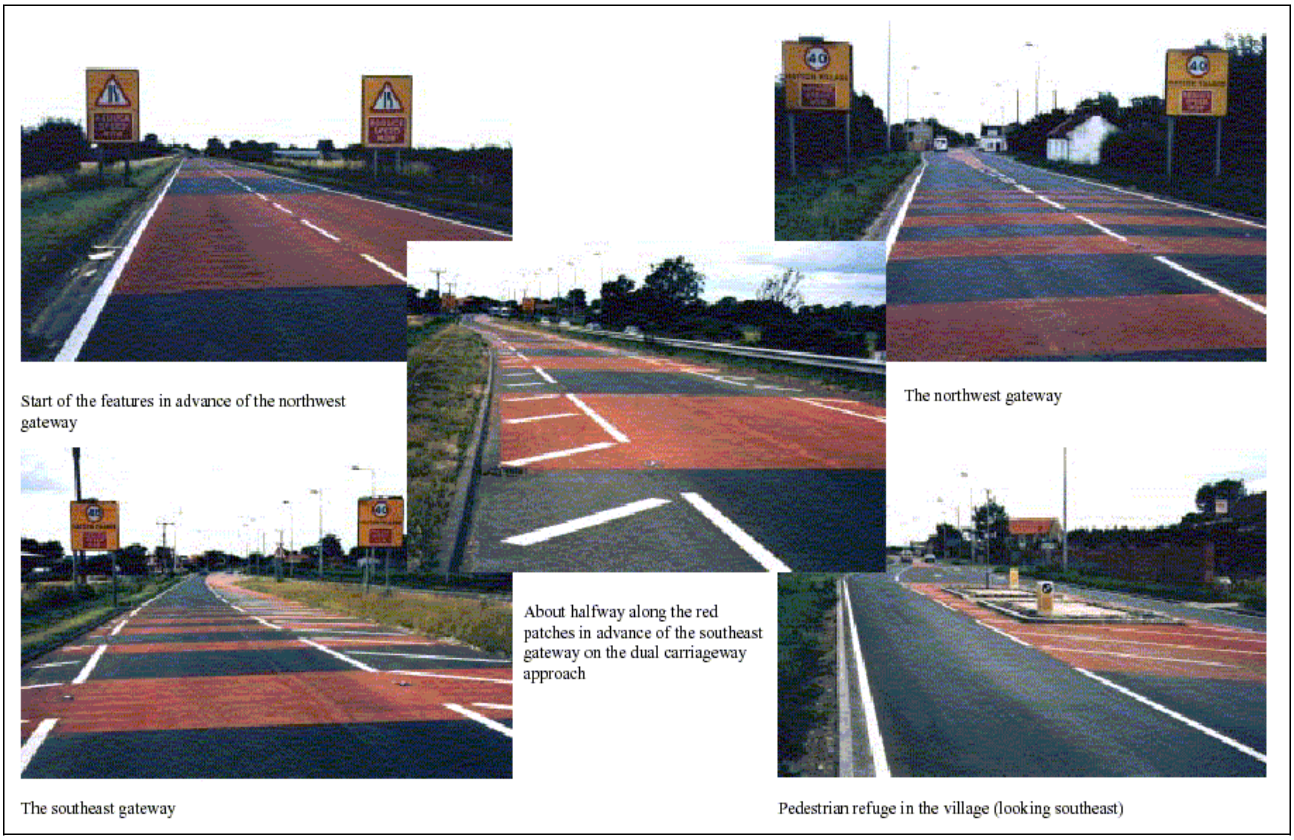


Figure 5.10 Traffic calming features at Thorney [5.12].

5.3.5 Rural trunk road, Hayton

Figure 5.11 shows examples of the traffic calming features installed at Hayton. As part of the scheme the 96 km/h (60 mile/h) speed limit was reduced to 64 km/h (40 mile/h). On each main road approach to the village resurfacing was carried out which incorporated a set of 24 red patches of reducing length and spacing. These were preceded by signs: “REDUCE SPEED NOW” and “ROAD NARROWS” and these were installed in advance of the gateway feature. Side hatching narrowing the lane width was superimposed on the red patches on the dual carriageway approach. At each gateway, signs comprising a 40 mile/h speed limit roundel, the village name and “REDUCE SPEED NOW” on a yellow background were erected on each side of the carriageway. Within the village, two pedestrian refuges and an island linked by centre hatching on a red background was installed.

Following installation the speed was reduced by 32 km/h at one gateway and typically 16 km/h in the village. Noise monitoring was carried out close to one gateway. Maximum levels of light and heavy vehicle noise fell by approximately 10 and 7 dB respectively. It was considered these reductions were due both to the reduction in speed and the resurfacing work. Daytime $L_{A10,18h}$ levels fell by 9 dB and night-time $L_{A10,6h}$ traffic noise level was reduced by 13 dB.



Start of the features in advance of the northwest gateway

The northwest gateway

About halfway along the red patches in advance of the southeast gateway on the dual carriageway approach

The southeast gateway

Pedestrian refuge in the village (looking southeast)

Figure 5.11 Traffic calming features at Hayton [5.12].

Although no social survey was carried out, the occupier of the property where noise measurements were carried out complained about rapid changes in noise level as vehicles drove over the series of patches on the approach to the gateway.

5.4 References for chapter 5

[5.1] Abbott P, Phillips S, and Layfield R (1995). Vehicle and traffic noise surveys alongside speed control cushions in York. TRL Project Report PR103. TRL, Wokingham.

[5.2] Abbott P, Watts G and Harris G (2000). Traffic calming in Gloucester – influence on noise and ground-borne vibration. Proceedings of Internoise 2000, Nice.

[5.3] Department of Transport (1996). Road humps and ground-borne vibrations. Traffic Advisory leaflet 8/96.

[5.4] Harris G, Stait R, Abbott P and Watts G (1999). Traffic calming: Vehicle generated ground-borne vibration alongside sinusoidal, round-top and flat-top humps. TRL Report 416, TRL, Wokingham.

[5.5] Watts G, Harris G and Layfield R (1997). Traffic calming: Vehicle generated ground-borne vibration alongside speed control cushions and road humps. TRL Report 235.

[5.6] Watts G R, Stait R E, Godfrey N S, Chinn and Layfield R (2002). Development of a novel traffic calming surfae 'Rippleprint'. TRL Report TRL545, TRL, Wokingham.

[5.7] Watts G R,and R King (2004). Prediction of ground-borne vibration generated by heavy vehicles crossing a rumblewave device. TRL Report PPR 020, TRL, Wokingham.

[5.8] Wheeler A, Abbott P , Godfrey N, Lawrence and Phillips S (1996). Traffic calming on major roads: the A49 trunk road at Craven Arms, Shropshire. TRL Report 212. TRL, Wokingham.

[5.9] Wheeler A, Abbott P, Godfrey N, Phillips S and Stait R (1997). Traffic calming on major roads: the A47 trunk road at Thorney, Cambridgeshire. TRL Report 238. TRL, Wokingham.

[5.10] British Standard Institution (1993). Evaluation of measurement for vibration in buildings Part 2 Guide to damage levels from ground borne vibration. BS 7385 Part 2. British standards Institution, Chiswick.

[5.11] Watts G, Stait R, Godfrey N and Layfield R (2001). Optimisation of traffic-calming surfaces. Proceedings of Internoise 2001. The Hague.

[5.12] Wheeler A and Taylor M (1999). Traffic calming in villages on major roads: final report. TRL Report 385. Transport Research Laboratory, Wokingham.

6. Austrian experiences

Relating to an extensive literature research carried out by the Vienna University of Technology the following chapter describes Austrian experiences on the use of traffic management measures to reduce traffic noise. Tale 6.1 gives a list of the examined literature [6.1].

Table 6.1 Evaluated literature [6.1].

