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QUESTIM

Procedures for monitoring acoustic quality of large infrastructures

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QUietness and Economics STimulate Infrastructure Management

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CEDR Call2012: Noise: Integrating strategic noise management into the operation and maintenance of national road networks

QUESTIM: QUietness and Economics STimulate Infrastructure Management

Procedures for monitoring acoustic quality of large infrastructures

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Executive summary

The objective of QUESTIM work package 3 is to define and to develop a procedure for deriving categorical data from CPX measuring data for the use in a pavement management system and to provide a procedure for linking that data to geographic and land-use planning information in order to assess the meaningfulness of the acoustic state of the road surface with regard to noise protection issues.
Road traffic noise is the most important polluter in industrialised countries. Currently, tyre/road noise is the most important noise source of road traffic noise. Tyre/road noise is profoundly influenced by structural properties of the road surface. The acoustical condition of a road pavement should be made part of the road condition registration and evaluation system and the pavement management system (PMS). Therefore, a new attribute *noise* is defined. It can be implemented into a PMS directly by measuring the acoustic condition of the road surface or indirectly by calculating it with a model using the main properties surface texture, flow resistivity and sound absorption. This work focuses on the aspects of a direct implementation. The close proximity method (CPX) is chosen as the suitable measuring method which is the outcome of a comparison of established acoustic measuring methods and their limitations, pros and cons.
In order to be able to rank or rate the acoustical condition of a road CPX reference values are derived from gathered data for different road surface types. These define a neutral category of CPX levels that can be expected from a certain surface type.

For pavement management purposes of large road networks raw CPX-data is too detailed regarding noise impact and should be aggregated for easier handling. Additionally to the categorization of levels, the length of continuous “noise segments” should not be interrupted by negligible fluctuations. The derived aggregation method is the median function of the levels of five consecutive 100 m CPX segments and subsequent rounding to 0.5 dB. Optionally, the aggregation of CPX data can be completed by using the distance between a road segment and the nearest receiver to determine so called Relevant Noise Segments (RNS) for each single CPX value. A concept for the derivation of RNS is introduced. This add-on procedure helps to align the length of aggregated CPX segments with the distance to sensitive housings next to the road.

The relevance of the noise caused by the traffic on a particular road section depends on the existence and the distance of sensitive housings next to the road deserving noise protection. Noise protection is the result of planning and building permission processes which at the end stipulate the levels, technical and administrative measures that are mandatory to comply with legal noise protection requirements. The technical measures may include the road pavement and may tie it to a required minimum noise reduction level. This required level is linked to the acoustical performance of particular road surface types which finally can be related to a required minimum CPX-level the measured CPX levels have to be compared with. The level difference between the CPX reference value for a particular type of road surface and the CPX reference value for the standard road pavement is called Zero Rating Niveau ZNR. The ZNR is something like an offset and moves the zero point of the acoustical rating scale upward and downward.

Due to safety concerns and also expenditure road administrations are reluctant to accept CPX measurements done on passing lanes. It is discussed if the acoustic rating of a road section can be done in a reasonable way with just the data of the right lanes. When the surfaces of single lanes are renewed individually an aging model can be used in order to track the acoustical deterioration for separate lanes. The aging effect of low noise road surfaces is investigated, quantified and modelled in WP2.

1 Introduction

The objective of the QUESTIM project is to develop a scheme in which the performance of low noise road surfaces can be integrated in the general procedures of managing the pavement quality. Therefore it is necessary to have the following know-how and instruments available:

1. an understanding the development of performance over time of these surfaces
2. a prediction model for future behaviour based on generally available input parameters
3. a method to evaluate the performance of existing surfaces
4. an understanding of the life cycle costs of noise mitigation measures and the benefits expected when applying them
5. an understanding of present day Pavement Management Systems.

The objective of QUESTIM work package 3 is to define and to develop a procedure for deriving categorical data from CPX measuring data for the use in a pavement management system and to provide a procedure for linking these data to geographic and land-use planning information in order to assess the meaningfulness of the acoustic state of the road surface with regard to noise protection issues.

1.1 Definition of the Problem

Road traffic noise is the major pollution in industrialised countries. Currently, tyre/road noise is the most important noise source of road traffic noise. Tyre/road noise is profoundly influenced by structural properties of the road surface. Therefore, the overall effectiveness of noise control measures strongly depends on the acoustical condition of the road. Noise levels at receiver points next to the road increase with acoustical degradation of the road surface irrespective of the existence and the effect of secondary noise measures like noise barriers or the tightening of acoustical type approval limit values for road vehicles. For this reason, the acoustical condition of a road pavement should be made part of the road condition registration and evaluation system and the pavement management system (PMS). It is almost as important as skid resistance, transverse and longitudinal evenness and the structural integrity of a road pavement.

There are two options to implement the acoustical condition in the PMS:

- Indirect implementation of noise as a new attribute
  The sound emission of the tyre/road interaction depends on specific properties of the road surface. The main properties are surface texture, flow resistivity and sound absorption. These properties are directly influenced by pavement engineering properties, age, traffic load, etc. and would therefore fit very well in the system of pavement management. However, taking these properties as attributes for the PMS would cause the need for development of improved or even new measuring techniques and a sophisticated model which helps to rate the measurement results with respect to tyre/road noise. An example for such a model is SPERoN [1,2,3], which

[1] www.speron.net
[2] Beckenbauer, T., Klein, P., Hamet, J.-F., Kropp, W.: „Tyre/road noise prediction: A comparison between the SPERoN and HyRoNE models – Part 1", Proc. Acoustics'08 conference, Paris, 2008
[3] Kuijpers A., Peeters B., Kropp W., Beckenbauer T. (2007), "Acoustic Optimization Tool RE4 – Modelling refinements in the SPERoN framework", Rep. M+P, http://www.innovatieprogrammageluid.nl.

uses surface properties to calculate the acoustic performance. It is fed with measured 3d texture data, void induced airflow resistivity and sound absorption coefficient. The pass-by-level-spectrum can then be calculated based on these surface related characteristics, velocity and tyre data.

- Direct implementation of noise as a new attribute
  This approach provides for the direct measurement of road traffic noise, single vehicle noise or tyre/road noise. However, tyre/road noise does only predominate the total vehicle noise of passenger cars. Road traffic noise and single vehicle noise is influenced by the propulsion noise as well in case of heavy duty vehicles being involved in the noise measurement scenario. Therefore, the measuring method has to be chosen carefully (see chapter 2).

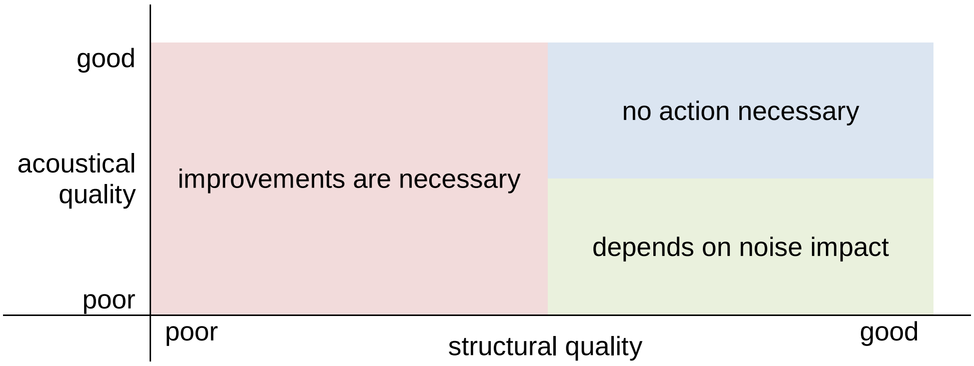


Figure 1: Need of improvements depends on acoustical and structural quality (evenness, structural integrity, skid resistance) and noise impact.

The need of a road surface improvement measure cannot solely be based on parameters that characterize their acoustic quality unlike the ones for the structural quality. As depicted in Figure 1 measures for the improvement of a road pavement become necessary as soon as structural properties such as grip, evenness (length- and crosswise), exceed a certain limit, which is required to keep the road condition safe. Such a limit cannot be appointed to the acoustic surface quality because that characteristic value would not solely determine if the protective goals are reached. The reason for that being is that noise protection does not depend on the road user's requirements but on the requirements that are related to land-use in the surrounding of the road. In case of acoustic surface quality the attribute characterizing noise and the required limit do not refer to the same parameter. Moreover, the required noise levels are not consistent along the roadway. They depend on land-use and population density.

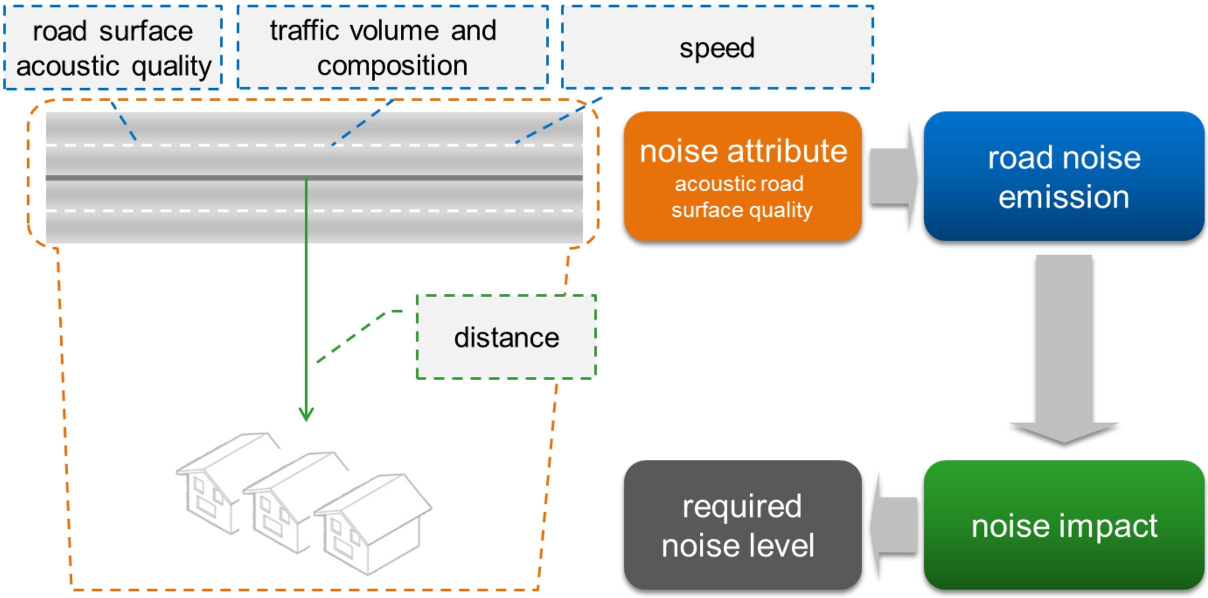


Figure 2: Schematic depiction of interdependent attributes.

The acoustic road surface parameters give information about the physical property and condition of a surface regarding the potential noise emission. In combination with traffic volume, traffic composition, speed and local road traffic conditions the noise emission of a road can be derived. The relation between interdependent attributes and the noise impact is depicted in Figure 2.

However, the acoustic quality of a road surface is just one parameter which determines the relationship between noise emission and noise impact on the one hand and between noise impact and measures needed to meet the noise protection requirements on the other hand. But in terms of pavement management attributes there are no more than this single parameter needed. The stack panel shown in Figure 3 clarifies this issue.

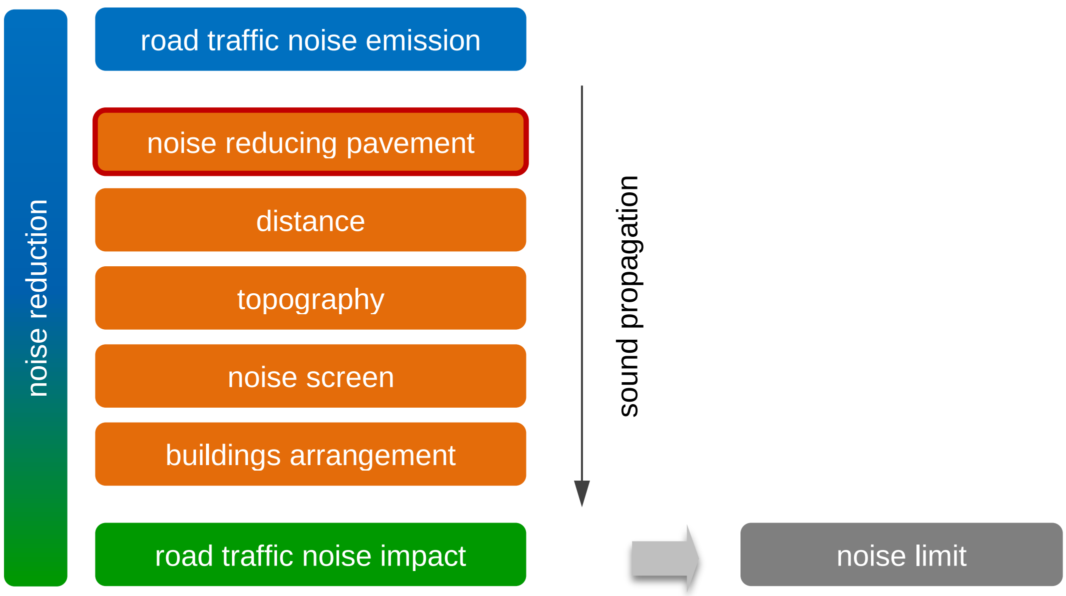


Figure 3: Contributing parameters concerning the reduction of the road noise impact

It is important to recognize that the problem of linking the road noise emission to the noise impact can be reduced to the noise reduction provided by the pavement. The road surface is one contributor within a set of contributors. Each contributor is characterized by a certain noise reduction value. The overall noise reduction is just the sum of the contributor's particular noise reduction values. The noise level effects of the different measures are determined by means of sound propagation calculations. Once a noise protection scheme has been prepared the contributions of the particular measures to the overall noise reduction are certain, including that of the road pavement. In the framework of land-use planning and building processes the required noise reduction value of the road surface is stipulated in the permission in many cases. However, in contrast to the contributions of distance, topography, noise screens and the building arrangement the contribution of the acoustic quality of the road pavement to the overall noise reduction value does change with time. But in terms of pavement management this means that there is no need to repeat the sound propagation calculations each time the acoustic quality of the pavement is surveyed. Any changes of the noise reduction value of the road surface affect the road traffic noise emission value only. Within certain limits the noise impact level changes correspondingly. Spectral shifts due to changes of the road surface can also change the propagation. Such spectral aspects could be taken into account after an introductory phase of the PMS procedure.

