ACOUSTICS OF THE ROAD SURFACES
FUNDAMENTALS, EXPERIENCE AND PRACTICE
CANTON OF AARGAU

3. Edition

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Foreword

The Canton of Aargau, and in particular its Noise Abatement Section, has been working intensively on the acoustics of road surfaces for many years. On the one hand, the acoustic properties of existing road surfaces are monitored across the entire cantonal road network using CPX measurements. On the other hand, the Noise Abatement Section is strongly committed to the further development and optimization of low-noise pavements. The wealth of experience in the field of road surface acoustics is compiled in this documentation as a working aid. It is a snapshot that shows the current state of knowledge. The aim of this documentation is to highlight the knowledge gained on the production and installation of low-noise pavements and to provide information on planning and practical implementation. Furthermore, the documentation deals with the advantages and disadvantages of the individual technologies and provides road construction authorities with recommendations for action. Various measurement procedures and methods are also explained. The documentation is aimed at all those working in the field of acoustics and is intended to provide an in-depth insight into the subject of the acoustics of road surfaces.

List of abbreviations

Abbreviation	Meaning
CPX	Close-Proximity
CT	Computer tomography
dB	Decibel
DSAK	Thin Asphalt Layer Cold (GER: Dünnschicht Asphalt Kalt)
EMPA	Swiss Federal Laboratories for Materials Testing and Research (GER: Eidgenössische Materialprüfungs- und Forschungsanstalt)
FEDRO	Swiss Federal Roads Office
FOEN	Swiss Federal Office for the Environment
H1	CPX test tyre for trucks
Hz	Hertz
ISO	International Organization for Standardization
L_CPX	CPX-Level
L_eq	Equivalent Continuous Sound Level
L_max	Maximum Sound Pressure Level
LNP	Low-Noise Pavement
LSP	Noise Abatement Project (GER: Lärmsanierungsprojekt)
LSV	Noise Abatement Ordinance (GER: Lärmschutzverordnung)
MA	Mastic Asphalt
OB	Surface Treatment (GER: Oberflächenbehandlung)
P1	CPX test tyre for normal cars
PA	Porous Asphalt
PmB	Polymer Modified Binders
PSV	Polished Stone Value
SDA 4	Semi-Dense Asphalt with a maximum grain size of 4 mm
SDA 8	Semi-Dense Asphalt with a maximum grain size of 8 mm
SEM	Sample Emission Measurements
ShoreA	Characteristic Value for Shore Hardness / Rubber Hardness
SPB	Statistical Pass-by
SPERoN	Statistical and Physical Explanation of Rolling Noise
StL-86+	Swiss road noise emission model 1986+
VC	Void Content
VSS	Swiss Association of Road and Transportation Experts (GER: Schweizerischer Verband der Strassen- und Verkehrsfachleute)
WS	Test Method According to Wehner/Schulze

1. Basics of road noise

In order to be able to successfully implement low-noise pavements in practice, it is of great importance to know the most important basics about the generation of road noise and tyre-road noise, as well as about the mode of action of low-noise pavements.

1.1 Road noise components

In Switzerland, every seventh person during the day and every eighth person at night is affected by excessive road noise [1]. In addition to airflow noise at the chassis, the two most important sources of road noise are rolling noise (sound generated by the interaction between tyres and the road surface) and propulsion noise (noise from the engine, gearbox and exhaust).

Recent research has shown that rolling noise in passenger cars dominates from a speed of about 16 km/h onwards when driving at a constant speed [2]. For trucks, this is the case at speeds of approximately 42 km/h, depending on the vehicle class [3]. For other vehicle types (tractors, motorbikes and construction machinery), it is to be expected that the crossover speed (speed at which the proportion of rolling noise exceeds the proportion of propulsion noise) is higher than for truck vehicle classes or that propulsion noise dominates over all speeds. Very loud vehicles (sports cars, modified or tuned vehicles, etc.) behave similarly, with propulsion noise often dominating over all speeds.

The importance of rolling noise in the overall generation of road noise (even at low driving speeds) is heavily dependent on the road surface.