Autors	Institution	Year of Publication, Country	Title	Traffic management Measure
Pucher et al.	Vienna University of Technology	2003, Austria	Real Traffic Noise Emission Factors and Reduction Scenarios Based on Complete System Optimization	Speed Reducing Measure
Pischinger et al.	Graz University of Technology	1995, Austria	Speed Limit 30/50 km/h in Graz	Speed Reducing Measure
Maurer, Pöschl	Arsenal Research	2002, Czech Rep.	The Use of Telematics for an Intelligent Speed Management	Noise Protection Facility
Dimbacher	ASFINAG (Motorway and High Speed Road Financing Corporation)	2003, Austria	ASFINAG announces the Fight against Traffic Noise	Noise Protection Facility
Rankl	Office of the federal State Government of Vorarlberg	1992, Austria	Determination of the Effects of Night Time Driving Bans for Heavy Vehicles by the Use of Noise Immission Measurements	Traffic Restrictions
Molzer	Office of the federal State Government of Tyrol	2003, Austria	Noise Protection in Tyrol	Traffic Restrictions

The literature shown above has been evaluated and the reports and articles that have been considered most relevant are presented in this deliverable in part 6.1 to 6.4 in a short way.

6.1 Speed reducing measures

6.1.1 Speed reduction in urban and suburban areas

In the context of an Austrian research project under the framework of Austria's Ministry for Transportation, Innovation and Technology (BMVIT) researchers from the Vienna University of Technology investigated the influence of different driving situations on the emission of traffic noise [6.2]. For this purpose a computation model was developed based on measured real-life traffic noise data using the SPB- measurement method [6.3]. Due to the influences of traffic composition, maximum speed and gradient on the vehicle sound emission levels, typical traffic conditions were defined. These chosen traffic situations are defined in Table 6.2.

Table 6.2 Typical traffic situations [6.2]. (AADT is average annual daily traffic).

Traffic Situation	Speed Limit v_{min} [km/h]	Speed Limit v_{max} [km/h]	AADT [Vehicles/24h]	Heavy Vehicle Share [%]
Urban Main Road	20	70	20.000	8
Urban Road in a Residential Area	20	50	150	0
Main Rural Road	50	120	10.000	8
Motorway on Level Ground	50	140	60.000	12
Motorway on Gradients	30	120	60.000	12

On each of these traffic conditions results of SPB- measurements in Austria on different road surfaces were collected and analysed. Additionally measurements took place in Vienna at several urban main roads. Different road surfaces were studied:

- Dense asphalt concrete.
- Cement concrete.
- Low noise road surfaces as low noise stone mastic asphalt, porous asphalt concrete and exposed aggregate cement concrete.

An example of SPB-measurements taken in Vienna in October 2003 is given in Figure 6.1.

Figure 6.1 SPB-measurements taken in Vienna, Austria [6.4].

Results of the regression analysis showing the influence of vehicle speed on the traffic noise of passenger cars and heavy vehicles are shown in Figure 6.2.

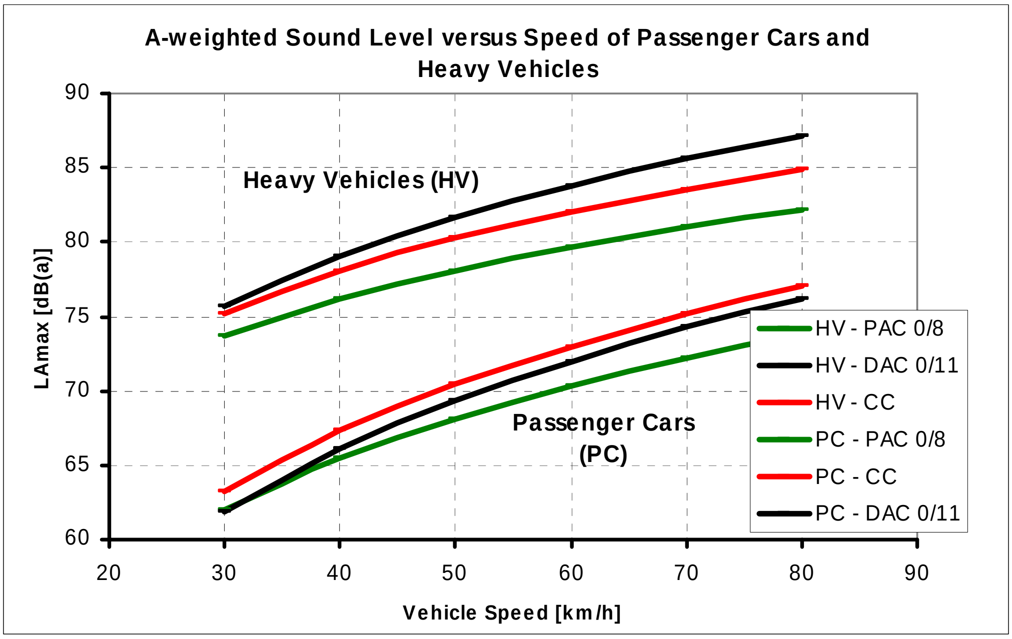


Figure 6.2 Influence of vehicle speed on the sound pressure level LAmax [6.3].

Analysing these data for passenger cars, a speed reduction from 60 km/h to 40 km/h leads to the following decrease of the maximum sound pressure level L_{Amax}:

Cement concrete:	ΔL_{Amax} = 5.7 dB
Dense asphalt concrete:	ΔL_{Amax} = 6.0 dB
Porous asphalt concrete:	ΔL_{Amax} = 4.9 dB

Regarding heavy vehicles, the following results can be shown:

Cement concrete:	ΔL_{Amax} = 4.0 dB
Dense asphalt concrete:	ΔL_{Amax} = 4.8 dB
Porous asphalt concrete:	ΔL_{Amax} = 3.5 dB

Under the assumption of vehicles driving with constant speed it is clearly to be recognized from these results that a speed reduction from 60 km/h to 40 km/h in urban areas may affect a mean noise reduction of approx. 5.5 dB for passenger cars and a mean noise reduction of approx. 4 dB for heavy vehicles depending on the used road surface. The noise reduction effect for trucks does not seem so significant because of the higher influence of the engine noise at low vehicle speeds [6.3].

6.1.2 30 km/h zones in residential areas

The implementation of 30 km/h zones in residential areas is a measure to reduce traffic noise as well as the risk of accidents either between different vehicles or between vehicles and people. A survey in Graz, Austria of different 30 km/h zones around the city shows the effect of such traffic calming measures [6.5]. The speed reductions were implemented by setting up signs at the beginning of the 30 km/h zones. At 10 different sections in Graz noise measurements took place to compare the situations before (speed limit 50 km/h) and after adopting 30 km/h zones. At each site the microphone was situated at the sidewalk, this leads to a microphone distance of 3.5 m and a microphone height of 2 m. The analysis of the results was proceeded according to the Austrian regulation RVS 3.02 [6.6] (former RVS 3.114) where a calculation procedure of the A-weighted sound pressure level LA,eq over a certain time is described. It will then be easy to compare measurement with calculation results. On each of the 10 different sites the measurement time was around 50 minutes. The obtained results vary between a realised noise reductions of 0.2 dB up to 1.9 dB. Table 6.3 gives an example of detailed results from one measurement site.

Table 6.3 Measurement results Vinzenzgasse, house no. 36, Graz, Austria [6.5].

	Before	**After**		**Reduction potential**
		Measurement	Standardised measurement [6.6]	
Date	15.06.1992	09.11.1993		
Time [hh.mm]	15.20 – 16.35	12.22 – 13.25		
Veh/Mmt-time	293	236		
Veh/h	234	225		
L_{eq} [dB(A)]	64,0	62,1	62.1	- 1.9
v_m [km/h]	27,6	28,3		+ 0.7
Sample size noise measurement [Veh]	293	236		
Sample size speed [Veh]	219	41		

Veh .... vehicles
L_{eq} .... energy equivalent sound pressure level over the measurement time
v_m .... mean vehicle speed

Another Austrian study [6.7] shows the influence of 30 km/h zones on the maximum sound pressure level measured according to the ISO 11819-1 standard (SPB-measurement method) [6.3]. The results are given in Figure 6.3.