1.2 Definition of the Attribute

The new road condition attribute is called *noise excitation*. Actually, *tyre/road noise* is meant. It is based on the ability of the road surface to excite vibrations on a rolling tyre and to influence aerodynamic effects within and the sound radiation from the tyre/road contact, depending on the roads surface’s texture and the road surface’s structural properties.

Following this definition the new attribute is considered a derived attribute, not a basic one in terms of a road condition evaluation system. This is because it needs the interaction with the tyre in order to become effective.

In principle, the values for this attribute are related to the usage of the road, rather than to its substance. However, differing from other usage-related characteristics like unevenness, rut depth, virtual water depth and skid resistance, noise is a functional characteristic of the road that is not or hardly relevant for the road user. It is relevant for people who are living in the vicinity of the road and who are not participating in the road traffic. For this reason, implementing noise in the pavement management system yields a new dimension concerning the registration and evaluation of road conditions.

2 Identification of an appropriate measuring method

An adequate measuring method should meet the following requirements:

- a direct implementation of noise as an attribute of the road pavement should be preferred
- a direct implementation leads to direct measurement of noise
- the noise measuring method should be target oriented in such a way that a continuous monitoring of entire road sections is possible with manageable effort
- it should be easily able to trace differences in measured noise levels back to differences in road surface conditions
- measurement method, boundary conditions and hardware as well as the evaluation of raw data should be definable and have to be traceable back to measurement standards.

2.1 Overview of candidate methods

In Table 1 suitable methods for the direct measurement of road noise, their advantages and disadvantages with respect to an acoustic road condition monitoring are summarized.

Table 1: Methods for the direct measurement of noise that is influenced by road surface characteristics.

SPB	**Statistical Pass-By**
Standard	ISO 11819-1
Description	Stationary measurement of the pass-by noise of single vehicles that are part of the traffic on the road section under investigation.
Advantages	Easily to perform with low technical effort. Both the noise of light and heavy duty vehicles can be measured. Trends in technical progress are involved in the measurement results. The determination of standard noise emission values for different road surfaces is based on this measurement method in many European countries. Well standardized method. Existing broad assessment background.
Disadvantages	Tyre/road noise is just a portion of the measured noise, especially for heavy duty vehicles. Boundary conditions hardly manageable. In order to achieve representative results a lot of vehicles have to be measured. Therefore, on roads with heavy traffic the measurements can be time consuming. Just one single point on the road and one driving lane is covered by a measurement. The monitoring of entire road sections increases the effort tremendously. Reference pavements are needed to calibrate the measurements.
CPB	**Controlled Pass-By**
Standard	–
Description	Stationary measurement of the pass-by or coast-by noise of specific vehicles

	with specified tyres.
Advantages	Easily to perform with low technical effort. Both the noise of light and heavy duty vehicles can be measured. Measurements are able to be referred to well-defined vehicles and tyres.
Disadvantages	Tyre/road noise can be made the dominant sound source if the vehicles pass with engine off (coast-by). Problems on public roads could arise. The problem of long term availability of specified tyres is not yet solved. Just one single point on the road and one driving lane is covered by a measurement. The monitoring of entire road sections increases the effort tremendously. Periodic calibration by means of comparisons with current vehicles and tyres is required. No international standard. No assessment background.
CPX **OBSI**	**Close Proximity** **On-board sound intensity**
Standard	ISO/DIS 11819-2 in connection with ISO (Draft) 11819-3
Description	Continuous measurement of the tyre/road noise in close proximity to a rolling tyre.
Advantages	Direct measurement of pure tyre/road noise. Well defined and well manageable measuring environment. Measurements can be performed continuously along an entire road section and on every lane. Thus, measurements are covering the entire road. Due to the use of standardized tyres differences in measurement results are directly related to differences in road surface characteristics. Well but not officially standardized method.
Disadvantages	Needs a special and complex measurement setup. The problem of poor reproducibility and long term availability of specified tyres is not yet solved. Periodic calibration by means of comparisons with current vehicles and tyres is required. No systematic assessment background.
Noise immission	
Standard	German Standard DIN 45642
Description	Measurement of the noise of the road traffic at long distances to the road.
Advantages	Easily to perform with moderate technical effort. Results represent the impact of road traffic noise at the receiver’s location and are thus related closely to the environmental noise control problem.
Disadvantages	Tyre/road noise is just a portion of the measured noise, especially for heavy duty vehicles. Measurements are affected severely by environmental conditions. No international standard. No broad and systematic assessment background.

The CPX method is the method that fits best to the requirements described above.

With respect to the noise impact the CPX method has the limitation of capturing only the noise of the tyre/road interaction, but not of the propulsion and aerodynamic sound sources. Disregarding the propulsion noise by the CPX measurement does not mean that it is disregarded in connection with the categorical rating value of a road section. It is indirectly accounted for by applying a zero rating niveau ZRN, see chapter 4. The ZRN is related to the overall noise reduction value that is stipulated in legal planning and permission procedures.

2.2 CPX method

In the CPX method, the average A-weighted SPLs emitted by specified tyres are measured over an arbitrary or a specified road distance, together with the vehicle testing speed, by at least two microphones per wheel track, located close to the tyres. For this purpose, a special test vehicle, which is either self-powered or towed behind another vehicle, is used. Reference tyres are mounted on the test vehicle, either one by one, or both at the same time. Two tyre types have been selected as reference testing tyres in order to represent the different tyre characteristics regarding their use for passenger cars (P) or heavy vehicles (H). The tests are performed with the intention of determining a tyre/road sound pressure level, here referred to as the CPX level, L_{CPX}, at a reference speed (mostly 50 km/h or 80 km/h). For each reference tyre the sound pressure level together with the corresponding vehicle speed are continuously recorded. The sound pressure level is determined for 20 m segments and normalized to a reference speed and temperature. Averaging is then carried out according to the purpose of the measurement (measuring a particular segment or a number of consecutive segments – a section). The results are two CPX indices: $CPXP_{vref}$ for tyre type P, $CPXH_{vref}$ for H that can be averaged to obtain a $CPXI_{vref}$ as a standard CPX-based index for single-value comparison of the acoustic performance of road surfaces. Measuring equipment and measurements are based on ISO 11819-2 standard.

Figure 4: Fig. 21 Example of a CPX system with two test tyres and enclosure (source Müller-BBM).

2.3 Uncertainty analysis of CPX results

The CPX measurement procedure is affected by several influencing factors that lead to variation in the results observed for the same subject. The source and nature of these perturbations are not completely known. The measurement uncertainty is determined in compliance with ISO/IEC Guide 98 3. Identified sources of uncertainty are those due to operational variations, instrumentation and external disturbances. Therefore the calculation of the overall uncertainty considers a total of six input quantities which allow for any uncertainty regarding:

		closed trailer	open trailer
u_1	Variations in the measurement procedure	0.2 dB	0.2 dB
u_2	Measurement equipment	0.3 dB	0.3 dB
u_3	Deviation environmental conditions	0.3 dB	0.3 dB
u_4	Background noise from external sources	0.1 dB	0.2 dB
u_5	Unwanted contributions from test and towing vehicle	0.2 dB	0.1 dB
u_6	Reference tyre	1.0 dB	1.0 dB

The values u_i of these input quantities are evaluated by the measuring engineer and the procedure given in ISO/IEC Guide 98 3. It can be based on existing statistical data, analysis of tolerances stated in the CPX standard ISO 11819-2 and the engineer's assessment.

The combined standard uncertainty is then calculated: $u = \sqrt{\sum_i u_i^2}$

Using typical values for the standard uncertainties for each source the uncertainty analysis results in a combined standard uncertainty in the CPX level of 1.1 dB.

The expanded uncertainty *U* is an additional measure of the uncertainty that defines an interval about the measurement result that may be expected to encompass a large fraction of the distribution. It is determined by multiplying the combined standard uncertainty *u* with an appropriate coverage factor *k* for a chosen coverage probability *p* as described in ISO/IEC Guide 98 3. Effectively the expanded uncertainty of the CPX level is 1.3 dB for a coverage probability of 80% and 2.2 dB for 95%.

As can been seen by the typical values for the standard uncertainties the combined standard uncertainty is dominated by the uncertainty caused by the reference tyres. In order to improve the accuracy of CPX measurements a strict quality control of the tyres with the following measures is necessary:

- Thorough incoming inspection
- Measurement of the dynamic properties i.e. point mobility (mechanical impedance)
- Cool (<7°C) and dark storage to slow down hardening of the rubber
- Frequent condition monitoring, especially during measuring season

2.4 Acoustic Road Condition Registration and Evaluation by Means of the CPX Method

The tyre/road noise of two different tyres (type P and type H) driven at constant speed (80 km/h on motorways and 50 km/h on urban roads) is recorded continuously along a particular lane. Corresponding to the procedure described in ISO 11819-2 and the practice for the continuous registration of usage-related road characteristics the sound pressure level is averaged a long road sections with a length of 20 m. The shortest section length in management systems for entire road networks usually is 100 m. The standard takes this in the informative annex G into account and suggests the acoustic signal should be averaged over 100 m long "composite segments" derived by averaging five 20 m segments.

2.5 CPX Reference Values

To specify the acoustic quality of a road CPX reference values for the rolling noise for both tyre types and at two different speeds (50 km/h and 80 km/h) are derived from CPX data gathered for standard road surfaces in Germany, the Netherlands and in Switzerland.

Table 2: Summary of the evaluated road sections grouped by surface type, arithmetic average of CPX-indexes and standard deviations in dB(A), standard surface types are marked with x.

country	*v*, km/h	surface type	Std.	number of samples	$\overline{CPX_P}$	$\overline{\Delta CPX_P}$	$\overline{CPX_H}$	$\overline{\Delta CPX_H}$
DE	50	LOA D 05		12	87.8	0.8	89.7	0.5
DE	50	DSH-V5	x	4	88.2	0.5	91.2	0.4
DE	50	SMA8 S LA		24	90.3	0.5	90.8	0.5
DE	80	DSH-V5	x	42	94.6	0.5	98.0	0.5
DE	80	PA8	x	7	94.9	0.7	96.2	0.8
DE	80	GA LA5	x	12	97.3	0.5	98.2	0.4
DE	80	MA11	x	2	98.0	0.5	98.2	0.4
DE	80	DSH-V8	x	5	98.3	0.3	99.0	0.4
DE	80	Waschbeton	x	8	98.4	0.5	98.4	0.4
CH	50	Nanosoft		8	83.9	0.9	86.7	0.8
CH	50	Rugosoft		2	84.1	0.7	86.8	0.4
CH	50	ACMR4	x	2	86.4	0.5	87.9	0.3
CH	50	SMA11	x	1	91.2	0.3	91.3	0.3
CH	50	ACMR11	x	1	91.3	0.8	90.7	1.4
CH	80	ACMR8+		4	93.5	0.6	95.9	0.6
CH	80	ACMR8	x	4	94.4	0.5	96.5	0.5
CH	80	PA8	x	5	94.7	0.9	96.2	0.8
CH	80	SMA11	x	1	97.5	0.5	98.4	0.4
NL	80	Micropave	(x)	5	90.5	0.5	94.6	0.4
NL	80	ZSA-SD	(x)	7	91.4	0.6	94.1	0.5
NL	80	Decipave	(x)	1	91.9	0.3	94.6	0.6
NL	80	Deciville	(x)	1	92.8	0.5	96.0	0.5
NL	80	Topfalt	(x)	4	92.0	0.5	93.3	0.4
NL	80	Redufalt	(x)	2	91.9	0.4	94.3	0.5
NL	80	KonwéCity	(x)	4	93.8	0.5	95.6	0.4
NL	80	KonwéStil	(x)	2	90.7	0.3	93.7	0.3
NL	80	SMA-NL 8G+	x	9	95.0	0.6	95.6	0.6
NL	80	SMA RD Pave	(x)	3	94.7	0.5	97.3	0.4
NL	80	Brugflex	(x)	2	94.7	0.3	95.0	0.4
NL	80	ZOAB	x	1	94.2	0.9	92.9	0.9
NL	80	ZOAB+	(x)	1	94.7	0.3	93.3	0.4
NL	80	ZOAB-Panacea	(x)	1	94.5	0.3	93.2	0.3
NL	80	ZOAB+ staalvezels	(x)	1	94.9	0.3	95.6	0.8
NL	80	ZOAB 16+	(x)	2	95.0	0.2	95.0	0.3
NL	80	LEAB-PA+	(x)	1	94.9	0.4	93.7	0.3
3	2	15 standard 32 total	15	191 total	30 combinations with standard surfaces, of a total of 35			

Table 3: Schematic of road pavement types.