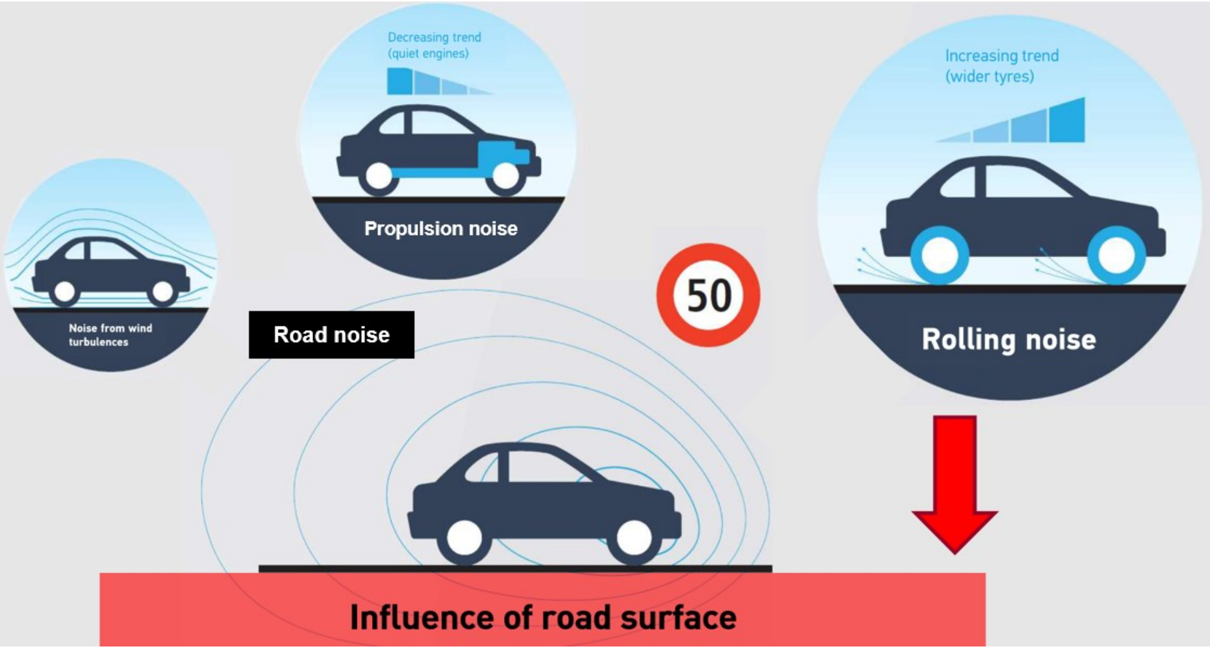


Figure 1: Influence of the road surface on the generation of road noise for speeds above 30 km/h; size of the pictograms depending on their contribution to the total sound energy (Source: [4], modified by Grolimund + Partner AG)

Accordingly, low-noise pavements are an effective noise protection measure in urban areas (30 – 50 km/h), overland/rural areas (60 – 80 km/h) as well as on motorways (80 - 120 km/h). However, it must be noted that in rural areas, the noise reduction achieved by low-noise pavements can be compromised if there is a very high proportion of trucks or a large number of very loud vehicles.

1.1.1 Influence of the velocity

In one study [2], 14 vehicles built between 2002 and 2015 were investigated with regard to noise emission with different gear selection, driving speed and weighted according to their prevalence on Swiss and European roads. Figure 2 shows the noise emissions of an average European vehicle fleet. The black line describes the total noise emissions, the orange line represents the share of rolling noise and the green line the share of propulsion noise. The crossover speed, i.e. the speed at which the rolling noise component is higher than the propulsion noise component, is 15.7. km/h [2].