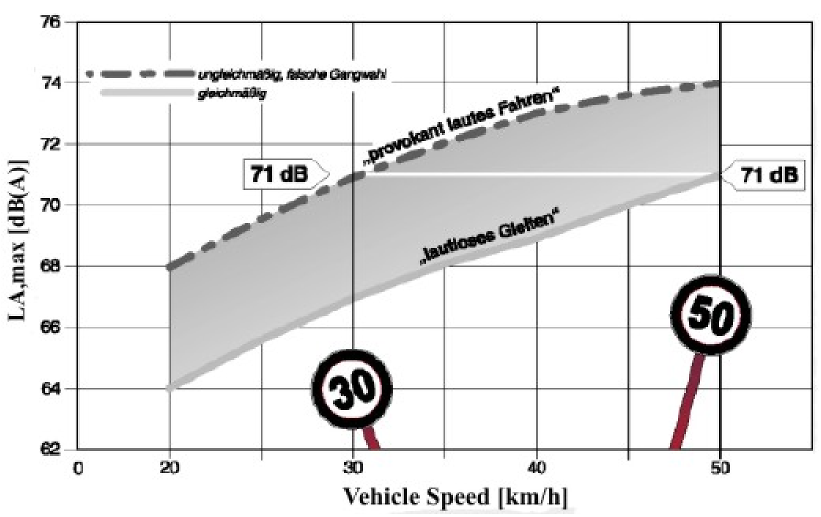


Figure 6.3 Influence of 30 km/h zones on LA,max [6.7].

As can be seen in Figure 6.3, a possible reduction of 3 - 4 dB can be achieved by implementing a speed reduction to 30 km/h. In addition if a driver drives provokingly "loud" in a 30 km/h zone, for example by using a lower gear, the pass by noise won't be even louder than by driving with a speed of 50 km/h. That is because of the dominating influence of the tyre-road noise on the overall traffic noise, even for low driving speeds. In other words, even if you are driving in the most "loudish" way (according to the engine of the vehicle) with a speed of 30 km/h, you will not be louder than by driving with a speed of 50 km/h [6.7].

Another positive effect is the significant reduction of accidents with insurances in 30 km/h zones compared with standard urban roads (speed limit 50 km/h). Westhauser et al. are stating this reduction potential to be about 25% [6.7].

In Vienna, Austria, for example, many 30 km/h zones are implemented in residential areas for traffic safety reasons, but also because of rising noise problems; approx. 34% of all roads [km] are so called traffic-calmed zones (see Figure 6.4).

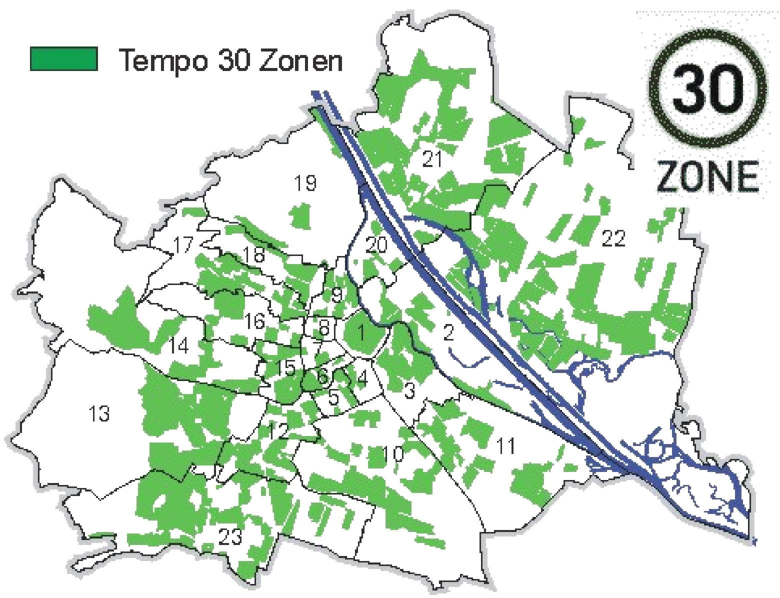


Figure 6.4 30 km/h zones in Vienna, Austria [6.8].

6.2 Speed and noise management measures

6.2.1 Multifunctional noise protection facility

In Styria, Austria, a pilot project with the aim of reducing traffic noise started in the year 2000. The target zone is a residential area situated near the Austrian highway A2 frequented by more than 34.000 vehicles/24 h (1998) with heavy traffic contributing up to 20 % to the total traffic during night hours.

The idea was the following: Conventional methods of traffic noise reduction like noise barriers provide a basic noise protection and are in some cases no longer sufficient. Therefore a dynamic interactive traffic management system controlled by environmental parameters was created with a range of advantages like:

- Traffic noise reduction.
- Reduction of air pollution due to traffic.
- Enhancing road security.
- Optimising the traffic flow.

In addition, photovoltaic elements that form an integrated part of the noise barrier were installed to produce environmentally friendly energy while reducing traffic noise, too [6.9]. The former noise barrier in comparison with the rebuilt one with photovoltaic elements on the top is shown in Figure 6.5.

Figure 6.5 Before and after situation (adopted from [6.10]).

The concept of this multifunctional noise protection facility is based on the fact that the vehicle speed has a great influence on the related noise emission. A dynamic speed management allows reducing noise especially during those hours when the residents in the neighbourhood of the highway suffer from noise levels considerably exceeding the legal noise limits ($L_{Aeq,day}$ = 60 dB, $L_{Aeq,night}$ = 50 dB according to [6.11]).

A complex noise measurement system that registers and processes noise emission and immission data, traffic parameters and environmental data allows identifying noise caused by traffic and activating the implemented telematic system when the legal noise levels specified in [6.11] are exceeded. The result is a speed limit adapted to the situation so that the speed limit is reduced when the noise is too high. At the same time the traffic flows more smoothly and therefore an improved road safety can be stated.

The schemata of the “Multi-Functional Noise Protection Facility” at Gleisdorf is shown in Figure 6.6.

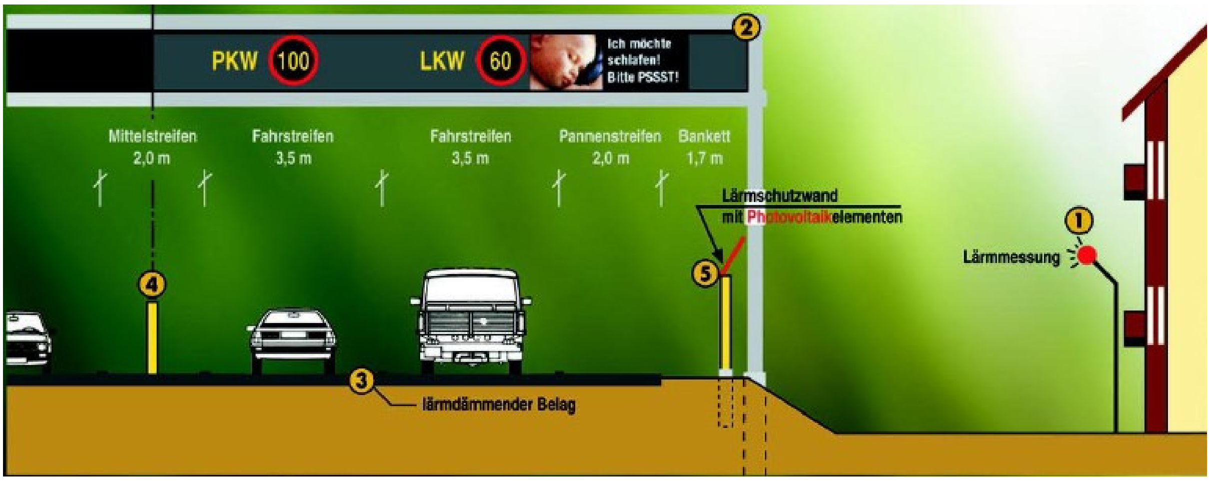


Figure 6.6 Schemata of the multi-functional noise protection facility Gleisdorf [6.10].