<table>
<tr><th rowspan="2">Type of Pavement</th><th rowspan="2">Max. aggregate size</th><th rowspan="2">Void content</th><th colspan="3">National implementation</th></tr>
<tr><th>D</th><th>CH</th><th>NL</th></tr>
<tr><td colspan="6">Impervious asphalt pavement types</td></tr>
<tr><td>Asphalt Concrete</td><td></td><td>< 8 Vol.-%</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Stone Mastic Asphalt</td><td>4 mm</td><td>< 8 Vol.-%</td><td></td><td>ACMR 4</td><td></td></tr>
<tr><td>8 mm</td><td>< 8 Vol.-%</td><td></td><td>ACMR 8</td><td></td></tr>
<tr><td>11 mm</td><td>< 8 Vol.-%</td><td>SMA 11</td><td>ACMR 11
SMA 11</td><td></td></tr>
<tr><td rowspan="2">Mastic Asphalt</td><td>5 mm</td><td>< 8 Vol.-%</td><td>GA LA 5
the stone size refers to the surface dressing</td><td></td><td></td></tr>
<tr><td>11 mm</td><td>< 8 Vol.-%</td><td>MA 11</td><td></td><td></td></tr>
<tr><td rowspan="2">Thin Layer hot rolled</td><td>5 mm</td><td>< 8 Vol.-%</td><td>DSH-V5
LOA 5</td><td></td><td></td></tr>
<tr><td>8 mm</td><td>< 8 Vol.-%</td><td>DHS-V8</td><td></td><td></td></tr>
<tr><td colspan="6">Semi dense asphalt pavement types</td></tr>
<tr><td>Stone Mastic Asphalt</td><td>8 mm</td><td>10-16 Vol.-%</td><td>SMA 8 LA</td><td>ACMR 8+</td><td>SMA-NL 8G+
SMA RD Pave</td></tr>
<tr><td rowspan="3">Thin Layer semi dense</td><td>4 mm</td><td>10-16 Vol.-%</td><td></td><td>Nanosoft</td><td>Micropave</td></tr>
<tr><td>5 mm</td><td>10-16 Vol.-%</td><td></td><td></td><td>Deciville</td></tr>
<tr><td>6 mm</td><td>10-16 Vol.-%</td><td></td><td>Rugosoft</td><td>Decipave
ZSA-SD</td></tr>
<tr><td colspan="6">Porous asphalt pavement type</td></tr>
<tr><td>Porous Asphalt</td><td>8 mm</td><td>> 18 Vol.-%</td><td>PA 8</td><td>PA 8</td><td>ZOAB
ZOAB +
ZOAB-Panacea
ZOAB + staalvezels
LEAB-PA+</td></tr>
<tr><td colspan="6">Impervious cement concrete pavement type</td></tr>
<tr><td>Exposed Aggregate</td><td>8 mm</td><td>< 8 Vol.-%</td><td>Waschbeton</td><td></td><td></td></tr>
</table>

The summary in Table 2 gives an overview of a total of 191 road sections that were evaluated: up to 76 standard surfaces of the same built per country and speed. The data also consists of nonstandard surfaces for comparison and are marked with an x. The age of each surface when measured was 1 year ±2 months in Germany and Switzerland and in the Netherlands less than 1 year. The listed CPX-values are arithmetic averages of the CPX-indexes and arithmetic averages of their standard deviations for tyre type P and H for each combination of country, speed and surface type. The CPX-indexes themselves represent the average of an entire road section. Table 3 itemizes the different kinds of road pavements listed in Table 2. Though the abbreviations of the surface types differ amongst producer and country, there aren't as many physical differences. The number indicates the maximum aggregate stone size.

For each combination of country, speed and surface type the arithmetic mean and median average, the standard deviation and the maximum and minimum extreme values of the CPX index values were calculated. For the Netherlands the four ZOAB types were grouped and the SMA RD Pave was combined with the six SMA 8 sections.

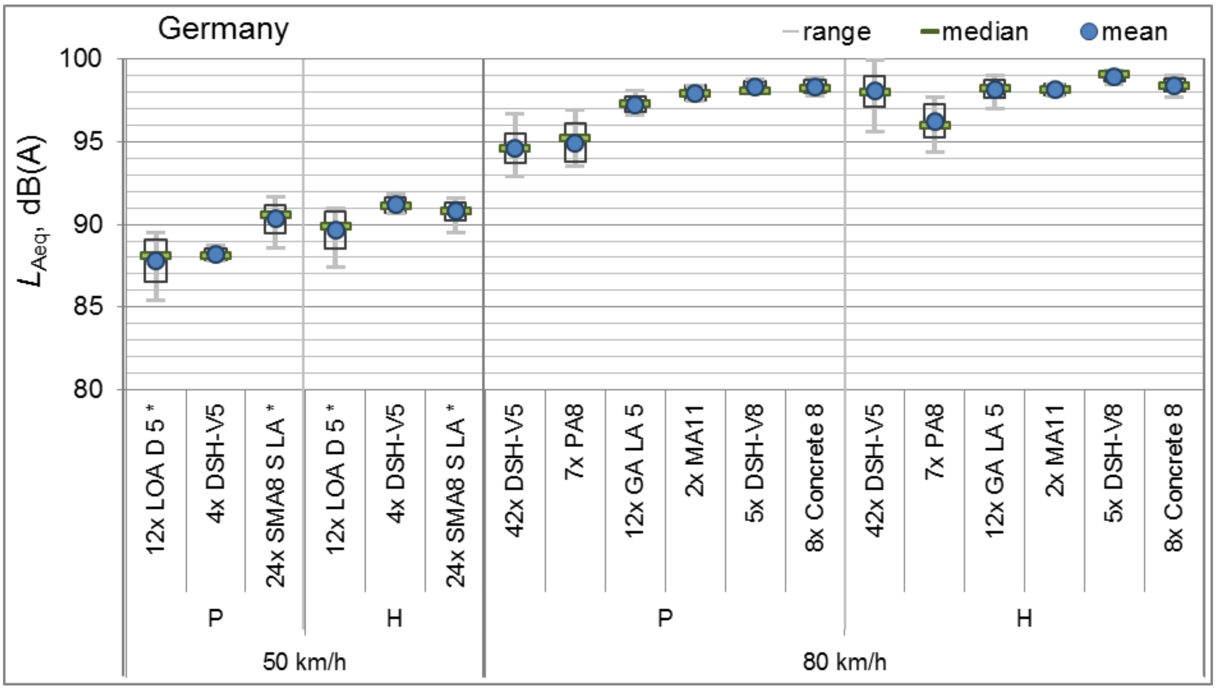


Figure 5: Average CPX levels in Germany, at 50 and 80 km/h for tyre type P and H (arithmetic mean and median). The mean standard deviations are represented by the black boxes. The range equals the difference of the extreme values (maximum minus minimum).

The amount and type of a surface, its average values, the standard deviation and the range as difference of the extreme values are plotted for each country in Figure 5 to Figure 7. The surfaces are sorted by speed and tyre type. The order of the surface is then oriented by the mean value of the P tyre, starting with the lowest. This way the surfaces are ranked by their acoustic performance with respect to the tyre type P. Differences to the H type tyre become apparent, for instance due to void content. (Note that the calculated attributes equal the mean value when the amount is one or almost when very few values are nearly the same.) Clearly the single values cannot be used solely to define a reference value, but they can be used to estimate the spread for similar types for instance regarding the maximum aggregate size (e. g. Micropave, Decipave and Deciville in the Netherlands).

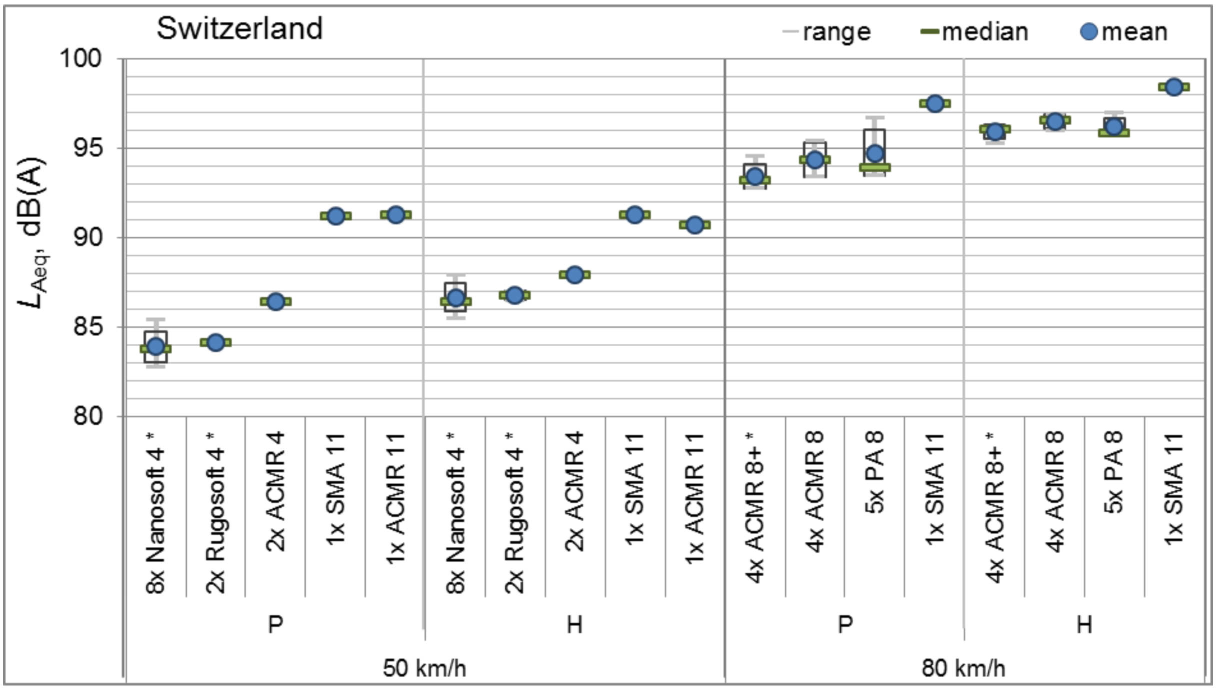


Figure 6: Average CPX levels in Switzerland, at 50 and 80 km/h for tyre type P and H (arithmetic mean and median). The mean standard deviations are represented by the black boxes. The range equals the difference of the extreme values (maximum minus minimum).

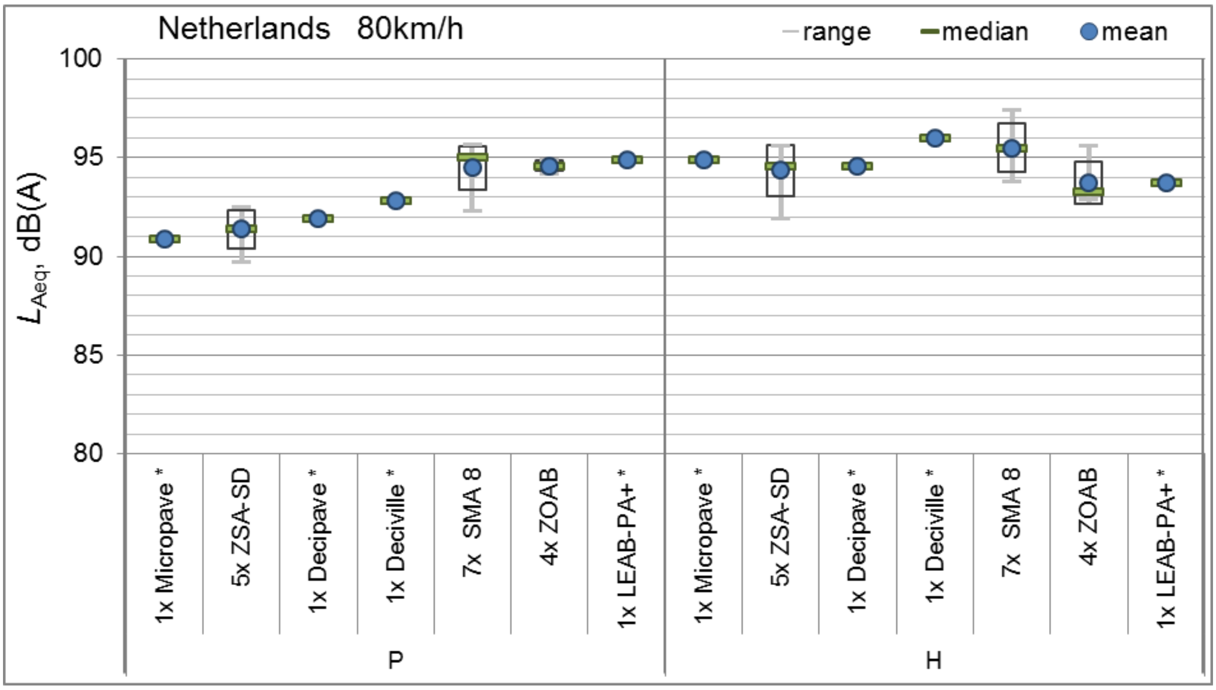


Figure 7: Average CPX levels in the Netherlands, at 80 km/h for tyre type P and H (arithmetic mean and median). The mean standard deviations are represented by the black boxes. The range equals the difference of the extreme values (maximum minus minimum).

The graphs show level changes that correspond to changes of the maximum aggregate stone size and also with the porosity of the surfaces. Therefore in order to derive reference values the CPX indexes of the road sections are regrouped by their porosity (dense, semi, porous) and maximum aggregate stone size.

In Table 4 the regrouped mean values are each listed with an uncertainty $\Delta\mathrm{CPX}$, a confidence interval between the D1 and D9 deciles and the range of the extreme values. The uncertainty $\Delta\mathrm{CPX}$ is calculated by dividing the combined standard uncertainty u of a CPX measurement (from chapter 2.3) by the square root of the number of measurements of one surface type $\Delta\mathrm{CPX} = u/\sqrt{n}$ (note that this is the same for tyre type P and H).

The confidence interval is the range that contains 80% of the CPX values. The amount of surface types varies from 1 to 54. The confidence interval loses its meaning for small amounts. The reference values are plotted in Figure 8 and Figure 9.