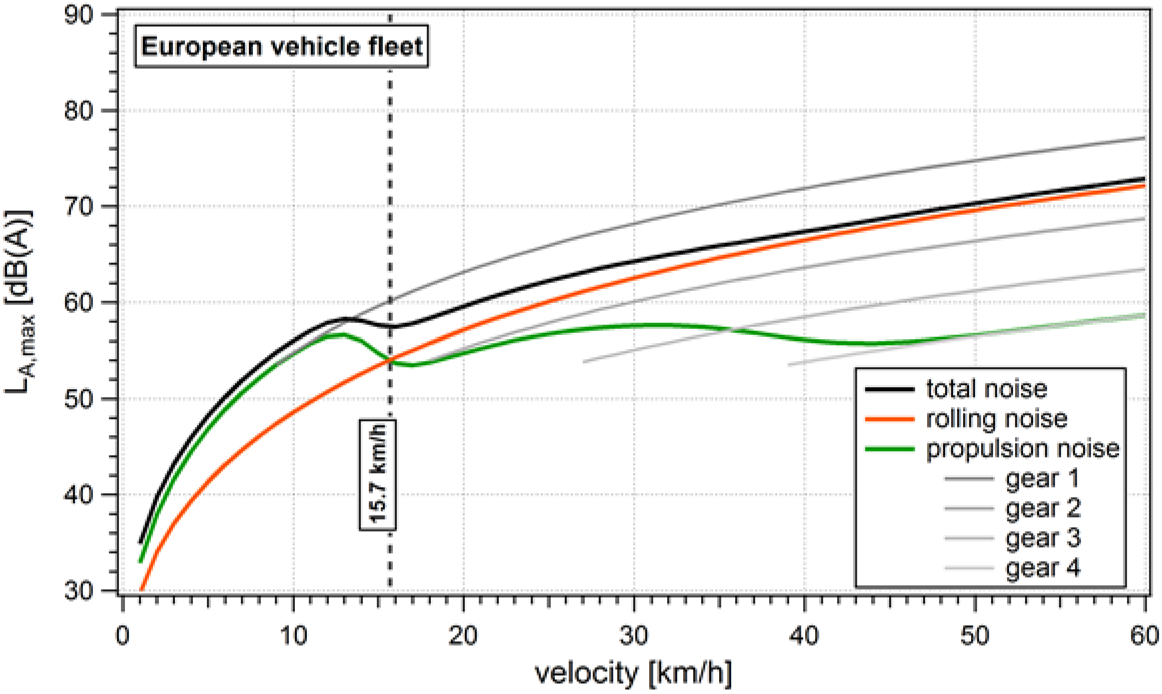
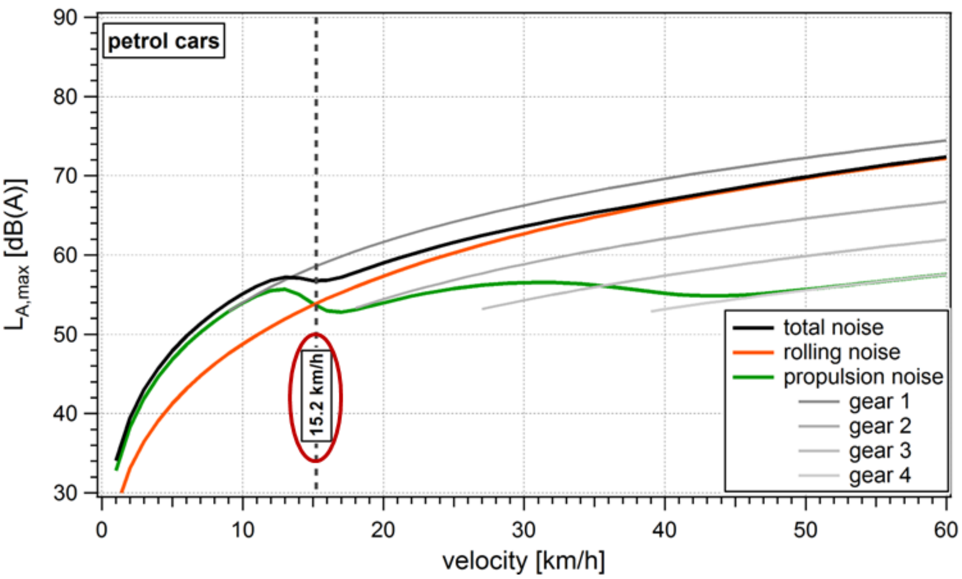
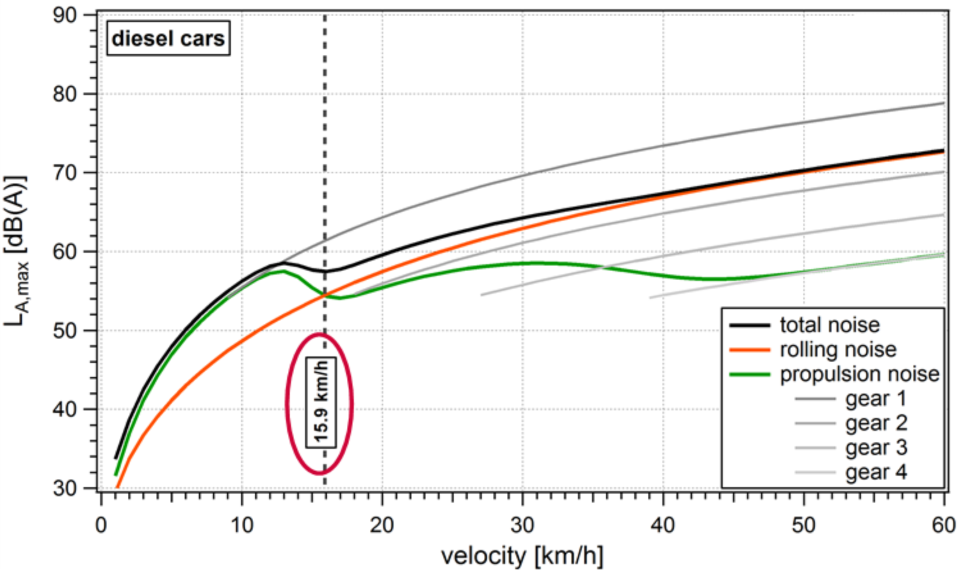
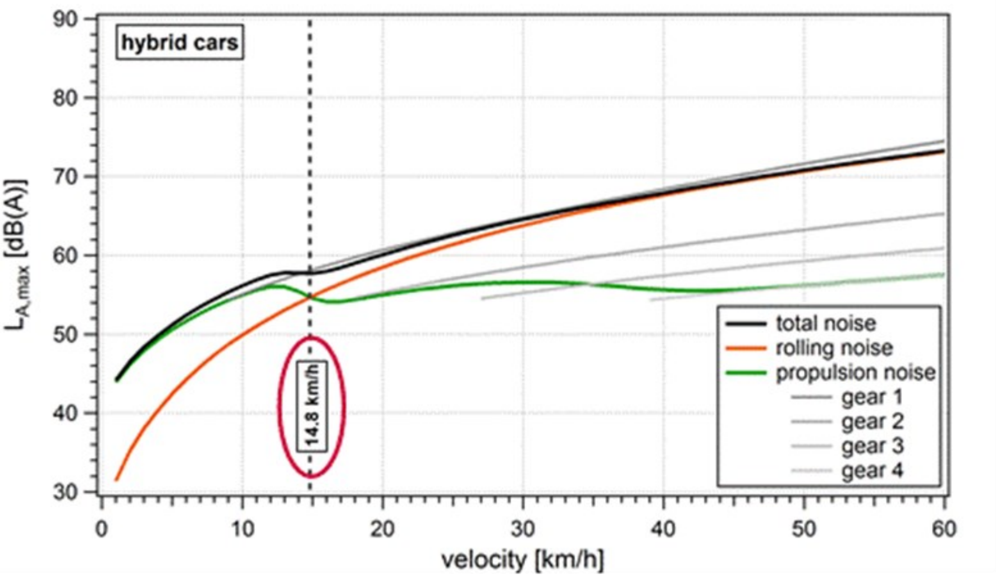