Table 6.4 Description of the multi-functional noise protection facility Gleisdorf.

1	……….	Noise Measurement Facility in the Location of Gleisdorf
2	……….	Traffic Management Device - Automatic Speed Signs with added Psychological Signs (Please PSST! I Want To Sleep). PKW and LKW are light and heavy vehicles.
3	……….	Noise Reducing Road Surface (Cement Concrete with Longitudinal Grooves)
4	……….	Mean Noise Barrier (height of 2,0 m)
5	……….	Noise Barrier (height of 3,0 m) with additional Solar Generators

To reduce the driving speed of the passing vehicles 3 different speed schemata could be implemented according to the existing noise situation at the noise measurement point (1) shown in Figure 6.6. Each speed schemata with its own speed reductions are pointed out in Table 6.5.

Table 6.5 Speed reduction schemata.

Schemata	Speed limit passenger cars [km/h]	Speed limit heavy vehicles [km/h]
1	100	80
2	100	60
3	80	60

Noise emission measurement results show that the best reachable noise reductions in comparison with the initial situation (speed limit of 130 km/h for heavy vehicles and passenger cars) will be up to 6 dB in case of the highest speed reductions for heavy vehicles and passenger cars [6.12].

The good will of the drivers rather than fear of being caught speeding is counted upon to have the speed limits observed. This is done through the signs in Figure 6.7 and 6.8.

Figure 6.7 Sign "Fast Is Loud" [6.10].

Figure 6.8 Sign "Please PSST! I Want to Sleep" with signed speed limits [6.10].

Speed measurements show that the speed reduction of 80 km/h for heavy vehicles is accepted by most of the drivers, but 60 km/h is only accepted by 10 %. Regarding passenger cars more than 50 % adhere to the speed limits but a general speed reduction could be observed anyway.

6.3 Traffic Restrictions in Special Periods

6.3.1 Night Time Driving Restrictions for Heavy Vehicles

An investigation on the influence of driving restrictions for heavy vehicles (> 7,5 tons) on an Austrian rural road (B 312 Loferer Straße) was implemented in the west of Austria in 1991 [6.13]. The B 312 has a generated traffic of about 7100 Veh/24 h in one driving direction with a heavy vehicle share of approx. 18 %.

Table 6.6 Influence of night time driving bans on the overall noise at the B312, Austria based on noise measurements [6.13].

Traffic management measure	**$L_{A,eq}$ over the night time (22:00-05:00) [dB]**	**$\Delta L_{A,eq}$ [dB]**	**Effect of measure**
Before situation year 1986	70.4	--	--
Implementation of night time driving bans for heavy vehicles with special exceptions (April 1986)	68.3	2.1	45% reduction of heavy vehicles
Reduction of special exceptions of night time driving bans (Dezember 1990)	66.6	3.8	45% reduction of heavy vehicles, 50% low noise heavy vehicles
	65.4	5.0	45% reduction of heavy vehicles, 100% low noise heavy vehicles
Implementation of night time driving bans for heavy vehicles without special excep-tions (January 1991)	63.2	7.2	86% reduction of heavy vehicles, 100% low noise heavy vehicles

On the studied road the following traffic management measures were accomplished step by step:

- 1986: Implementation of night time driving bans (between 22:00 and 05:00) for heavy vehicles (> 7.5 tons) with the possibility of special exceptions.
- 1986 till 1990: Significant reduction of the number of exceptions.
- 1991: Implementation of generally night time driving bans (between 22:00 and 05:00) for heavy vehicles (> 7.5 tons).

Table 6.6 shows the results of immission noise measurements taken between 22:00 and 08:00 in the years 1986 till 1991. Measurement results are shown as $L_{A,eq}$- values (energy equivalent sound pressure level over the measurement-time). ΔL_{Aeq} shows the comparison between the initial situation (before April 1986) and the actual measure-ments.

A low noise heavy vehicle has (per definition of the Austrian Federation of Noise Abatement - ÖAL [6.14]) an L_{Amax}-value regarding an accelerated pass-by measure-ment of 80 dB.

Other research projects in Tyrol, Austria are showing more or less the same effect. There is, however, one critical effect of the implementation of such traffic bans at night. Traffic increases intensely in the early morning hours between 05:00 and 06:00, as can be seen in Figure 6.9.

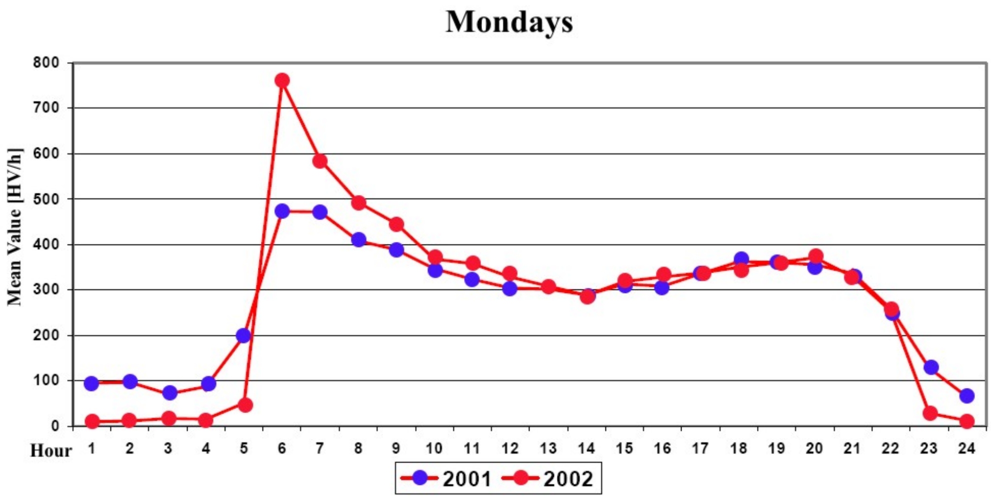


Figure 6.9 Distribution of heavy traffic over 24 hours on Mondays [adopted from 6.15].

Regarding the early morning hours an increasing traffic level of about 40 - 50 % could be realised [6.15] which follows from a traffic change from the night time to the early morning. This gives an increase of noise from 5 - 8 o'clock in the morning with the highest increase from 5 to 6 o'clock.

6.4 Roundabouts and traffic lights

6.4.1 Roundabouts

A Swiss example (see [6.16]) indicates the possible effect on traffic noise of an implemented roundabout on a highly frequented road. In Basel, Switzerland, a traffic light- regulated crossing was replaced by a roundabout in 2002. The following effects were expected:

- Improved traffic flow.
- Increased traffic safety.
- Reduced traffic noise.

Figure 6.10 shows the crossing before and after the implementation of the roundabout.

Figure 6.10 Before and after situation (adopted from [6.16]).

The first measurement series on the initial situation of the crossing took place in April 2001 over a time period of 4 weeks. Over this time the $L_{A,eq}$-value was calculated for the two different time frames:

- Day time from 6 till 22 o'clock.
- Night time from 22 till 6 o'clock.

The microphone for the noise measurements was situated on the facade of one dwelling on the first floor next to one traffic light (see Figure 6.11).

Figure 6.11 Microphone position for noise measurements [6.16].

Table 6.7 Measurement results before and after implementation of the roundabout [6.16].

Measurement Results:		**Sound Pressure Level L_{Aeq} [dB]**	
	Crossing (April 2001)	**Roundabout (June 2002)**	**Reduction Potential**
Day (6:00 - 22:00)	70.1	68.4	-1.7
Night (22:00 - 6:00)	63.4	60.5	-2.9
Difference day/night	6.7	7.9	

After completion of the roundabout in June 2002 another one month measurement series was accomplished at the same place with the same microphone position. The mean speed of the arriving vehicles was about 50 km/h. Results of the two measurement series are shown in Table 6.7.