Table 4: Reference values grouped by porosity and maximum aggregate stone size, arithmetic average of CPX-indexes for the nominal speed *v*, uncertainty, confidence interval between D1 and D9 (decile) and range of extreme values in dB(A).

v, km/h	void cont.	max grain, mm	country	n	tyre type P, dB(A)			tyre type H, dB(A)			uncer. ΔCPX, dB(A)
					mean CPX_P	80%c.i. D1-D9	max-min	mean CPX_H	80%c.i. D1-D9	max-min	
50	dense	4	CH	2x	86.4	–	–	87.9	–	–	0.8
50	dense	5	DE	16x	87.9	3.0	4.1	90.0	2.6	4.4	0.3
50	dense	11	CH	2x	91.2	0.1	0.1	91.0	0.5	0.6	0.8
50	semi	4	CH	10x	83.9	1.8	2.6	86.7	1.8	2.4	0.3
50	semi	8	DE	24x	90.3	2.2	3.1	90.8	1.6	2.1	0.2
80	dense	5	DE	54x	95.2	3.5	5.2	98.1	2.2	4.3	0.1
80	dense	8	CH	4x	94.4	2.0	2.0	96.5	0.8	0.9	0.6
80	dense	8	DE	13x	98.3	0.9	1.1	98.6	1.0	1.6	0.3
80	dense	11	CH	1x	97.5	–	–	98.4	–	–	1.1
80	dense	11	DE	2x	98.0	0.7	0.9	98.2	0.6	0.7	0.8
80	semi	5	NL	26x	91.4	2.5	3.2	94.2	1.8	4.1	0.2
80	semi	8	CH	4x	93.5	1.3	1.8	95.9	0.7	0.9	0.6
80	semi	8	NL	12x	94.8	2.0	4.5	95.9	3.1	3.6	0.3
80	semi	16	NL	2x	94.7	0.2	0.3	95.0	0.2	0.3	0.8
80	porous	8	CH	5x	94.7	2.7	3.2	96.2	1.0	1.2	0.5
80	porous	8	DE	7x	94.9	2.8	3.4	96.2	2.3	3.3	0.4
80	porous	16	NL	7x	94.7	0.7	1.1	94.1	2.3	2.7	0.4

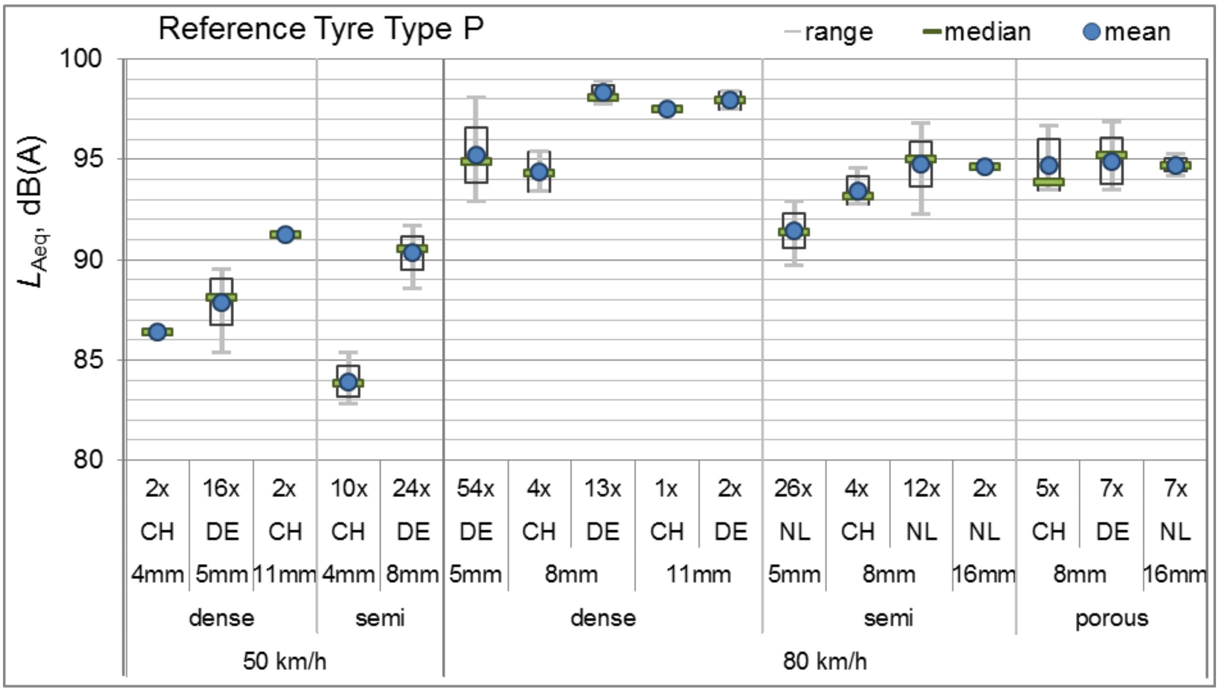


Figure 8: Average CPX levels for tyre type P, at 50 and 80 km/h (arithmetic mean and median). The mean standard deviations are represented by the black boxes. The range equals the difference of the extreme values (maximum minus minimum).

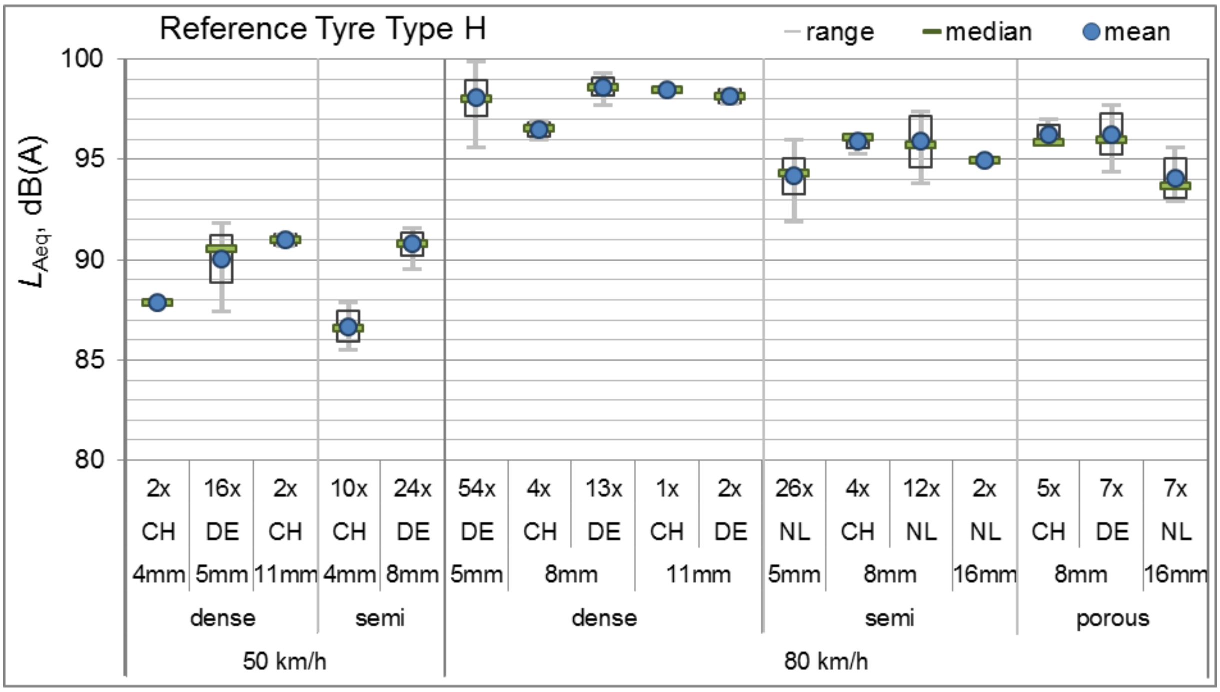


Figure 9: Average CPX levels for tyre type H, at 50 and 80 km/h (arithmetic mean and median). The mean standard deviations are represented by the black boxes. The range equals the difference of the extreme values (maximum minus minimum).

Conclusion
The collected data is grouped by the pavement types that are defined by their maximum aggregate size and void content. In order to derive reliable CPX reference values on which a categorical rating system can be based the amount of measured road sections per surface type should not be too small. In this gathered data set only three types are represented by more than 20 measured road sections, five contain less than 10, see Table 5.
The data originated from only three countries and thus the derived average CPX levels cannot represent the surface types for other countries. Certainly, the principal physical behaviour of a surface type will roughly be the same within a certain range, but variances due to differences in the construction cannot be accounted for.

Table 5: Data regrouped by the physical properties of the surface: maximum aggregate stone size and porosity with focus on the amount of measured road sections ($CPX_{P/H}$ are the average levels and ΔCPX the uncertainty).

v, km/h	void content	max grain, mm	n	$CPX_{P,}$ dB(A)	$CPX_{H,}$ dB(A)	$\Delta CPX_{,}$ dB(A)
50	dense	4	2	86.4	87.9	0.8
50	dense	5	16	87.9	90.0	0.3
50	dense	11	2	91.2	91.0	0.8
50	semi	4	10	83.9	86.7	0.3
50	semi	8	**24**	**90.3**	**90.8**	**0.2**
80	dense	5	**54**	**95.2**	**98.1**	**0.1**
80	dense	8	17	97.4	98.1	0.3
80	dense	11	3	97.8	98.2	0.6
80	semi	5	**26**	**91.7**	**94.4**	**0.2**
80	semi	8	16	94.5	96.0	0.3
80	semi	16	2	94.7	95.0	0.8
80	porous	8	12	94.8	96.2	0.3
80	porous	16	7	94.7	94.1	0.4

3 Data Aggregation

3.1 Smoothing Methods

For pavement management purposes raw CPX-data is too detailed in two ways: Instead of the exact sound pressure level value a categorical quantity should represent the acoustic condition of a road segment and its relevance with respect to the local conditions e. g. existence of receivers, kind of receivers (dwellings, required noise reduction value of the road surface). For easier management the length of the road segments should be as long as possible. Therefore, the aggregation of the CPX-data has to meet these requirements. In order to determine a suitable smoothing method for data aggregation, six mathematical operations were investigated and compared using CPX data of a 65 km long road section: maximum, minimum, quantile and median value, arithmetic and energetic average. Each operation is applied to eleven consecutive 100 m-segments around the central segment that is being smoothed (five segments before and after). The CPXI index values were used as input and rounded to 0.5 dB afterwards.

In each of the following diagrams the blue lines represent the raw CPXI values that were rounded to 0.1 dB. A distinctive section of 15 km was chosen to illustrate the effect of each smoothing method. As can be seen in the left diagram of Figure 10 the rounding to 0.5 dB its self already leads to some smoothing.

Maximum Value
From a pavement management standpoint the use of a maximum value can make sense because it reflects the worst case of a road section. However for the sound impact the maximum value overrates the real noise situation. The right diagram of Figure 10 shows long continuous levels that are kept up by peaks, but the slopes are shifted: rising slopes to the left (in opposite driving direction) and falling slopes to the right (in driving direction). The length of the shift is significant. It accumulates up to several hundred meters. Because of this effect the maximum value is not suited for an aggregation applied in this way.

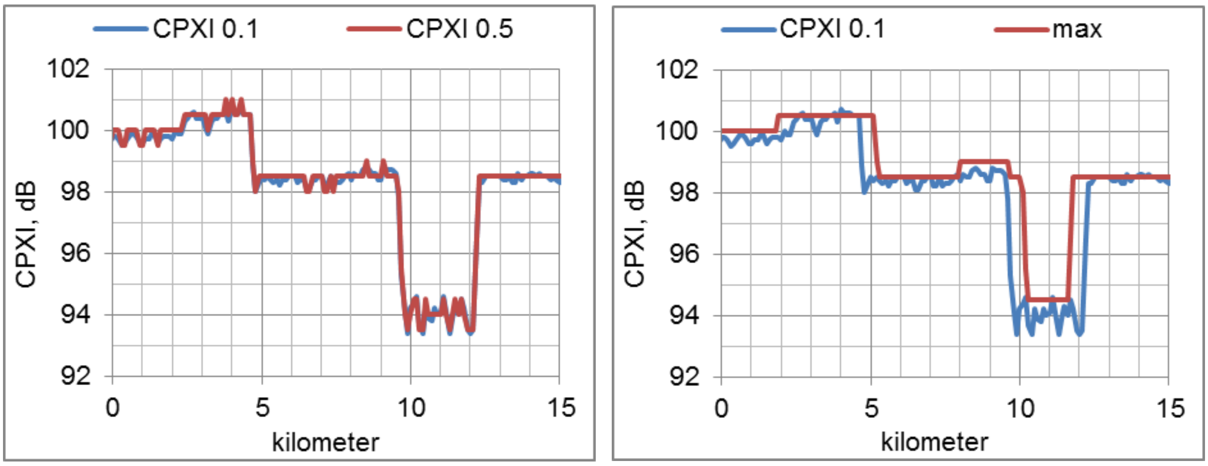


Figure 10: Smoothing of CPXI-values, left: only rounded to 0.5 dB, right: maximum value over eleven 100 m-segments with rounding to 0.5 dB.

Arithmetic and Energetic Average
The methods applying arithmetic as well as energetic average values generate continuously adapting curves with numerous steps, see Figure 11. Thereby steep slopes decline gradually

and are no longer recognizable as sharp changes for instance where the type of road surface changes. Also the average length of continuous levels is short.

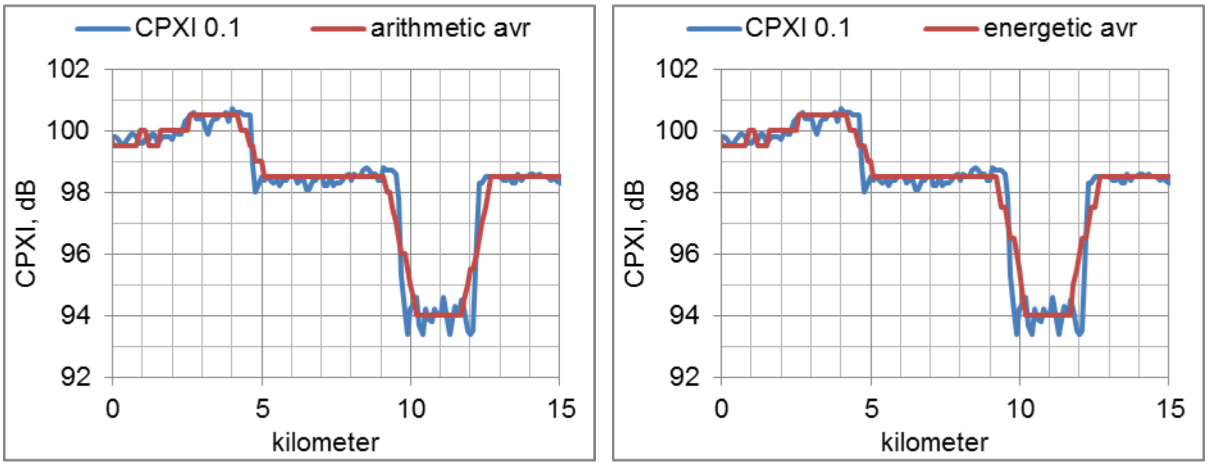


Figure 11: Smoothing of CPXI-values, left arithmetic, right energetic average, each over eleven 100 m-segments with rounding to 0.5 dB.

Median and Quantile Value

The diagrams in Figure 12 show the curves of the 0.75 quantile and median value. Because the 0.5 quantile is equivalent to the median and corresponds to the maximum value when it approximates the limit towards 1, accordingly the 0.75 quantile lies between median and maximum value. As the latter the quantile also shifts slopes. The median does not show this behaviour at all. Both generate long continuous levels and are robust against spikes.