Figure 2: Noise emissions as a function of speed - average European vehicle fleet (Source: [2])

Broken down by the type of propulsion, the crossover speed for petrol vehicles is 15.2 km/h, for diesel vehicles 15.9 km/h, and for hybrid vehicles 14.8 km/h. Lower overall noise emissions were generally measured for electric vehicles. The hybrid vehicles showed slightly higher rolling noise levels compared to the electric vehicles, which in the present sample can probably be attributed to their greater weight and the related wider tyres (see Figure 3) [2].


petrol cars
15.2 km/h
total noise
rolling noise
propulsion noise
gear 1
gear 2
gear 3
gear 4
$L_{A,max}$ [dB(A)]
velocity [km/h]


diesel cars
15.9 km/h
total noise
rolling noise
propulsion noise
gear 1
gear 2
gear 3
gear 4
$L_{A,max}$ [dB(A)]
velocity [km/h]


hybrid cars
14.8 km/h
total noise
rolling noise
propulsion noise
gear 1
gear 2
gear 3
gear 4
$L_{A,max}$ [dB(A)]
velocity [km/h]

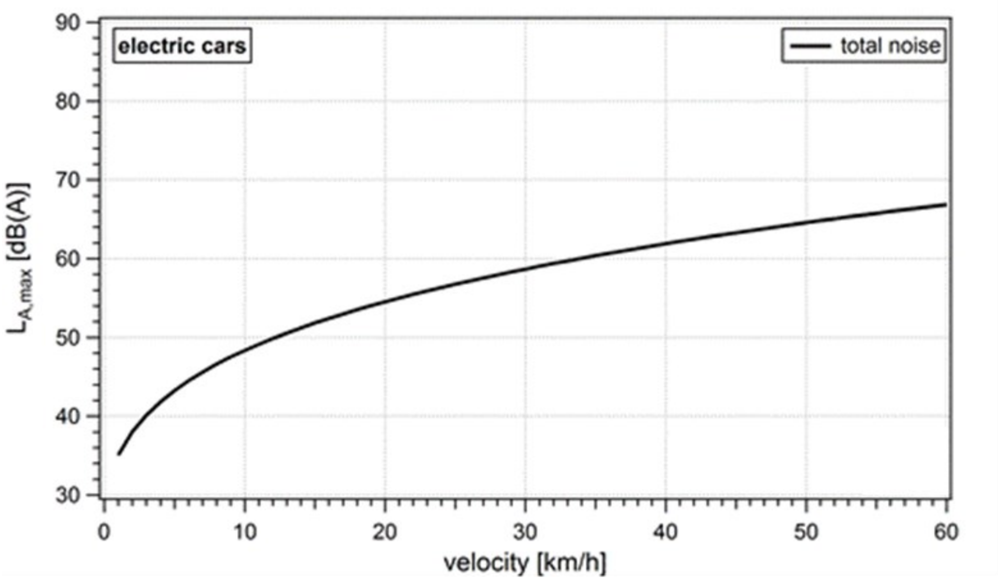


Figure 3: Noise emissions as a function of speed for petrol, diesel, hybrid and electric vehicles (Source: [2])

For all vehicle groups, the propulsion noise of driving in first gear shows the highest emission values. When driving in first gear (especially when starting from a standstill), low-noise pavements are hardly effective. This must be taken into account, for example, in 30 km/h zones with physical measures that force vehicles to stop (e.g. transversely offset, lateral parking or obstacles) (see also chapter 1.1.2). As early as second gear, the rolling noises with which low-noise pavements gain their effectiveness begin to dominate.

Figure 4 shows the proportions of rolling noise and propulsion noise for trucks as a function of the speeds driven.