6.5 References for chapter 6

[6.1] Haberl, J.: "Austrian contribution to SILVIA Deliverable D12: Recommendations on Additional Noise Reducing Measures," file name:"SILVIA-TUW-043-01-WP5-20040907-D12_AustrianParticipation", Vienna, September 2004.

[6.2] Pucher, E., Litzka, J., Haberl, J., Girard, J., Walcher, R., Geieregger, M., Kalivoda, M., Bukovnik, M.: "Reale Lärm-Emissionsfaktoren des Straßenverkehrs und Reduktionsszenarien durch Gesamtsystemoptimierung (Real-Life Noise Emissions Factors for Street Traffic and Noise Reduction Scenarios Through Complete System Optimisation)," Final Report of the Austrian Advanced Automotive Technology A3 Programme, FFF Project No. 806215, Vienna, December 2003.

[6.3] ISO 11819-1:1997: Acoustics – Method for measuring the influence of road surfaces on traffic noise – Part 1: "The Statistical Pass-By Method," International Organisation for Standardization (ISO), Geneva, 1997.

[6.4] Pucher, E., Haberl, J.: " Reduktionspotenzial des Straßenverkehrslärms - Reales Lärmverhalten und Beurteilung (Potential of Traffic Noise Reduction – Real-Life and Noise Estimation)," Lecture in the context of the event „ Road Construction Engineering". Vienna University of Technology, Institute for Road Construction and Maintenance, Vienna, June 2004.

[6.5] Pischinger et al.: "Tempo 30/50 in Graz (Speed Limit 30/50 km/h in Graz)," Series of Publications of the Institute for Railway Engineering and Transport Economy and the Institute for Highway Engineering and Transportation Planning at the Graz University of Technology. Graz University of Technology, Graz, September 1995.

[6.6] RVS 3.02:1997: "Umweltschutz – Lärmschutz (Environment Protection – Noise Protection)," Forschungsgesellschaft für das Verkehrs- und Straßenwesen, Vienna, 1997.

[6.7] Westhauser et al.: "Ein Leitfaden zur Verkehrsberuhigung (A manual for traffic noise abatement)," Amt der NÖ Landesregierung, Austria, 2004. http://www.noel.gv.at/service/ru/ru7/Downloads/t30_leitfaden.pdf.

[6.8] http://www.wien.gv.at/verkehr/organisation/veberuhi.htm.

[6.9] Maurer, P., Pöschl, B.: "The Use of Telematics for an Intelligent Speed Management," Paper for the 15th ICTCT Workshop on Speed Management Strategies and Implementation, Brno, Czech Republic, October 24th - 25th, 2002.

[6.10] http://www.asfinag.at/.

[6.11] Ministry for Economic Affairs and Labour: „Dienstanweisung – Lärmschutz an Bundesstraßen (Instruction – Noise Abatement on Roads)", Zl. 890.040/2-VI/14a/99, Vienna, December 1999.

[6.12] Aigner, G.: „Alternativen im modernen Lärmschutz. Was kann die neue MLA wirklich? (Alternatives in Modern Noise Protection)," Presentation at the „Symposium Lärmschutz", Asfinag, Krems, June 2003.

[6.13] Rankl, Ch.: „Ermittlung der Auswirkungen von LKW-Nachtfahrverboten auf der B 312 Loferer Straße durch Immissionsschallpegelmessungen (Determination of the Effects of Heavy Vehicle Night Driving Bans on the B 312 (Loferer Straße) by noise immission measurements)," Presentation at the

Meeting „Geräuschemission von Schwerfahrzeugen“, Bayerisches Landesamt für Umweltschutz, Munich, October 1992.

[6.14] ÖAL (Austrian Federation of Noise Abatement): “Kriterien für lärmarme Lastkraftwagen und Omnibusse (Criteria for Low Noise Heavy Vehicles and Busses)”, ÖAL Richtlinie 29, Vienna, 1987.

[6.15] Molzer, Ch.: „Lärmschutz in Tirol - ein Erfahrungsbericht (Noise Protection in Tyrol – State of the Art Report),“ Presentation at the „Symposium Lärmschutz“, Asfinag, Krems, June 2003.

[6.16] Plüss, P., Meury, F., and Mohler, P.: „Verringerung der Lärmbelastung durch die Umgestaltung einer ampelgeregelten Kreuzung in einen Kreisel (Decrease of Noise Emissions by Transforming a Traffic Light-Regulated Crossing into a Roundabout),“ Strasse und Verkehr Nr.10, VSS Schweizerischer Verband der Strassen- und Verkehrsfachleute, Zurich, October 2003.

7. Other international experiences

Other relevant international literature has also been found during the literature search as well as in the publication “Traffic Calming” [7.4] from the United Kingdom. Some highlights are presented in this chapter.

Table 7.1 Evaluated international literature.

Authors	**Institution**	**Year of publication, country**	**Title**	**Traffic management measure**
Bérengier	Laboratore Central des Ponts et Chaussées	France	Acoustical impact of traffic flowing equipments in urban area	The impact of roundabouts on noise and modelling of noise
Kathmenn and Cannon	Aachen University	Germany, 1999	Speed limits as noise reducing measure in Germany	
Ellenberg and Bedeaux	CERTU	France, 1999	Calming waves for safety	The use of green waves to reduce speed

7.1 Roundabouts on arterial roads

It is common that big arterial roads and main avenues in urban areas create noise problems. In order to improve the situation and reduce the speed, roundabouts have been constructed instead of intersections. Some French results are presented in [7.1]. If the volume of traffic is unchanged after the construction of a roundabout, the equivalent noise level (L_{Aeq}) will be reduced due to a reduction of the number of acceleration and deceleration periods. On this background the noise reduction depends on the design and layout of a roundabout such as the radius, the number of lanes and the number of entry/exit roads. It is important to reduce the braking and acceleration periods through the optimisation of the radius at the same time as it is important not to create congestion zones along the various roads leading to the roundabout.

Table 7.2 Noise reductions measured at three French roundabouts in relation to a before situation with different types of intersections [7.1].

Site	**Before situation**	**Noise reduction in day period (L_{Aeq}) in dB**	**Noise reduction in night period (L_{Aeq}) in dB**
Malemort	Intersection with traffic lights	2.0	-
Namtes	Intersection with traffic lights	3.0 - 4.0	2.0 – 3.0
Egleton	Intersection with full stop signs	1.0 - 3.0	1.0 - 2.5

Table 7.2 shows the results form measurements before and after the construction of three roundabouts in France. Reductions of the equivalent noise level (L_{Aeq}) of 1 to 4 dB have been achieved.

7.2 Speed limits as noise reducing measure

Because of a public pressure for reduced noise, a number of trial sections of motorways have been selected in Germany. Speed limit signs have been mounted along motorways with signs saying: “noise protection” in order to reduce the traffic noise (See Figure 7.1).

Figure 7.1 Speed limit sign supplemented with “Noise reducing” sign. An example from Germany. Picture from [7.2].

Table 7.3 shows examples of the noise reductions that can be predicted, if it is assumed that all vehicles follow the reduced speed limits. Different speed limits are used for light and heavy vehicles. Noise reductions of 1 to 4 dB can be expected if all drivers follow the reduced speeds. As the percentage of heavy vehicles is increased the noise reduction is reduced.

Table 7.3 Predicted reductions of equivalent noise level ($L_{Aeq,24h}$) for different strategies of speed reduction [7.2].

Speed limit before		Speed limit after		Noise reduction in dB	
Light vehicles in km/h	Heavy vehicles in km/h	Light vehicles in km/h	Heavy vehicles in km/h	10 % heavy vehicles	20 % heavy vehicles
130	80	100	80	1.9	1.2
130	80	100	60	2.6	2.3
130	80	80	60	3.8	3.1
130	80	130	60	0.5	0.8

13 trial sections with reduced speed limits have been established in Germany on a total of more than 50 km of motorway. Series of noise measurements have been carried out before and after introducing the reduced speed limits. Reductions of 1.0 to 3.5 dB have been measured. It is concluded in [7.2] that drastic speed limit reductions necessitate long term presence of the police for enforcement purposes.