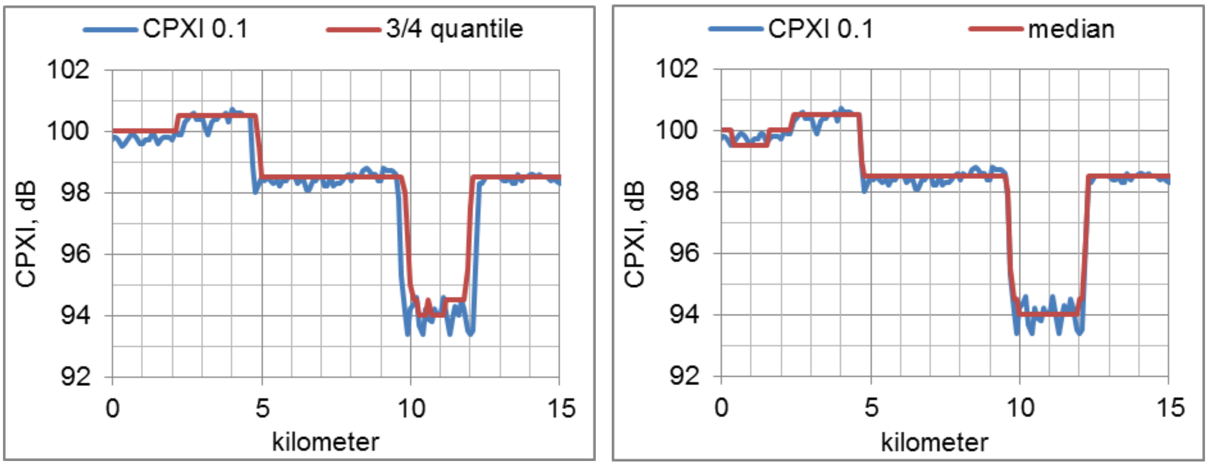


Figure 12: Smoothing of CPXI-values, left 0.75 quartile value, right median value, each over eleven 100 m-segments with rounding to 0.5 dB.

The amount of levels and the average length of continuous levels of the different mathematical operations are gathered in Table 6.

In this comparison the median operation turns out to be the method of choice and is used from here on for the aggregation.
In the following section the parameters for the smoothing operation, especially the amount of segments to be considered, will be determined by s sensitivity analysis using sound propagation calculations.

Table 6: Comparison of different mathematical operations concerning the remaining number of levels and average length of continuous levels.

mathematical operation	number of levels	average length in m
round 0.1 dB	37	131
round 0.5 dB	12	297
arithmetic average	14	670
energetic average	14	670
maximum value	8	1354
0.75 quantile	11	929
median	**10**	**1016**
minimum value	10	833

3.2 Sensitivity Analysis

For a better overview the aggregation should smooth similar acoustic values over long sections. With this analysis a minimum section length will be derived, so that the change of the noise impact is negligible.

The calculation model that is used is shown in Figure 13. The straight road is 100 km long with four parallel lanes, which are ±3.6 m and ±7 m off centered, respectively. Receiver points are positioned every 25 m alongside the road in 100 m distance over a length of 1 km. The minimal section is in the middle and is varied from 100 m to 1 km length and -10 dB to +10 dB emission level relative to the rest of the road.

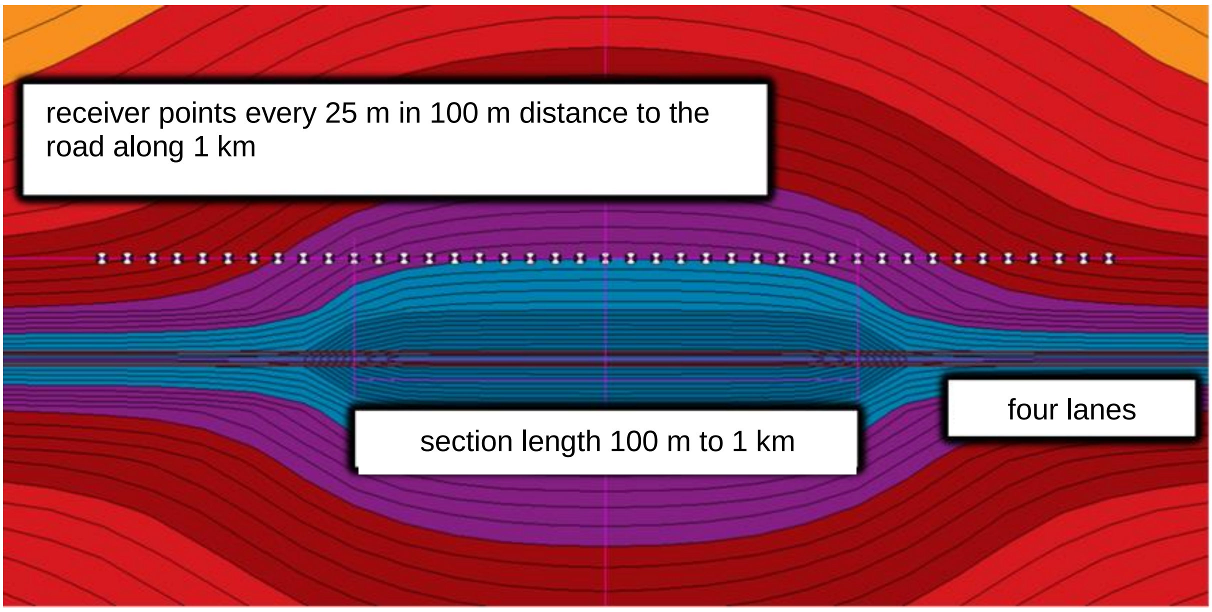


Figure 13: Schematic of the calculation model to determine a minimal section length with negligible effect on the sound impact (noise map shown for +10 dB emission level of the middle section relative to the rest of the road).

The diagrams in Figure 14 show the relative sound pressure levels at the receiver points for sections with a length of 100 m, 200 m, 500 m and 1 km. The sections are indicated by a grey bar at the bottom of each diagram.

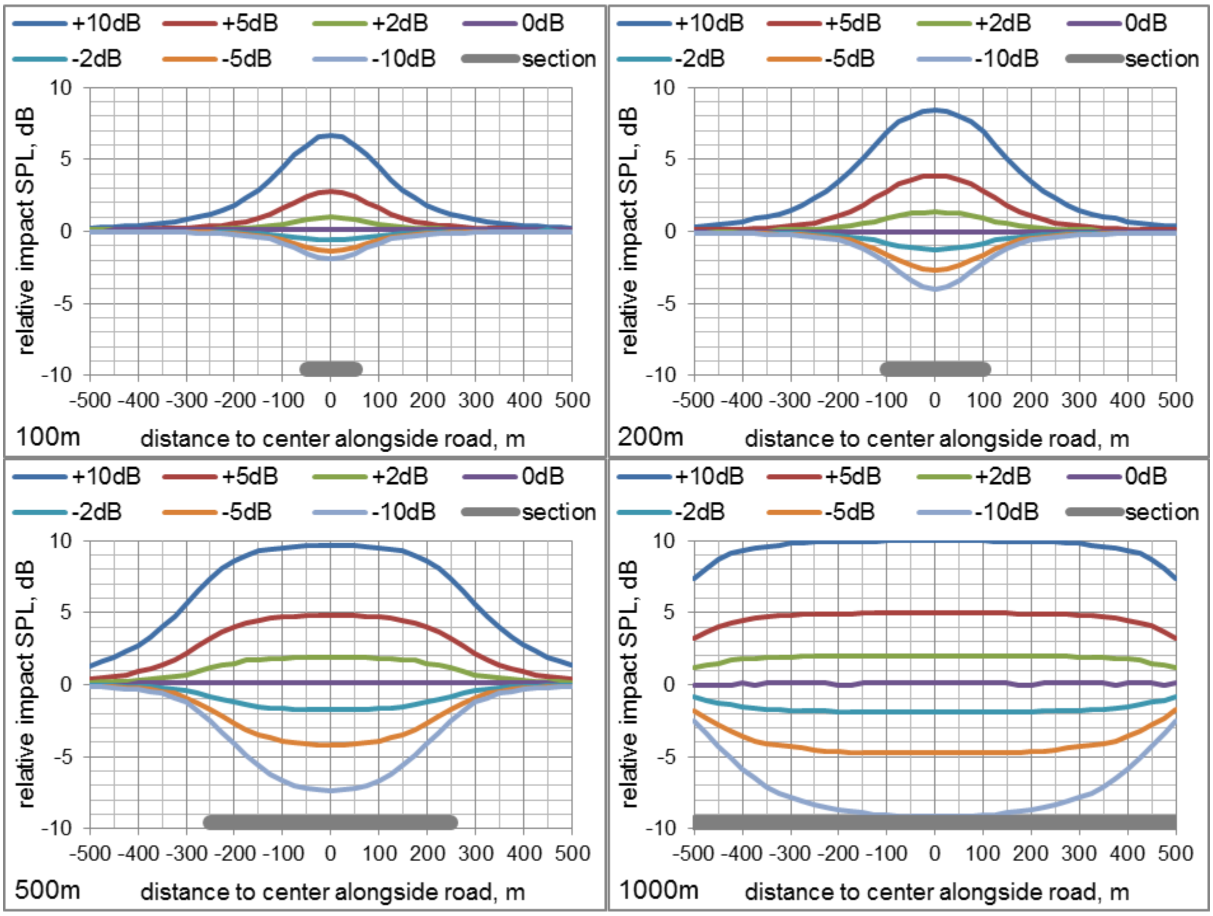


Figure 14: Relative sound pressure level at receiver points at 100 m distance alongside a road for different relative emission levels of a 100 m, 200 m, 500 m and 1 km long section in the middle of the road (grey bar at the bottom).

As can be seen at 500 m section length the positive emission level differences are reached at the receiver points and plateaus are formed. The negative emission level differences begin to be fully developed on the impact side at sections lengths not shorter than 1 km. The -10 dB curve still only reaches -9 dB at its minimum

The dependence of the noise impact on the distance to the road is shown in Figure 15. For this diagram the receiver points were positioned perpendicularly to the road at 10 m to 5 km distance. Here, the relative sound pressure level at the receiver points is the difference in a scenario, were the middle section has +10 dB higher emission relative to the rest of the road (0 dB). The section is positioned in the middle and its length is also varied from 100 m to 2000 m (legend). Short sections have less an effect at large distances than long ones. The road section that has an influence on the receiver points gets bigger with growing distance.

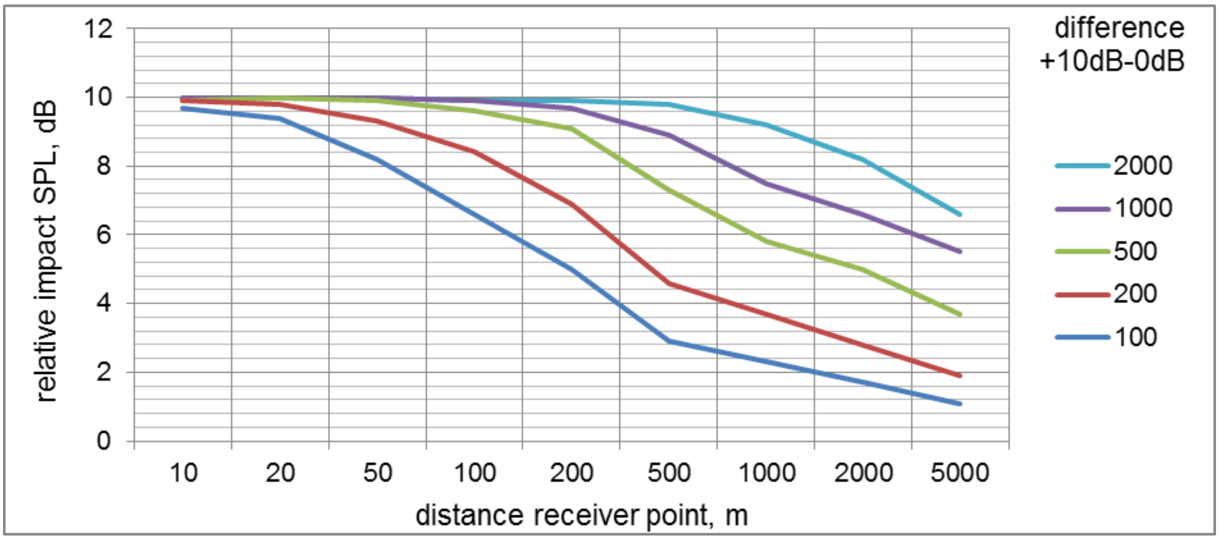


Figure 15: Relative sound pressure level difference at receiver points (impact) of a 10 dB louder section to 0 dB as a function of the receiver distance for section lengths from 100 m to 2 km.

Conclusion
A section of 500 m length with a different emission level shows its effect partially at a receiver distance of 100 m. Longer sections show full effect on the noise impact even with lower emission levels than surrounding sections. However, a minimum section length of 500 m would underrepresent short but loud subsections. Nonetheless, the 500 m can be used as an evaluation length for the aggregation with the median function. The CPX values of 500 m length are used for the aggregation, but the data is not segmented strictly into intervals of at least 500 m length. This way, values fluctuating around a particular level are smoothed but changes of the level itself are rendered automatically.

3.3 Comparison of Aggregation Methods

The effect of the aggregation on the noise impact can be shown very effectively by subtraction of two noise maps. The raw CPX values are used as a reference to show how the aggregated data change the noise map.

The road in the calculation model has four lanes with the assumptions listed in Table 7. The CPX_P and CPX_H values each are averaged arithmetically over 100 m, rounded to 0.1 dB and are used separately for the emissions of cars and trucks.

Table 7: Assumptions for the four road lanes.

lane	direction	distance	cars / h	trucks / h	v, km/h
1 normal lane	+	7.0 m	1000	255	120
2 passing lane	+	3.5 m	500	-	120
3 passing lane	–	-3.5 m	500	-	120
4 normal lane	–	-7.0 m	1000	255	120

For the calculation with the aggregated data the median value of five 100 m-segments with a subsequent rounding to 0.5 dB is used. The noise maps of both variants are calculated with a 10 m resolution for both coordinates and then subtracted arithmetically from one another. For a comparison with a different kind of aggregation the calculation is repeated with the maximum value.

Figure 16 shows a subtracted noise map for the 40 km long road section with median aggregation. In Figure 17 the same extract is shown with maximum value aggregation. The colouring is chosen in such a way that negligible differences of ±0.2 dB appear white. Positive differences, where the aggregation leads to higher noise impact, are coloured “warm” red to violet, negative are correspondingly “cold” green to blue.