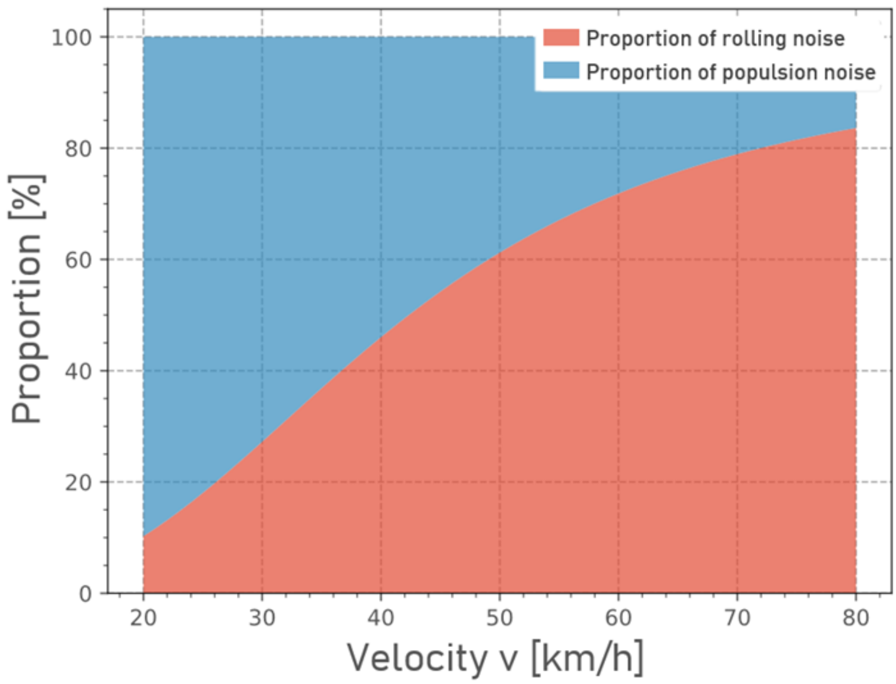


Figure 4: Noise emissions as a function of speed for trucks according to SonROAD18 (truck pass-by at constant speed according to Swiss10-converter , calculation SS-50) (Source: Grolimund + Partner AG according to [3])

According to the above figures, the rolling noise contributions can be calculated for different speeds, which are shown in Table 1 and Table 2. These values are valid for constant driving scenarios and can be used as an indicator for the effectiveness of low-noise pavements in situations with low actual speeds and constant driving. For mixed traffic, the sound energy components for the individual vehicle categories must also be considered.

Table 1: Rolling noise as a proportion of the total noise according to SonROAD18 (car pass-by at constant speed) and handling proposal for considering the effect of low-noise pavements. (Source: Grolimund + Partner AG)

Speed	**20**	**30**	**40**	**50**	**60**	**80**	**100**	**120**
Energy share rolling noise	0.46	0.72	0.85	0.90	0.93	0.96	0.97	0.97
Effectiveness of LNP (handling proposal)	1/2	3/4	1	1	1	1	1	1

Table 2: Rolling noise as a proportion of total noise according to SonROAD18 (pass-by of two-axle trucks at constant speed) and handling proposal for considering the effect of low-noise pavements. (Source: Grolimund + Partner AG)

Speed	**20**	**30**	**40**	**50**	**60**	**80**	**100**	**120**
Energy share rolling noise	0.15	0.34	0.52	0.65	0.75	0.85	-	-
Effectiveness of LNP (handling proposal)	1/6	1/3	1/2	2/3	3/4	1	-	-

The pavement effect at low speed was estimated in the study by Egger et. al. (2016) for a newer vehicle fleet [5]. Generally, the acoustic performance of low-noise pavements decreases with speed. This can be explained by the fact that the relative contribution of rolling noise to total noise also decreases with decreasing speed [5].

The effect of SDA 4 and SDA 8 pavements at low driving speeds can therefore be estimated as follows:

Table 3: Effect of pavement at low speeds with mixed traffic 8% (Source: [6])

Effect LNP	conventional	SDA 4 pavement	SDA 8 pavement
Effect LNP @ 50km/h	0	-3.0	-1.0
Effect LNP @ 30km/h	0	-1.9	-0.6

Similarly, the 30 km/h speed limit measure has a reduced effectiveness, when combined with low-noise pavements. This must be considered when planning noise protection measures. There is a need for research to reliably predict the combination of low-noise pavements and 30 km/h speed limits.

1.1.2 Influence of the driving behaviour

In principle, the driving behaviour at low speeds contributes more to noise emissions than in the higher speed range. Accordingly, noise emissions are significantly influenced by gear selection and acceleration style (prudent, impetuous). The engine speed, as well as the maxima in driving speed and acceleration, have a direct effect on noise emissions [7]