7.3 Green waves

Traffic lights and green waves are usually optimized in order to improve the capacity of a road network. In [7.3] some French experiences on optimization of green waves in order to reduce speed and ensure an even driving pattern is described. The scheme is called “Calming Green Waves”. This has been tested in four towns.

The objective is that the drivers understand that the signals are tuned such that their journey will remain comfortable if they drive at a safe speed. Three parameters are important for the adjustment of traffic lights: the speed of coordination, cycle duration and green wave bandwidth. By slowing the speed of the green waves through increasing the offset between switching on the green signals at two intersections, the drivers will be encouraged to adopt a speed near to the green wave to avoid being stopped by a red signal. The following constants were used in the experiments:

- Cycle time 50 to 60 seconds.
- Bandwidth 20 to 25 seconds.
- Speed of green wave 40-45 km/h.

The following results were obtained:

- The average speed was reduced by 15 km/h for groups of vehicles.
- The 15 % fastest reduced their average speed by 22 km/h.
- The number of cars exceeding the speed limit was reduced.

No noise measurements have been performed but due to the reduced speed it is believed [7.3] that the noise has been reduced. When selecting the speed of the green wave it is important to choose a speed over 35 km/h, because at lower speeds there is a risk of increasing braking and acceleration instead of having a steady speed.

7.4 References for chapter 7

[7.1] Bérengier, Michel. Acoustical impact of traffic flowing equipments in urban area. A paper from Laboratore Central des Ponts et Chaussées, Centre de Nantes, France.

[7.2] Kathmenn, T ; Cannon, R. Speed limits as noise reducing measure in Germany. Highway & Transportation, pp 8-11, September1999.

[7.3] Ellenberg, Marc; Bedeaux, Jean-Francois. Calming waves for safety. Traffic Technology International, pp 55-58, April/May 1999.

[7.4] TRL Library Services. CTx01 Traffic Calming (1991-2001). Transportation Research Laboratory. United Kingdom. 2001..

8. Catalogue on traffic management and noise effects

The main conclusions that can be drawn on the background of the international literature survey (chapters 4 to 7) are listed as a catalogue of traffic management measures in the following tables. The measured or predicted effect on noise is included as well as key comments to the individual measures. Details on the layout and design of the different measures can be found in the relevant chapters. References to the key sections are included.

8.1 The different measures

In table 8.1 the results from the effect of constructing roundabouts is summarised:

- Noise reductions of 2-4 dB are seen near roundabouts. The design of the roundabout is important for the effect on noise.
- No noise reductions at a distance of around 100 m from roundabouts if there are no speed reducing measures on the streets leading to a roundabout.
- In a case with a mini roundabout a social survey showed complaints about noise from body-rattle and braking and accelerating even though a noise reduction was measured.

Table 8.1 List of effect of roundabouts.

Measures used	**Effect on noise reduction (L_{Aeq})**	**Remarks**	**Country and reference section**
Roundabout instead of intersection without traffic lights. Speed limit before and after 50 km/h.	2 dB close to the roundabout. 0 dB 100 m from roundabout	No measures were established on the roads leading to the roundabout.	Norway Section 4.7
Roundabouts on urban roads in combination with other speed reducing measures.	2 dB	The noise reduction was predicted.	Sweden Section 4.9
Mini roundabout on rural trunk road through village in combination with other speed reducing measures. Speed limit before and after 48 km/h.	3 - 5 dB measured as $L_{A10,18h}$	A social survey showed complains about noise from body-rattle and braking and accelerating around mini roundabout.	Great Britain Section 5.3.2
Roundabout instead of an intersection with traffic lights on arterial road. Speed on nearby road sections 50 km/h	2 dB daytime 3 dB night time	The noise was measured over 4 week periods.	Switzerland Section 6.4.1
Roundabout instead of intersection with traffic lights on arterial road.	2 - 4 dB daytime 2 – 3 dB night time	Noise reduction depends on design of roundabout.	France Section 7.1
Roundabout instead of intersection with full stop signs on arterial road.	1 - 3 dB daytime 1 – 3 dB night time	Noise reduction depends on design of roundabout.	France Section 7.1

In table 8.2 the effects of implementing traffic calming measures is summarised:

- Noise reductions of 1 - 4 dB are normally seen.
- In some case no noise reduction has been observed.
- In some cases quite big speed reductions have been achieved, and there rather high noise reductions of 5 – 9 dB have been measured.
- In some cases noise annoyance increases even though the noise decreases.
- When measures like humps and raised areas and the like are used it may cause increased noise, increased annoyance, or both.

Table 8.2 List of effect of speed reductions on road sections.

Measures used	**Effect on noise reduction (L_{Aeq})**	**Remarks**	**Country and reference section**
Environmentally adapted through roads with different speed reducing measures along a road	1 - 3 dB	Social surveys showed a significant reduction in annoyance	Denmark Section 4.1
Roads with a combination of speed reducing measures	2 dB	An increase of 2 dB of the maximum noise level was seen at road sections with raised level	Sweden Section 4.9
Environmentally adapted street with narrowed driving lanes	0 dB 1 - 3 dB (L_{Amax})	Speed reductions were only observed at the entrance to the street.	Norway Section 4.10
Environmentally adapted street with displacement of the lanes and raised levels at pedestrian crossings	0 – 2 dB Pedestrian crossings increase of 2 dB (L_{Aeq}) and 4-6 dB for L_{Amax}	A social survey showed increased noise annoyance at pedestrian crossings with raised levels	Norway Section 4.10
Traffic calming	3 – 6 dB	Problems with heavy vehicles at road humps	Great Britain Section 5.3.2
Traffic calming	2 dB	A social survey showed that 50 % thought the noise had increased	Great Britain Section 5.3.3
Traffic calming	3 - 5 dB	A social survey showed that people thought the noise had increased	Great Britain Section 5.3.4
Traffic calming. With a speed reduction from 96 to 64 km/h	9 dB		Great Britain Section 5.3.5
30 km/h zones implemented by speed limit signs	0 – 2 dB		Austria Section 6.1.2

The effect of road humps are summarised in Table 8.3:

- Round-top/circle type road humps can reduce the noise by 1 – 4 dB.
- There can be problems with rattling noise from heavy vehicles.
- A social survey indicates increased noise annoyance near circle-top humps.
- There is a need for further research in annoyance.
- Flat top humps increases noise by up to 6 – 8 dB.

- The effect of humps on noise depends very much on the percentage of heavy vehicles.

Table 8.3 List of effect of road humps.

Measures used	**Effect on noise reduction (L_{Aeq})**	**Remarks**	**Country and reference section**
A series of circle-top humps on a main road	1 – 4 dB	A social survey showed increased annoyance near the humps	Denmark Section 4.2
Round-top/circle-top humps	1 - 3 dB	Measured on a test track	Great Britain Section 5.1.1
Flat-top humps	6 – 8 dB increase	Measured on a test track	Great Britain Section 5.1.1
Narrow speed cushions which are humps with gab for heavy vehicles to pass without vertical deflection of the wheels	0 – 2 dB increase	Measured on a test track	GreatBritain Section 5.1.1

Rumble areas of different kinds are sometimes used as pre-warnings before roads with speed reduction or they are used directly as speed reducers. In Table 8.4 the experiences with this kind of traffic management is summarised:

- It can be seen that rumble areas normally lead to an increased noise level.
- British tests of a sine wave shape type indicate that there is a potential to develop rumble areas that do not produce significant additional noise in the surroundings but only inside the vehicles.
- In a survey it is suggested to ad 5 dB to the measured equivalent noise level in order to compensate for the increased annoyance because of an impulse character of the noise.

Table 8.4 List of effect of rumble areas and special pavements.