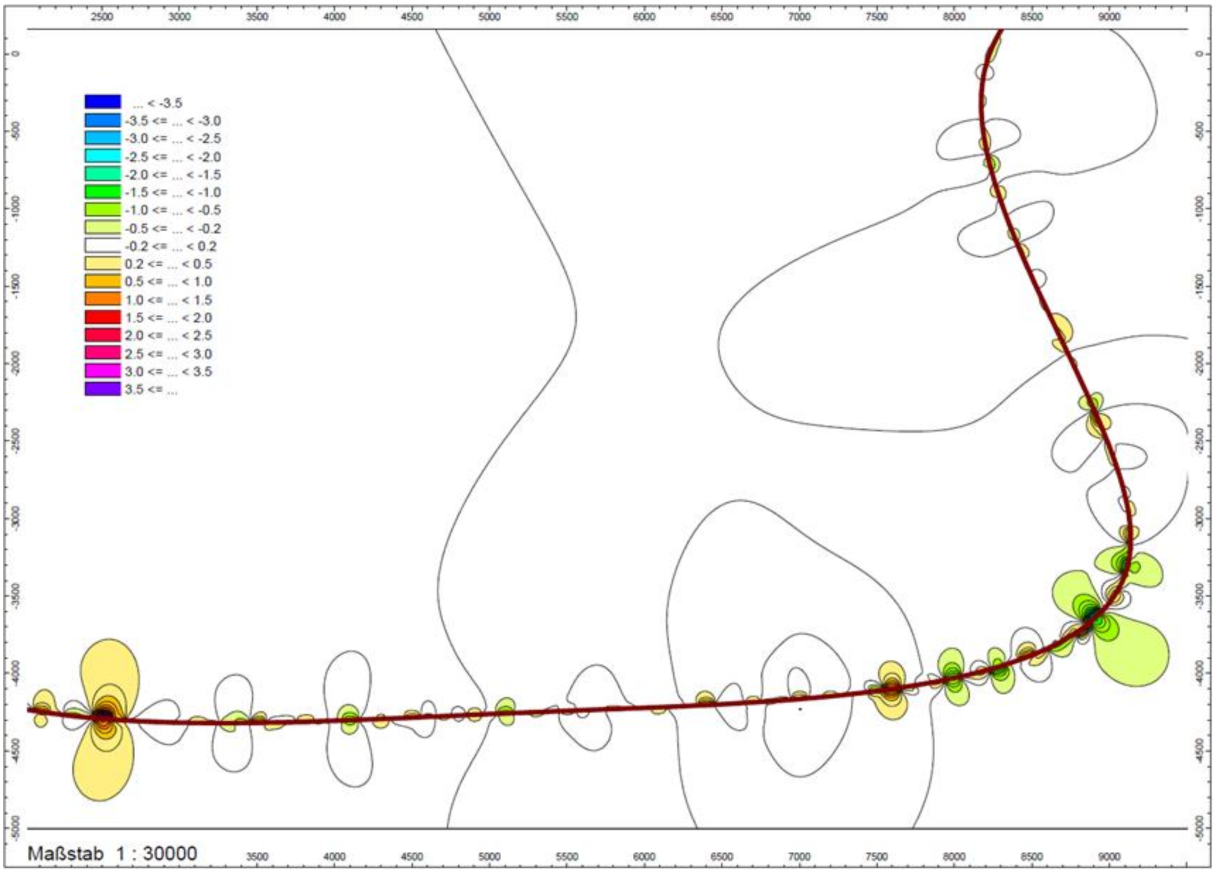


Figure 16: Subtracted noise maps: « aggregated minus raw CPX data », Aggregation: Median of five 100 m-segments with rounding to 0.5 dB.

The overrating caused by the maximum value aggregation over large areas of up to 2 dB becomes evident in Figure 17. There are no negative differences in the displayed extract. In comparison Figure 16 has mostly white areas with single deviations located next to the road at single 100 m-segments. The two biggest “double bubbles“ show differences of more than ±1 dB at distances less than 100 m. In both cases only one 100 m-segment differs strongly from its surrounding: The heart of the green double bubble contains a smoothed 4.5 dB peak and the orange one a 5 dB dip. The local effects of the smoothed peaks and dips can be prevented by means of an inverse peak filter with a threshold. For instance, only peaks smaller than 3 dB than the median would be smoothed, bigger ones remain (possible for dips as well). Despite of these extremes the median aggregation over 500 m hardly changes the sound impact at all.

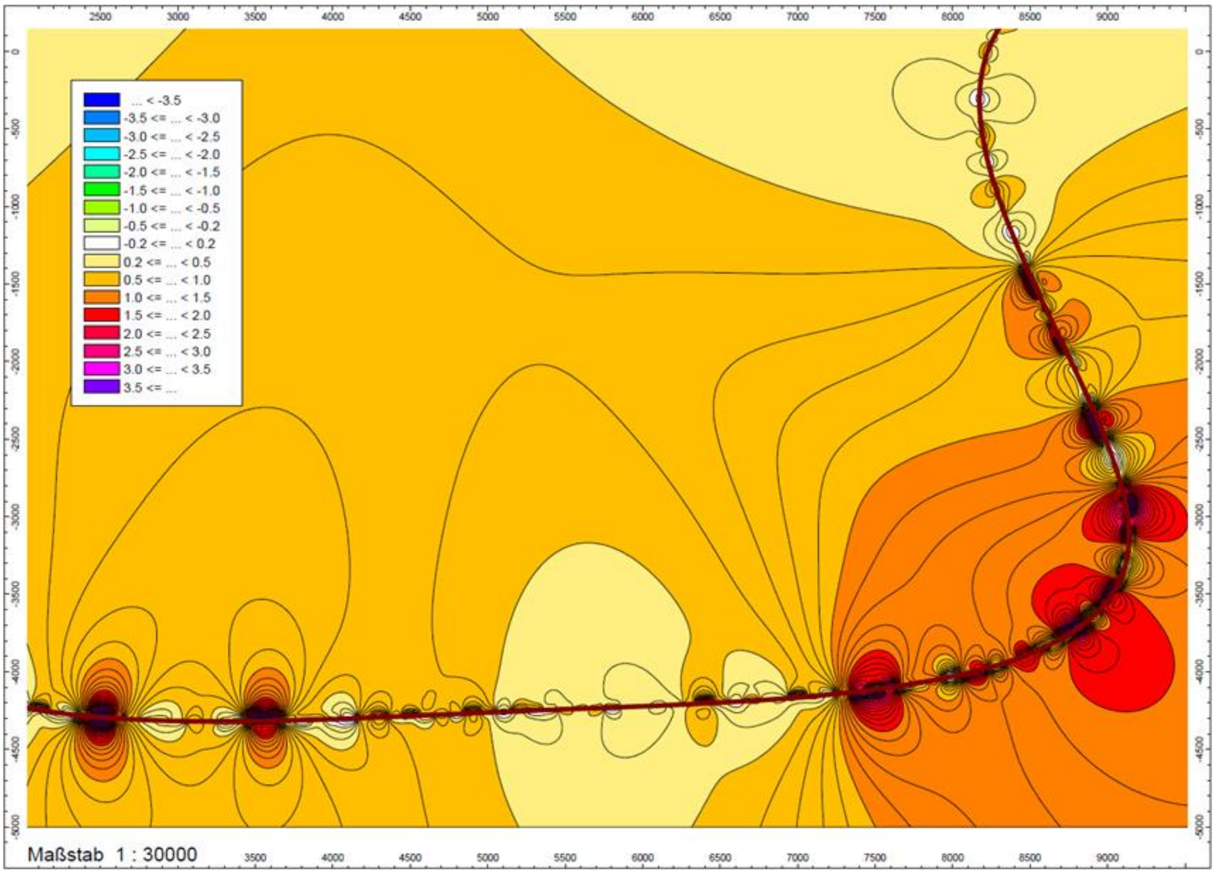


Figure 17: Subtracted noise maps: « aggregated minus raw CPX data », Aggregation: Maximum value of five 100 m-segments with rounding to 0.5 dB.

Conclusion

A smoothing method that applies the median function to five consecutive 100 m sections (last two, middle one and next two) and subsequent rounding to 0.5 dB is introduced. It smoothes the data by increasing the average sections length and reducing the number of different levels, while having negligible effects on the noise impact.

3.4 Noise impact relevant aggregation of CPX-Data to Relevant Noise Segments (RNS)

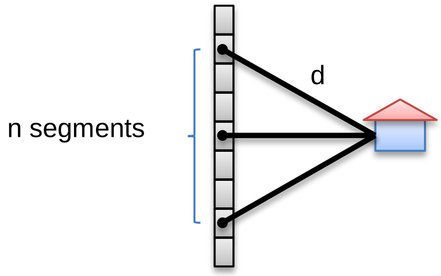
Optionally, the aggregation of CPX data can be done by using the distance to the nearest receiver to determine Relevant Noise Segments (RNS) for each single CPX value. A concept for the derivation of Relevant Noise Segments (RNS) is introduced.

3.4.1 Length of a Relevant Noise Segment

In order to determine over what length CPX-data can be aggregated the distances of receivers to the road are key. As shown in 3.2, with growing distance between the road and the receiver the effective length of a particular road section involved in the noise impact at the receiver's location grows. Along a straight and acoustic homogeneous road the sound pressure level decrease of the farthest to the nearest of *n* 20 m-segments is:

$$\Delta L_p = 20\,\mathrm{lg}\frac{d}{\sqrt{d^2+\left(20m\frac{n-1}{2}\right)^2}}$$

ΔL_p decrease of sound pressure level
d distance receiver to road segment in m
n number of 20 m-segments



With a level decrease of -10 dB the number of contributing 20 m-segments is:

$$n = \frac{3d}{10\mathrm{m}} + 1$$

The distance *d* can be easily derived by using a geographical information system. Buildings as well as road sections are represented in different layers. Using the coordinates of a particular road segment and a particular building the distance can be easily calculated by means of an arithmetic module which is implemented.

3.4.2 From Overlapping to Relevant Noise Segments

The amount of contributing segments as a function of the distance to the nearest building can be used as a parameter for the aggregation along the road for one segment. The contributing segments of all original CPX-segments overlap. The general idea hereby is that the maximum value of overlapping sections is appointed to each segment. The process is schematically shown in Figure 18.

1	2	3	4	5	6	7	8	9	10	11	12	13
87	89	92	95	**97**	95	92	89	87				
	88	90	93	96	**98**	96	93	90	88			
		87	89	92	95	**97**	95	92	89	87		
89	90	91	93	95	97	98	**99**	98	97	95	93	91
				86	88	91	94	**96**	94	91	88	86
89	90	92	95	97	98	98	99	98	97	95	93	91

Figure 18: Schematic of overlapping sections. The number of segments (the length of the RNS) and the level decrease depend on the receiver distance.

Not only the number of segments of a contributing section (their length) but also the level decrease within the section is determined by the receiver distance. An overlapping section contains all segments with a level decrease of less than 10 dB. In the example in Figure 18 the number of contributing segments of sections 5, 6, 7 and 9 is the same. Number 8 (yellow) is larger. The overlap of the contributing sections indicates that a neighbouring segment, despite of its level decrease, is louder.

The reference to the noise impact is based on the topographical circumstances of the buildings which are nearest to the road. The distance of CPX-segments of a contributing section to the nearest buildings is hereby the key parameter to determine the acoustic range of a road section. In the following this distance is referred to as the receiver distance. The shorter the receiver distance is the smaller the range is. The schematic in Figure 19 shows how the minimum distance or rather the distance to the nearest building a_{min} is sought out. Figure 20 shows an example how the distance a_{min} can be derived automatically – in this case from a geographical and buildings information system. a_{min} can easily be determinend by means of the coordinates of the houses and the 20 m-segments.

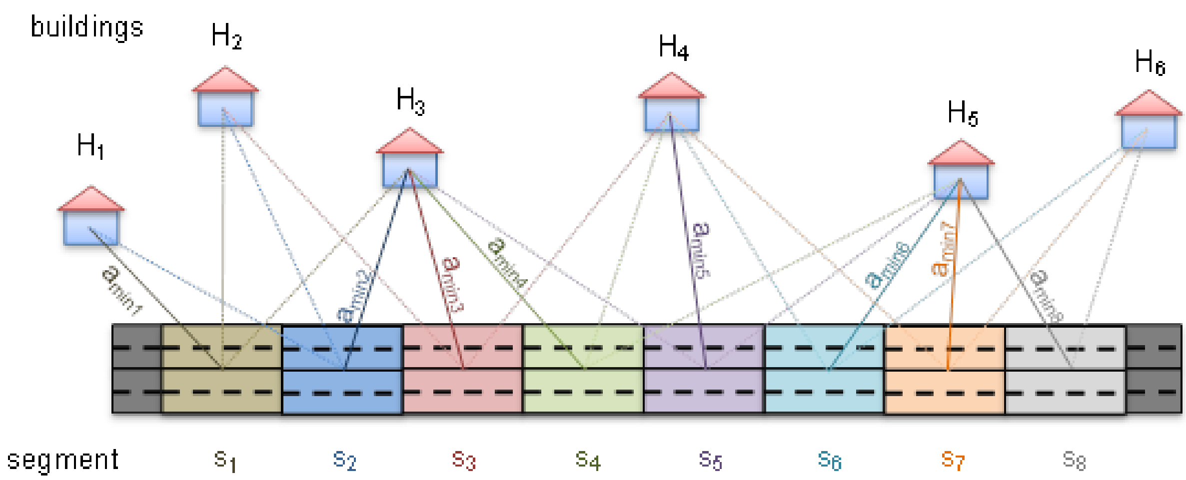


Figure 19: Schematic of the minimum distance of each 20 m-segment to the nearest building in the surrounding.

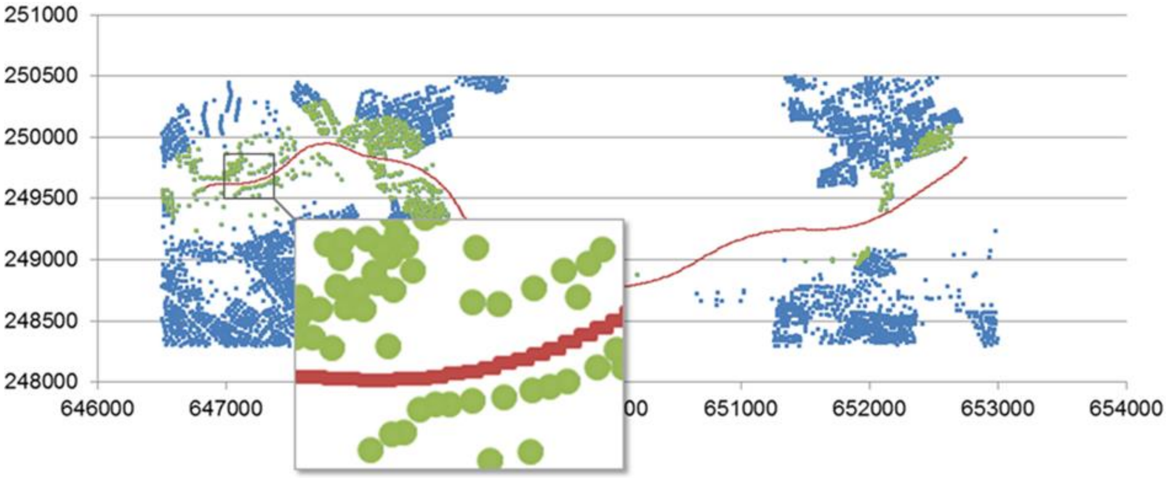


Figure 20: Example of a real topography of a road with buildings, represented by house-dots, taken from a geographical registry of buildings and roads.