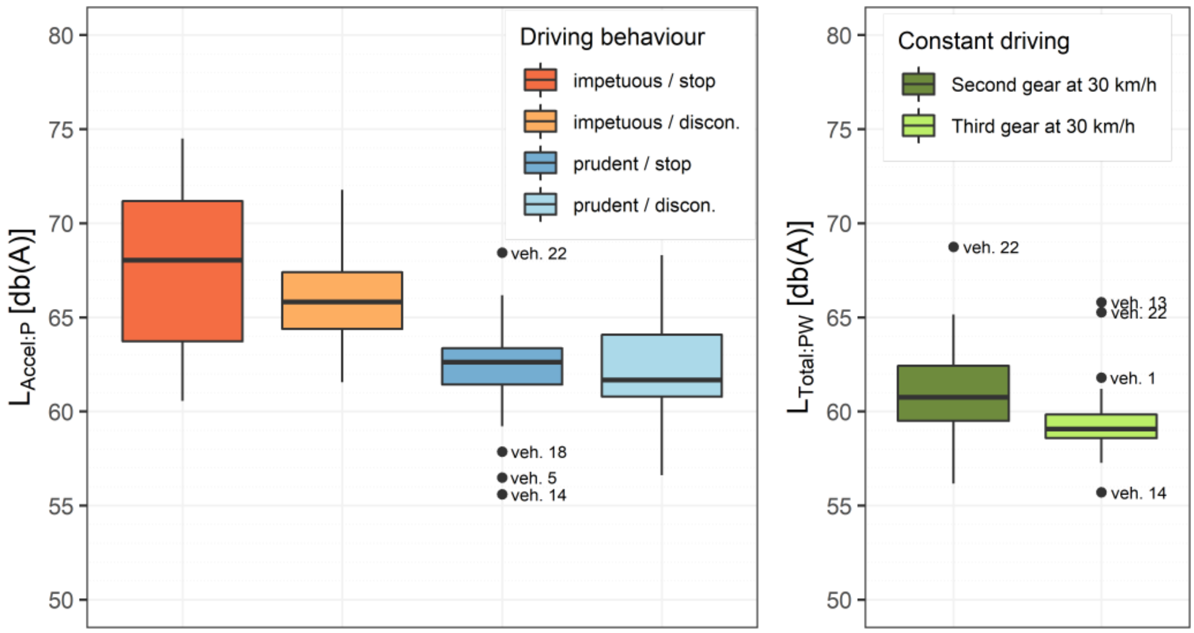


Figure 5: Statistical distribution (boxplots) of the total noise per acceleration scenario compared to the total noise at constant driving in 2nd and 3rd gear (Source: [7])

The following typical inner-city situations are influenced to a greater extent by the driving behaviour:

- Node/Roundabout
- Traffic lights
- Structural measures in 30 km/h zones that force vehicles to stop.
- Pedestrian crossing
- Traffic lights
- Crossings/Right of way
- Roadway stops
- Area after tight cornering situations
- Speed change urban area – overland / rural area
- Gradients

Based on experience, it can be assumed that the disruptive effect of acceleration is particularly present when acceleration to higher speeds is possible. For example, if accelerating from 0 to 50 km/h, impetuous (and more annoying) accelerating is more likely due to the longer acceleration process than, for example, accelerating from 0 to 30 km/h. It is also to be expected that accelerating on overland roads from 50 to 80 km/h will have an increased effect on the annoyance of residents.

1.2 Tyre-road noise

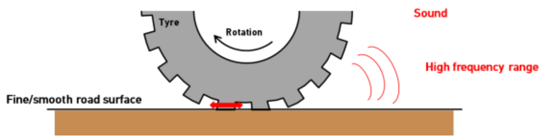
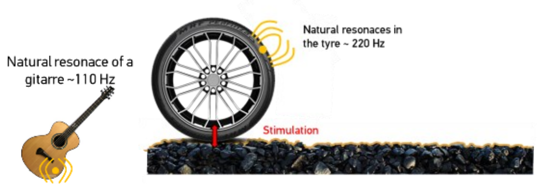
1.2.1 Noise generation mechanisms

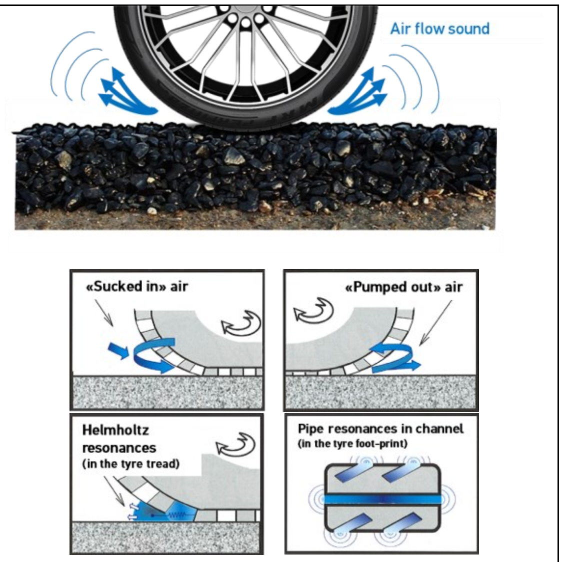
Tyre-road noise can be described and summarised by the following four noise generation mechanisms:

- Vibration sound (radial and tangential)
- Cavity resonances
- Airflow noise
- Horn effect (sound amplification)

The following table explains the four noise generation mechanisms in more detail.

Table 4: Explanations of noise generation mechanisms (Source: Grolimund + Partner AG according to [8], [9], [10], [11])

Vibration sound (radial)	▪ Varying surface height (texture road surface) ▪ Varying contact area tyre (tyre tread) ▪ Change in contact forces → vibration→ sound generation ▪ Sound frequency: f = v / λ→ low to medium frequency range (according to Kuijpers & van Blokland 2001 [8])	
Vibration sound (tangential)	▪ Stick-slip: sticking forces between tyre and road surface ▪ Essential for: - fine/smooth road surfaces (e.g. parking garages) - tyre block treads (truck tyres of the drive axle) → high frequency range (according to Sandberg & Ejsmont 2001 [9])	
Cavity resonances	▪ Natural resonances in the tyre similar to the body of a musical instrument (according to Mohamed et al. 2015 [10])	

Airflow noise	▪ Pumped out and sucked in air in the contact zone ▪ Helmholtz resonances in the tyre tread ▪ Resonances in the tyre profile of the footprint → high frequency range (according to Sandberg & Ejsmont 2001 [9])	
Horn effect (sound amplification)	▪ Tyres and road surfaces form a horn ▪ Car tyre horn effect (depending on tyre width): from approx. 500-700 Hz (up to max. approx. 1500 Hz) (according to Peters & Kuipers 2010 [11])	

1.2.2 Spectrum of tyre-road noise

The spectrum of tyre-road noise can be simplified into three main frequency ranges, which are characterised by different sound generation mechanisms:

- **Low (T):** In the low-frequency range, mainly vibration-related generation mechanisms are dominant in sound generation. The contributions of cavity resonances and airflow noise play a rather subordinate role.
- **Medium (M):** In the medium frequency range, the transition from vibration sound to airflow sound takes place. At the same time, there is a contribution from cavity resonances of the tyres.
- **High (H):** The high-frequency range is mainly characterised by airflow noise. In the latest research, however, it is assumed that vibration-related sound generation in this frequency range is much lower, but not completely negligible.