Measures used	**Effect on noise (L_{Aeq})**	**Remarks**	**Country and reference section**
Rumble areas with thermoplastic strips or cut down stripes across the road	2 – 4 dB increase	Suggestion of plus 5 dB for impulse noise	Denmark Section 4.3
Rumble areas with paving stones	2 dB increase	Suggestion of plus 5 dB for impulse noise	Denmark Section 4.3
Rumble strips along the roadside made of thermoplastic	0 – 10 dB for the maximum level ($L_{Apeak,max}$)	Suggestion of plus 5 dB for impulse noise	Denmark Section 4.5
Raised levels with paving stones	3 dB increase	A social survey showed increase annoyance	Norway Section 4.10
Rumble wave devices	0 dB	Raises noise inside vehicles	Great Britain Section 5.2

Table 8.5 shows a list of other more special measures that can also have an effect on noise. There is a need to develop and investigate these measures further in order to optimise their use for noise reduction.

Table 8.5 List of effect of other special measures.

Measures used	Effect on noise reduction (L_{Aeq})	Remarks	Country and reference section
Automatic speed limits when noise is to high combined with signs about noise annoyance to neighbours	Up to 6 dB	On-line noise measurements near houses determines speed limits and warning signs	Austria Section 6.2.1
Speed limit on motorway combined with signs about noise reduction	1 – 4 dB	Depends very much on the police enforcement of the reduced speed limit	Germany Section 7.2
Night time restrictions on heavy vehicles	Up to 7 dB at night time	Ban on heavy vehicles from 22 to 05. Might increase noise in the morning period from 5 to 9	Austria Section 6.3.1
Green waves	No measurements Potential for noise reduction	There is a potential for speed reductions and even driving pattern	France Section 7.3

8.2 Catalogue of traffic management

Table 8.6 Catalogue of various traffic management measures and their effect on traffic noise.

Traffic management measure	Potential effect on noise reduction (L_{Aeq})	Remarks
Traffic calming / Environmentally adapted through roads	1 – 4 dB	Combination of speed reduction measures on road sections
30 km/h zone	0 – 2 dB	For roads where only speed signs were used as a measure to enforce slow driving
Roundabouts	2 - 4 dB	Complains about noise from body-rattle, braking and accelerating have been observed
Circle-top road humps	1 – 4 dB	Increased annoyance has been observed
Flat-top humps	6 – 8 dB increase	
Narrow speed cushions	0 – 2 dB increase	
Night time restrictions on heavy vehicles	Up to 7 dB at night time	Increased noise in the morning period
Speed limits combined with signs about noise disturbance	1 – 4 dB	
Rumble strips of thermoplastic	2 – 4 dB noise increase	Suggestion of plus 5 dB for impulse noise
Rumble areas of paving stones	2 - 3 dB noise increase	Suggestion of plus 5 dB for impulse noise
Rumble wave devices	0 dB	Raises noise inside vehicles

In table 8.6 the effect of different traffic management measures is summarised as a kind of general conclusion based on the retrieved surveys of the different measures (see Table 8.1 to 8.5). The effect of the different measures depends very much of the precise design and implementation of the measures as well as on how they are accepted by the drivers. Generally it can be concluded that noise reductions of up to 4 dB can normally be achieved but in special situations even higher reductions may be reached. Some speed reducing measures have the opposite effect as they cause an increase of noise.

Even though some social surveys have been conducted in relation to traffic management there is a need for more and detailed knowledge about the perception of noise. In some surveys the annoyance is decreased and in other it is increased.

9. Conclusions and recommendations

This chapter summarises the conclusions from the literature survey on noise effects of traffic management, and some final recommendations will be outlined. This will be followed by a short evaluation of using a combination of noise reducing pavements and traffic management in order to reduce noise. Needs for new research will also be highlighted.

9.1 Traffic management

The goal of traffic management schemes is normally to improve traffic safety for people in the vehicles as well as for the pedestrians and cyclists travelling along a road. At the same time it is a goal to achieve a general improvement of the environment around a road in order to increase the quality of life for people living and working in the neighbourhood of a road. This is done by reducing noise, improving the visual quality of the environment, etc.

There are some general relations between noise levels and traffic volume, the percentage of heavy vehicles as well as the speed. These relations can be seen in Table 9.1 to 9.3 for situations with constant speed.

Table 9.1 Noise reduction caused by a 10 km/h reduction in speed (driving with constant speed) based on new Nordic emission data (se Chapter 2).

Change in speed	Noise reduction light vehicles	Noise reduction heavy vehicles
From 60 to 50 km/h	2.1 dB	1.7 dB
From 50 to 40 km/h	2.7 dB	2.1 dB
From 40 to 30 km/h	3.7 dB	2.7 dB

From Table 9.1 it can be seen that a speed reduction of 10 km/h for light vehicles reduces the noise by up to 2 to 4 dB depending on the starting point. For heavy vehicles the reduction potential is 2 to 3 dB. For speed reductions of 10 km/h in the speed range from 110 to 60 km/h the noise reduction will be about 1 to 2 dB for roads with 10 % heavy vehicles.

Table 9.2 Noise reductions caused by reductions in the traffic volume (se Chapter 2).

Reduction in traffic volume	Reduction in noise
10 %	0.5 dB
20 %	1.0 dB
30 %	1.6 dB
40 %	2.2 dB
50 %	3.0 dB
75 %	6.0 dB

In some cases traffic management is used to reduce the amount of traffic on a road and/or to reduce the percentage of heavy vehicles. From Table 9.2 it can be seen that a 10 % reduction of traffic only leads to a 0.5 dB noise decrease, whereas a 50 % reduction decreases noise by 3 dB. On a road with 10 % heavy vehicles the noise will be reduced by 1 to 2 dB if all the heavy vehicles are removed (see Table 9.3).

Table 9.3 Noise reductions caused by reductions in the percentage of heavy traffic based on the Nordic prediction method (se Chapter 2) .

Reduction in percentage of heavy vehicles	50 km/h	80 km/h
From 5 to 0 %	0.7 dB	1.0 dB
From 10 to 0 %	1.4 dB	1.9 dB
From 15 to 0 %	2.0 dB	2.6 dB

The driving pattern also has an influence on noise levels, although uneven driving patterns usually do not dominate under normal driving conditions. The effect of uneven driving patterns can be seen in Table 9.4. At moderate accelerations the noise can increase by around 2 dB where such accelerations occur (which may be on rather limited locations) depending on the mix of vehicles. This is a little less than the reduction achieved by a speed reduction of 10 km/h. It is therefore important to design speed reduction measures in such a way as to avoid accelerations and decelerations as much as possible and to ensure that the accelerations do not occur at or near the position of dwellings or other noise-sensitive areas.

Table 9.4 The influence on noise emission of uneven driving pattern (acceleration/deceleration). The noise influence is presented in relation to a reference case of constant speed of 50 km/h based on the Harmonoise Model (see Chapter 3).

Acceleration/deceleration	Vehicle type	Noise influence	Note
1 m/s^2	Light	1.7 dB	Moderate acceleration
2 m/s^2	Light	4.5 dB	High acceleration
0.5 m/s^2	Heavy	+ 2.1dB	Moderate acceleration
1 m/s^2	Heavy	+ 4.5 dB	High acceleration
- 1 m/s^2	Light	- 0.8 dB	Slow deceleration
- 2 m/s^2	Light	- 1.17 dB	High deceleration
- 1.5 m/s^2	Heavy, 2 axles	- 4.5 dB	Moderate deceleration

In table 9.5 the effect of various traffic management measures is summarised as a general conclusion based on the retrieved surveys of the different measures. The effect on noise is based on estimates of up to approximately 10% of heavy vehicles. The effect of the different measures depend very much of the precise design and implementation of the measures as well as on how they are accepted by the drivers. Generally it can be concluded that reductions in average noise levels, L_{Aeq}, up to 4 dB can normally be achieved but in special situations even higher reductions may be reached. But some speed reducing measures might increase noise like rumble areas and paving stones.