In order to compare the aggregation using receiver distances for the determination of RNS length and level decrease within a RNS it is applied to the 6.7 km long road section depicted in Figure 20. The influence of the distance can be seen in Figure 21 between the segments 41 to 61 and 291 to 311: This part of the CPX_P data is in fact duplicated, but the receiver distances around segment 300 are much greater than in the beginning. Although this method shows good adaptation to the data curve and respects the receiver distances, the mean segment length is very short. Also the amount of remaining values is 13 and should preferably be smaller. Finally, there is an effect which disqualifies this way of data aggregation for the use in a pavement management system. Around segment number 300 it can be seen that the section with low CPXP values (segment no. 290 to 310, black curve) is constricted by the aggregation process (red curve). This is due to the fact that quite long distances between the road and houses exist at this road section (see Figure 20). These long distances lead to something what could be signified as "cross-talk" effect. The louder road sections before and behind the quiet section affect the noise impact along the segment numbers 290 up to 310. From a noise protection point of view this result is quite comprehensible but it totally disagrees with the purpose of a pavement management system. From a PMS point of view this result would mean that the acoustical quality of the road section between segments no. 290 and 310 is not better than 98 dB(A) CPXP level. In reality, the entire section is in a very good acoustical condition with CPXP levels lower than 97 dB(A).

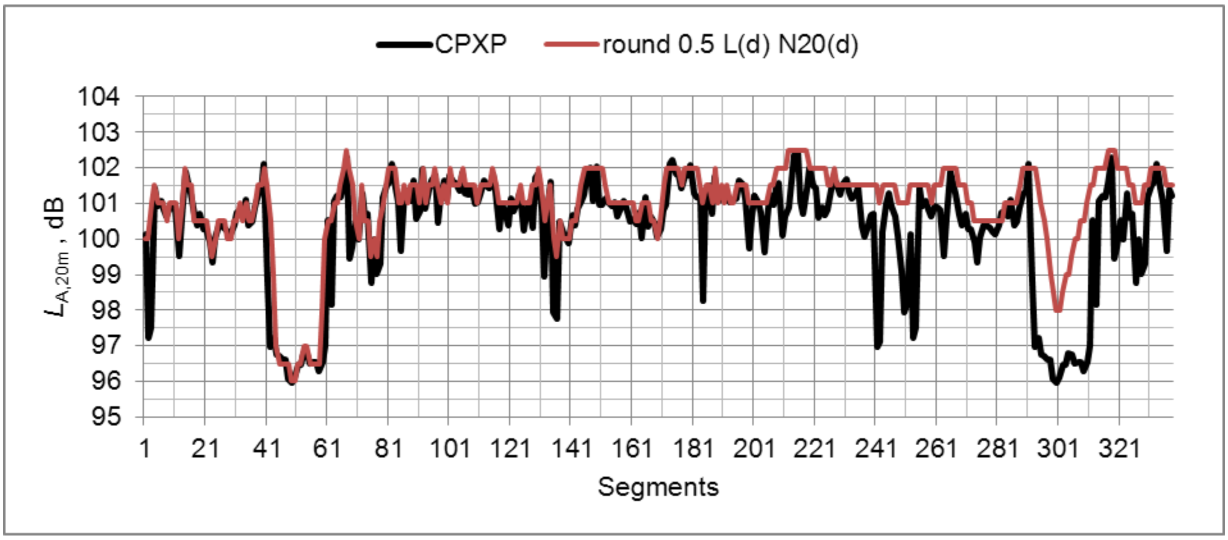


Figure 21: The number of segments for a RNS is determined by the distance of receivers. The level decrease is taken into account for each RNS. The maximum value of the overlapping RNS is rounded to 0.5 dB.

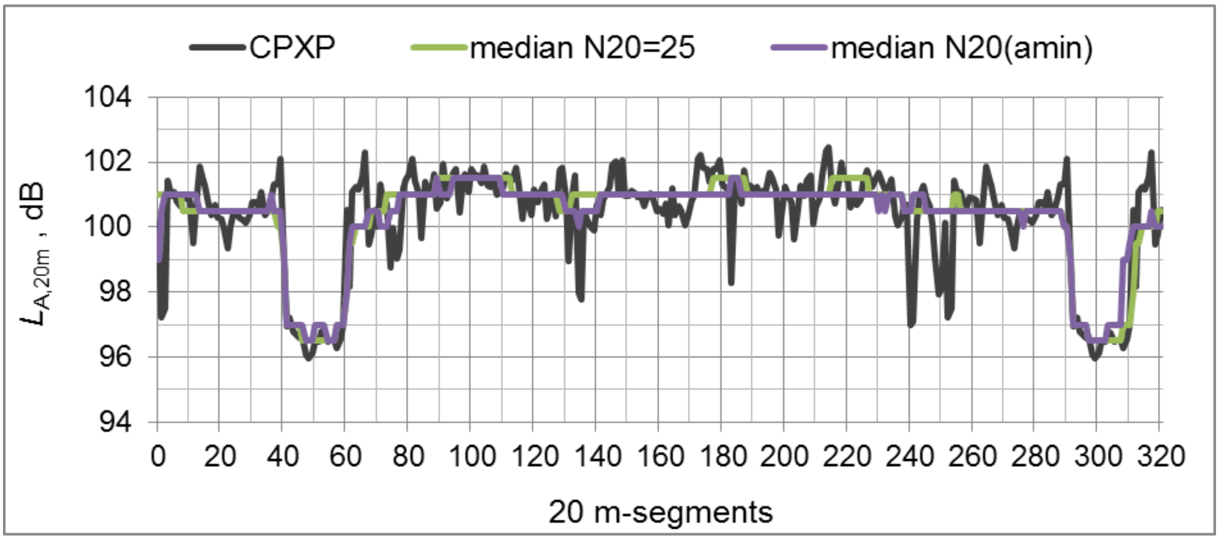


Figure 22: Comparison of number of 20 m-segments: green: fixed 25, purple: dependent on the receiver distances a_{min} (each median and rounded to 0.5 dB).

It seems that it is not necessary to calculate the level decrease within a RNS but its length should be adapted to the distance to the nearest receiver. Therefore, the aggregation method is simplified, where the lengths of RNSs depend on the distance, but the level doesn't. The median value within the RNS is taken and rounded to 0.5 dB steps. Figure 22 shows a comparison of the median value over a fixed amount of 25 20 m-segments (= 500 m) with the median value over an amount that depends on the distance. The values are again each rounded to 0.5 dB steps afterwards.

The visible differences of the two curves are few and small. Both show a similar behaviour in adaption to the data and the amount of remaining levels is the same (nine). But the average length of continuous levels differs by a factor of nearly 1.5:

Number of segments	Average length of continuous levels
As a function of receiver distance	130 m
Fixed (25x 20 m = 500 m)	193 m

The segment numbers as a function of receiver distance reach from 7 to 203 and have an average of 50. Although this average is twice as high as the fixed amount it does not lead to longer continuous levels. Responsible are the heterogenic distances of buildings along the road that change from very near to far. The median of the segment numbers is only 31. The frequency distribution of the amount of 20 m-segments is shown in Figure 23.

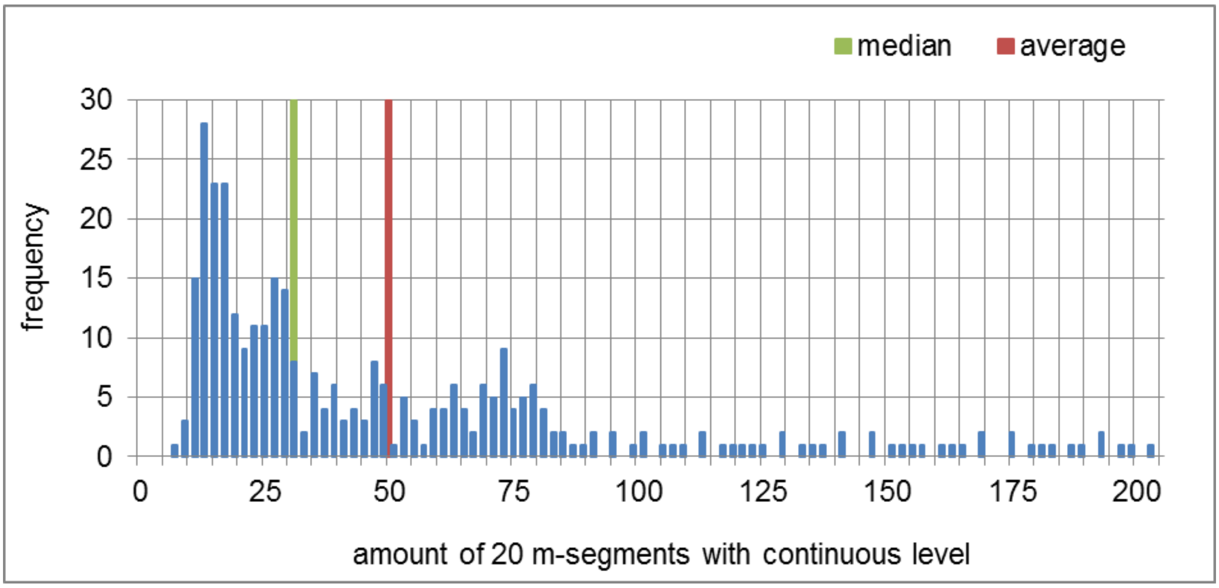


Figure 23: Frequency distribution of the amount of 20 m-segments with continuous level.

The development of the methodology for aggregation was first done with the raw CPX 20 m-segments. As inquiries towards road administrations have shown most PMS are based on 100 m section lengths. In order to adapt the RNS method, an arithmetic averaging of five 20 m-CPX-segments to 100 m-intervals is done before applying the median and rounding function. Figure 24 shows the same comparison as Figure 22 for 100 m-intervals. For the green curve the median was applied to five consecutive 100m-intervals. For the red curve the number of 100 m-intervals is determined by the distance to the next building. In this example the differences are rather small. In both cases seven levels remain. The average length of continuous levels is 347 m for green and 330 m for the red curve. Stepping from 20 m to 100 m section length lets both methods converge concerning the data aggregation, i.e. the number of different CPX levels and the average length of constant CPX level. However, taking the distance to the nearest receiver into account yields a different differentiation of the aggregated CPX data which is better adapted to the arrangement of noise receivers along the road section.

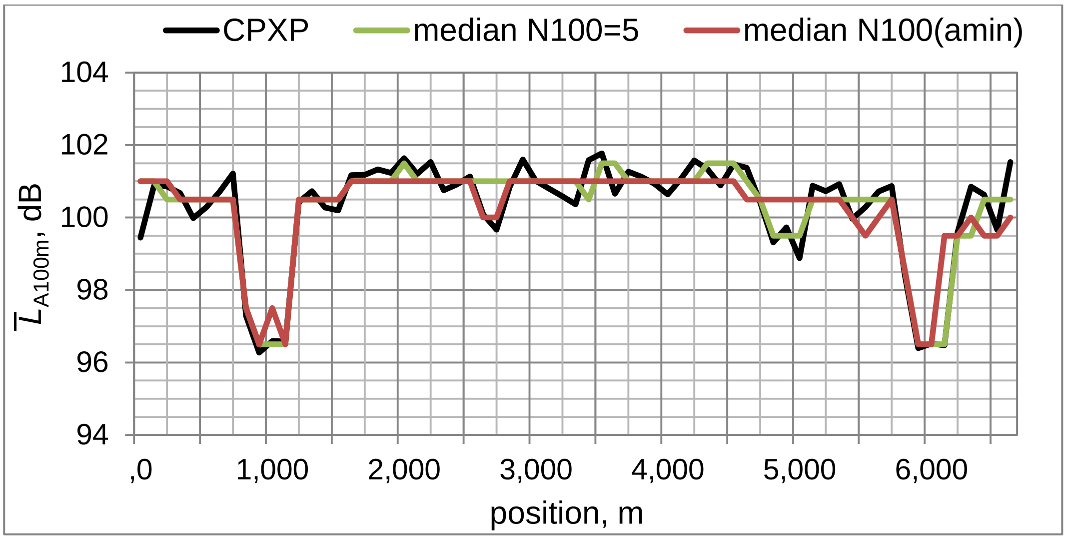


Figure 24: Comparison of number of 100 m-segments: green: fixed 5, red: dependent on the receiver distances a_{min} (each median and rounded to 0.5 dB).

Peakfilter

Due to the robustness of the median function towards single peaks and dips local discrepancies at the noise impact can arise compared to the use of non-aggregated data. In order to avoid these a comparison between the smoothed and unsmoothed values is made. The segments with differences above a threshold of 3 dB keep their original value.

4 ZRN – Zero Rating Niveau and Comparisons

The mean CPX levels per 100 m interval are not meaningful with respect to a pavement management system which has to be based on rating values. Therefore, the acoustic condition of a road section needs to be derived taking additional secondary attributes into account. These attributes are the conceded or legally obligated noise reduction values of the road surface. The conceded or legally obligated noise reduction value of a road pavement is specified by the road administrator's optional or legally obligated choice of a particular type of road pavement for the new construction or reconstruction of a road. The type of road surface defines the acoustic performance that can be expected from it either in its initial or future condition, after 3 years of usage for example. This procedure of defining a reference level for the rating of a usage-related attribute of the road pavement differs clearly from that for other attributes like unevenness or grip. These attributes can be referenced straight to limit values which every road surface has to meet, independently from its make and the environmental context. A particular road surface has to be safe, neither more nor less, and therefore, grip has to meet an acceptable skid resistance niveau. And this is the same for all kinds of road surfaces. In contrast to this, noise as a functional attribute is in relationship with environmental noise control requirements and is completely detached from road usage and road user issues. In general, the requirements are stipulated in terms of noise limit values which are valid for different types of land use.