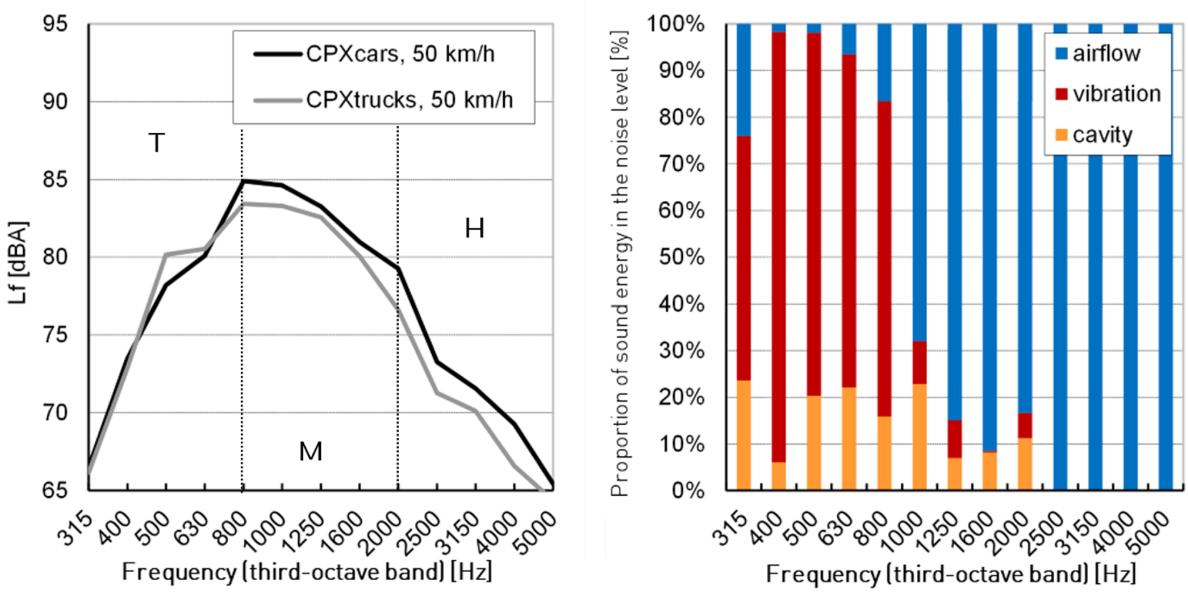


Figure 6: Example of a spectrum of tyre-road noise for cars and trucks (left) and the respective shares of different generation mechanisms in the sound energy per one-third octave band based on SPERoN modelling (Source: Grolimund + Partner AG).

1.2.3 Influence of the temperature

The air temperature influences the tyre-road noise, as the properties of the tyres change at different temperatures. Basically, the higher the temperature, the quieter the tyre-road noise (for explanations see also chapter 3.3.1).

1.3 Functionality of low-noise pavements

The following illustration shows how low-noise pavements work.