Vertical deflections such as humps and cushions can reduce the average levels due to significant speed reductions but the maximum levels can increase due to body rattle noise produced as some vehicles (especially empty container lorries) negotiate the deflection. The actual reduction in the average level will depend critically on the percentage of heavy vehicles in the traffic stream.

Table 9.5 Catalogue of various traffic management measures and their effect on traffic noise.

Traffic management measure	**Potential noise reduction (L_{Aeq})**
Traffic calming / Environmentally adapted through roads	Up to 4 dB
30 km/h zone	Up to 2 dB
Roundabouts	Up to 4 dB
Round-top/circle-top road humps	Up to 2 dB
Flat-top humps	Up to 6 dB increase
Narrow speed cushions	Up to 1 dB increase
Night time restrictions on heavy vehicles	Up to 7 dB at night time
Speed limits combined with signs about noise disturbance	1 – 4 dB
Rumble strips of thermoplastic	Up to 4 dB noise increase
Rumble areas of paving stones	Up to 3 dB noise increase
Rumble wave devices	0 dB

The following general conclusions and recommendations in relation to noise can be drawn:

1. Speed reductions reduce noise.
2. However the noise from some heavy vehicles can in some cases increase due to increased gear shifting and body rattle noises.
3. In order to achieve a reduced speed it is normally not enough just to install speed limit signs. It is also necessary to redesign and rebuild the road so that the physical layout matches the intended speed.
4. Visual speed reducers are often effective in reducing noise.
5. It is important to achieve as smooth a driving pattern as possible.
6. It is important to minimise uneven driving patterns. This can be done by having appropriate distances between speed reducers.
7. It is important to achieve driving patterns where the vehicles are not brought to a complete stop as this generates more noise from decelerations and accelerations.
8. Speed reducers which displace the vehicles to the left or to the right are often effective in reducing noise especially in the case of heavy vehicles.
9. Speed reducers which change the vertical height of parts of a road (like some types of road humps) can in some cases be problematic in relation to noise, especially for heavy vehicles, where body rattle noises can produce large peaks in noise levels as these vehicles cross the vertical deflections.
10. The use of rumble areas, for example with paving stones, increases noise.

11. There are reports of cases with increased perceived annoyance even though the average noise level has decreased.
12. There are reports on increases in the perceived noise annoyance because of impulse-like noise, rattling in the bodywork or cargo of heavy vehicles, as well as short-time changes in the sound level and frequency caused by gear shifting or changing in engine revolutions due to acceleration or braking of a vehicle.
13. Speed reducers, which change the vertical height of parts of a road, may produce perceptible levels of vibrations in nearby houses. This depends on the type of ground condition and distance from the vertical deflection to the nearest house foundations. Serious annoyance has been reported especially where houses are close to road humps built on soft ground such as peat soils and alluvium deposits.
14. Speed reductions generally have a good effect on traffic safety.

These are the general conclusions. In the literature study a few exceptions with well functioning cases are found that do not follow these conclusions. For example the Austrian “Multifunctional noise protection facility” where dynamic speed limit signs make the drivers reduce speed and by doing so the noise is reduced too (see Section 6.2.1).

In a Danish report (see Chapter 4) it has been suggested that 5 dB should be added as a “penalty” to the actual noise level if impulsive noise or similar is occurring (for example where rumble areas/strips or paving stones are used) to compensate for the increased perceived annoyance. Such an addition to the actual noise level is known from the Danish administration of external noise from industry. It must generally be concluded that more research is needed to investigate and quantify the effect of impulsive noise from road traffic, especially in relation to certain types of speed reducers.

A general recommendation could be, on the background of the existing knowledge, to place speed reducers which change the vertical height of parts of a road at a distance as long as possible from houses and dwellings where people are living.

9.2 Combination of traffic management and noise reducing pavements

It is obvious that it can be a good idea to combine traffic management measures and the use of noise reducing pavements in noise abatement schemes. Generally there does not seem to be any technical arguments for not combining these measures of noise abatement. However, it must be noted that porous pavements can be damaged on bends, junctions and roundabouts sites where forces at the tyre/road interface are relatively high. This must be taken into consideration when applying porous pavements on roads specially constructed to reduce speed. Speed reducers which displace the vehicles to the left or right may be problematic for the durability of porous pavements, because this will make the vehicles drive in curves for short distances. But other types of noise reducing pavements can be used in such cases.

In other parts of the SILVIA project the noise reducing effect of different pavement types are documented. On urban roads with speeds in the range from 40 to 60 km/h noise reductions of 1 to 4 dB can be achieved by using for example noise reducing thin layers or porous pavements. At higher speeds the noise reducing potential for these pavements may be up to 6 dB or even more. This noise reduction is of the same magnitude as or higher than the reduction which can normally be achieved by traffic management measures.

Noise reducing pavements and traffic management measures may influence the frequency distribution of road traffic noise in different ways, and this can have an influence on the total noise reduction. For simplification it can anyway be recommended to add (on a dB basis) the effect of the two types of noise reduction. It is therefore generally on urban roads possible to obtain noise reductions of 3 to 8 dB by combining the use of noise reducing pavements and traffic management measures. On highways with high speeds the potential for noise reduction may be up to 10 dB or even more. In [9.1] the effect of combining these measures is analysed in detail on an average arterial road in an urban area.

Generally noise reducing pavements has a better reduction effect on noise from light vehicles than on noise from heavy vehicles. This means that if a traffic management measure such as an environmentally adopted street or a 30 km/h zone has an effect on reducing the percentage of heavy vehicles the beneficial effects of the noise reducing pavements will be increased.

9.3 Research needs

The literature has shown that noise reductions due to introduction of traffic management schemes can result in both positive and negative responses from the inhabitants. In some cases social surveys have shown a significantly reduced perceived annoyance and in other cases the perceived annoyance has increased even though the measured average noise levels have decreased. As the main goal of noise abatement is to improve the life quality for people there is a need for further research in this field. Research themes could be:

- The effect of different designs of road humps and cushions on the perceived annoyance.
- The effect of different types of rumble areas and strips on the perceived annoyance.
- Development and optimization of traffic management schemes in order to reduce the perceived annoyance as much as possible.
- Investigation and quantification of the effect on the perceived annoyance of impulsive noise from road traffic, especially in relation to certain types of speed reducers like humps and rumble areas.
- The effect on the perceived annoyance when combining traffic management and noise reducing pavements in order to reduce noise.

Very few references have been retrieved where the use of advanced information technology and automatic traffic steering and management has been developed and investigated. Therefore there is also a need to focus on this field in research and development projects. In this research it will also be relevant to focus on projects where noise reducing pavements are included. There is a need to develop methods to build vehicle sensors into the surface of porous pavements without damaging the capacity of the porous pavement to lead rain water to the roadside.

There is also a need to further develop and test speed reducers such as rumblewave devices which can generate noise inside the vehicles but at the same time do not have any negative effect on the noise along the roads.

9.4 References for chapter 9

[9.1] Haberl, Jürgen; Bendtsen, Hans. Influence of different noise reducing measures – model of an average city," Report of the EU-project SILVIA (Sustainable Road Surfaces for Traffic Noise Control), GROWTH Project GRD2-2000-31801, Brussels, 2004.

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134	Noise emission from 4000 vehicle pass-bys - an Inter-Noise 2004 presentation www.vejdirektoratet.dk/publikationer/VIrap134/index.htm	Bent Andersen Hans Bendtsen
135	Thin open layers as noise reducing pavements - an Inter-Noise 2004 presentation www.vejdirektoratet.dk/publikationer/VIrap135/index.htm	Hans Bendtsen Bent Andersen
136	European co-operation in COST 347 - Bringing ALT activities closer together www.vejdirektoratet.dk/publikationer/VIrap136/index.htm	Gregers Hildebrand Michael E. Nunn
137	Traffic management and noise reducing pavements - Recommendations on additional noise reducing measures www.vejdirektoratet.dk/publikationer/VIrap137/index.htm	Hans Bendtsen Jürgen Haberl, Johan Litzka Ernst Pucher Ulf Sandberg Greg Watts

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