The required noise level reduction of a road pavement is to be defined as Zero Rating Niveau – *ZRN*. In case of a legal planning approval for the road section under investigation the Zero Rating Niveau corresponds to the noise reduction value of the type of road pavement which is stipulated as a requirement. The concession case corresponds to the situation where the public road administrator is induced to but not obliged to improve the acoustic performance of a road section due to unacceptable noise levels. The Zero Rating Niveau corresponds then to the noise reduction value of the road pavement which is needed to keep the noise impact below a certain level agreed upon or which the road administrator is willing to concede to the residents. In general, the same *ZRN* is valid for each driving lane.

Finally, the acoustic condition should be determined per relevant noise segment as a categorical quantity typically based on a five-stage scale. In order to determine the acoustic condition of a relevant noise segment its resulting (CPX-) level is compared with the zero rating niveau which is due for the particular road section. The higher the Zero Rating Niveau is the lower the acoustic condition value will be. Figure 25 shows the level differences between the relevant noise segment value and the Zero Rating Niveau for five segments on one lane. On the left the *ZRN* is 0 dB(A) causing level differences of up to 5 dB(A). In the diagram on the right the *ZRN* is decided to be -2 dB(A) causing level differences of up to 7 dB(A). The colours indicate acoustic condition categories the lev el differences could be attached to. In the first example the five segments occupy four different categories. The second one shows that differing categories are occupied due to the lower Zero Rating Niveau.

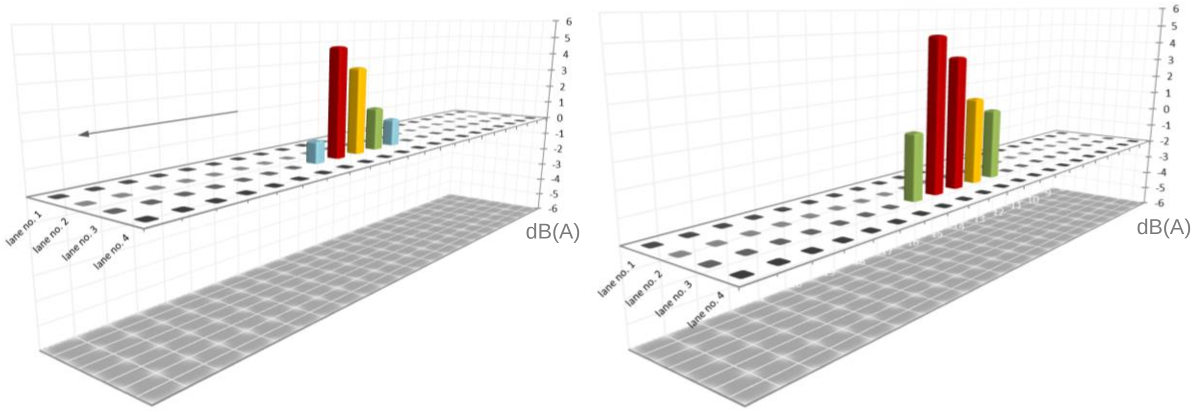
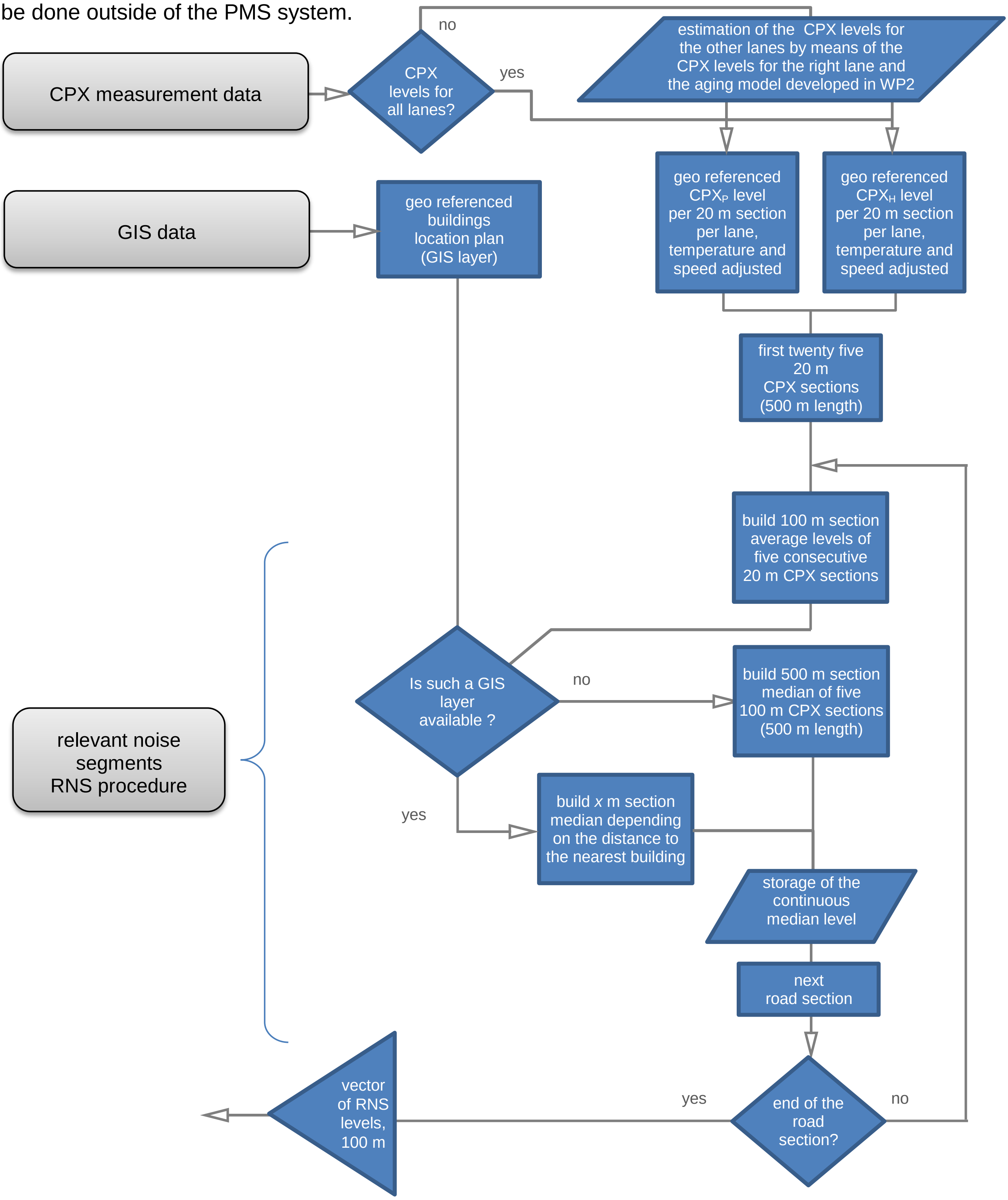


Figure 25: Effect of the zero rating niveau (*ZRN*) on the acoustic condition values. Left: *ZRN* = 0 dB(A), right: *ZRN* = -2 dB(A).

5 The recommended acoustic evaluation process

Based on the conclusions from the investigations reported in the previous Chapters, in Figure 26 a flow chart of the acoustic condition evaluation procedure is shown. This process generates information that serves as an input to a PMS system, i.e. all of the calculations will be done outside of the PMS system.



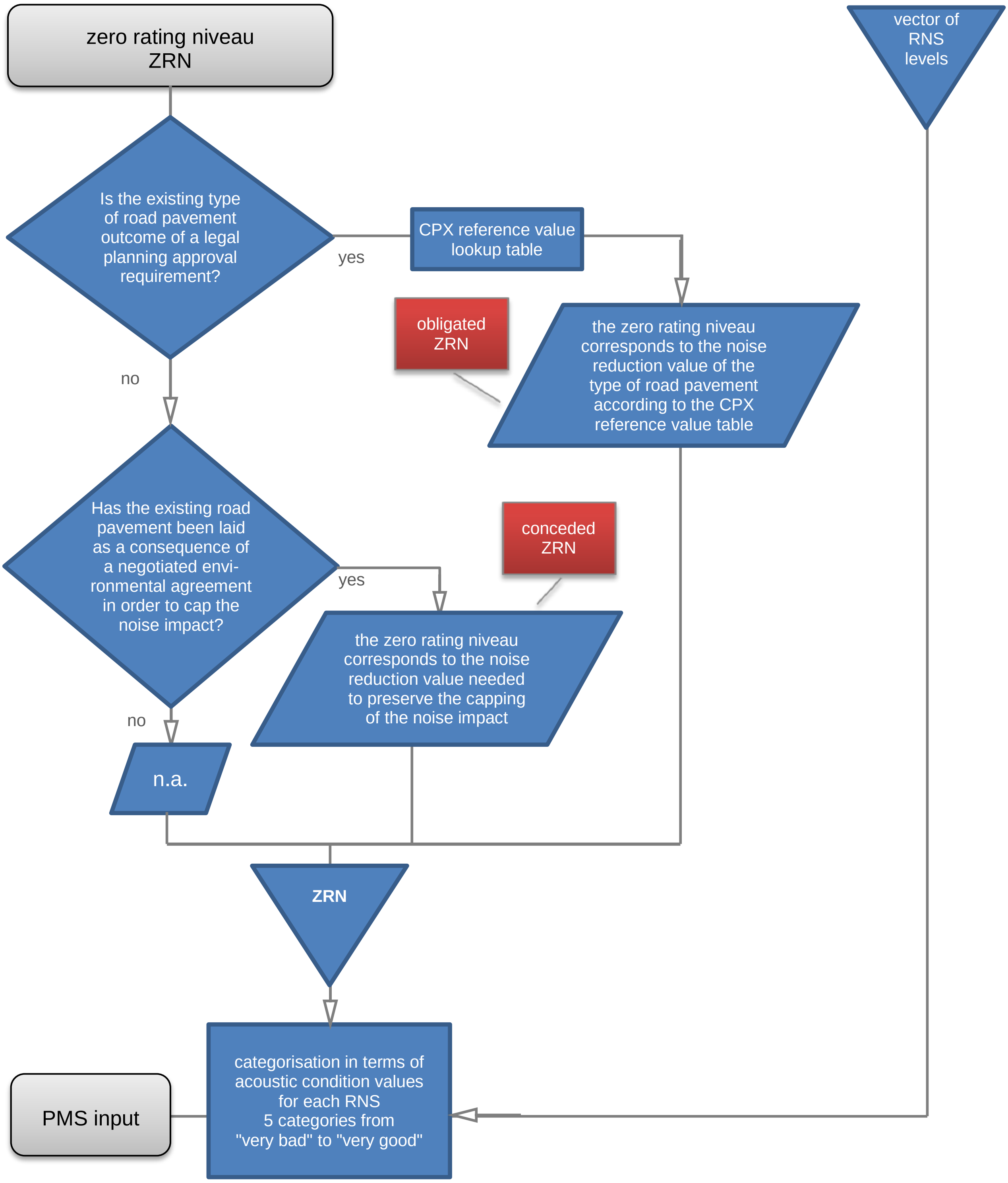


Figure 26. Flow chart of the acoustic road condition evaluation for one lane taking noise impact issues into account.

6 Conclusions

The work in WP3 addresses two main aspects of the implementation of the new attribute *noise* into a pavement management system:

1. The aggregation of raw CPX measurement segments up to longer segments which are meaningful with respect to the road maintenance and which homogenize the acoustic parameter without losing the relationship to the noise impact issue.
2. The introduction of a rating procedure which is strongly related to that what is needed in terms of noise protection issues without implementing a complex calculation procedure in order to take the relation between noise emission and noise impact resp. noise protection requirements into account.

The aggregation of the CPX data can be performed within and without the context of noise impact issues. Neglecting the noise impact the CPX-data should be aggregated as follows:

1. In terms of a pavement management system the road lanes should be considered and processed separately
2. Pavement management systems are based on consecutive 100 m road sections. Therefore, the CPX-samples should be made this long by averaging consecutive sets of five 20 m CPX-segments each.
3. Application of the median function over five consecutive 100 m sections for each 100 m section.
4. Application of the peak filter
5. Rounding of the remaining values to 0.5 dB.

Taking the noise impact aspect into account the procedure described above should be completed by application of the following steps:

1. In terms of a pavement management system the road lanes should be considered and processed separately.
2. Pavement management systems are based on consecutive 100 m road sections. Therefore, the CPX-samples should be made this long by averaging consecutive sets of five 20 m CPX-segments each.
3. Determination of the distances between each 100 m road section and the nearest building. If buildings do not exist or are not subject to specific protection issues, the distance would be set to infinite.
4. Determination of length (amount of 100 m sections) of Relevant Noise Segments for each 100 m road section based on the distances determined in step 3.
5. Application of the median function over the derived lengths of the Relevant Noise Segments for each 100 m section.
6. Application of the peak filter.
7. Rounding of the remaining values to 0.5 dB.

Finally, the application of the Zero Rating Niveau helps to introduce a rating scale for the results of the data aggregation in an automated way. The comparison of the aggregated levels with given reference levels makes it easy to decide whether the current acoustical behaviour of a road section is relevant with respect to noise protection or not. This supports the road administrator in his decision if a road section has to be prioritized concerning road maintenance for noise protection reasons. The ZRN can be set for an entire road section of several kilometres. The niveau is applied for each 100 m road section in the PMS.

According to road administrations pavement management systems are capable of handling separate lanes. The measuring or evaluation data of separate lanes should not be merged within the database. For analysis and review purposes of large road sections algorithms can be used to derive a global grade for rating. The algorithm could be based on the maximum value to show the worst case. In order to represent noise emissions or the noise impact, the averaging should be energy based and weighted by the traffic volume and composition of each lane.

A bigger concern to road administrations are the measurements on all lanes themselves. Of course the costs are a lot higher when measuring all lanes but there are also significant health and safety considerations that need to be addressed if measurements were to be done at 80 km/h in passing lanes. Therefore, the question arises if the acoustic rating of a road section can be done in a reasonable way with just the data of the right lanes.
Where the renewal of the road surface wasn't too long ago and was done on all lanes at the same time the differences between the lanes will be negligible. In time the acoustic deterioration of the right lane is higher than of the others because of heavy vehicles. Using just the data from the right lane for the entire road would be a bit pessimistic regarding the noise impact but could still be considered a worst case.
When the surfaces of single lanes are replaced it becomes a lot more complicated. One way to avoid measuring all lanes would be to incorporate an aging model into the PMS in order to track the acoustic deterioration of each lane. For this the traffic volume and composition is needed for each lane. The aging effect of low noise road surfaces is investigated, quantified and modelled in WP2.