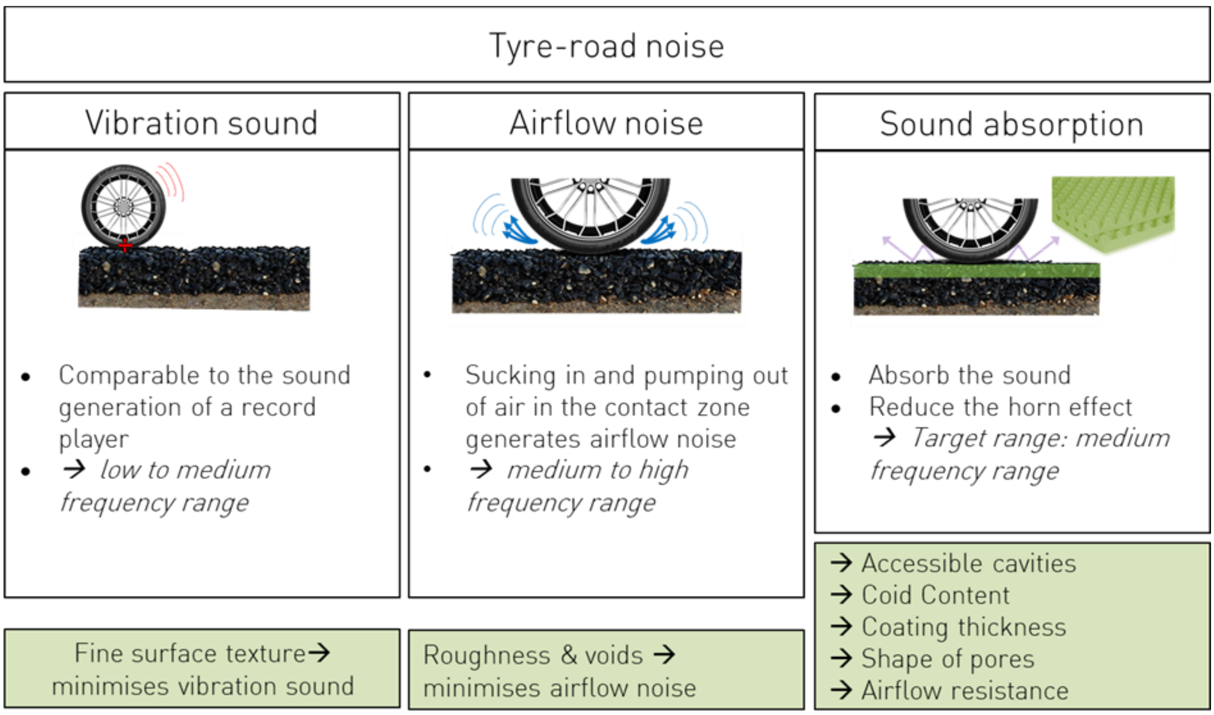


Figure 7: Functionality of low-noise pavements (Source: Grolimund + Partner AG)

Reduction of vibration sound

The surface condition of the road surface influences its acoustic quality. With a fine surface, the tyres of the vehicles are less stimulated, which reduces the vibration sound. At the same time, the reduced stimulation also results in fewer cavity resonances in the tyres. In general, concave textures stimulate the tyres to a lesser extent than convex textures. Strongly convex textures generally lead to an increase in vibration sound due to increased stimulation of the tyre when rolling over.

Reduction of airflow sound

The specific airflow resistance describes how easy it is for air to be pushed out from or be sucked into the tyre-pavement contact zone. The lower the airflow resistance, the easier this can happen, resulting in a decrease in airflow noise. Lower airflow resistance can be achieved by optimising the surface texture (with a certain degree of surface roughness) or by the presence of interconnected pores in the road surface. In the case of acoustic texture optimisation of road pavements (without significant voids in the pavement), slightly improved air flow properties can be achieved both by negative textures (e.g. ACMR – asphalt concrete macro rough) and fine positive textures (e.g. mastic asphalts, fine surface treatments).

Sound absorbing effect

The sound absorption properties of a road surface are highly frequency-specific and depend on its coating thickness, porosity, pore shape, as well as their degree of interconnection and specific flow resistance. The sound absorption properties of a road surface can have a great influence on the extent of the horn effect and on sound propagation. Their measurement is of great importance in the closer analysis of the acoustic effectiveness of semi-dense and porous pavements.

The sound-absorbing properties of a road surface are best when the highest possible degree is achieved in the frequency range in which the most sound energy is generated when vehicle tyres roll over the road surface. This is typically the case in the middle frequency range between 800 Hz and 1250 Hz.

2. Low-noise pavements

2.1 Definition of low-noise pavements

In Switzerland, a pavement is considered to be low-noise if an initial noise reduction of -3 dB is achieved and a noise reduction of at least -1 dB is achieved over the entire lifetime [12]. Pavements with an initial effect of -6 dB and an effect of -3 dB over the entire lifetime are considered to be low-noise pavements (LNP) with a high effect. The effect or noise reduction relates to the theoretical reference pavement of the Swiss road noise model StL-86+.

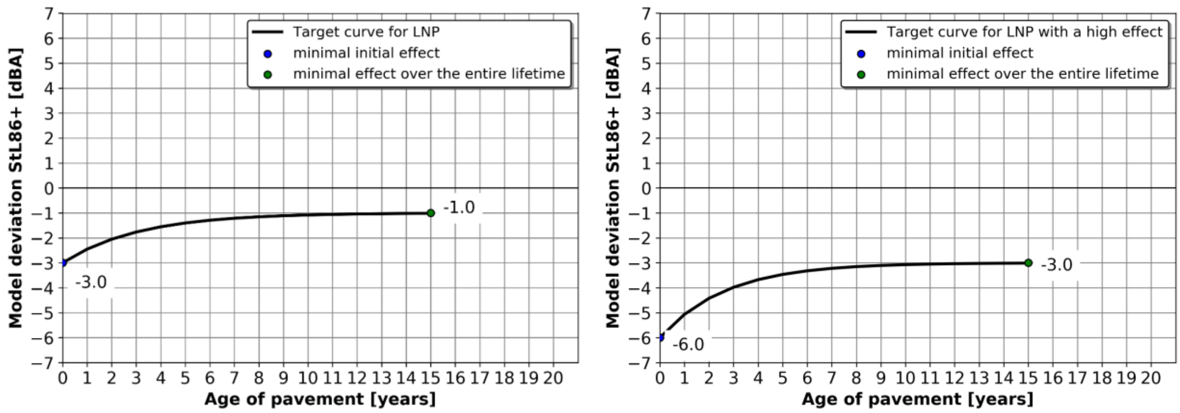


Figure 8: Target curves of the acoustic effect over the lifetime for LNPs. (Based on [12])

During the entire lifetime, low-noise pavements show a significant noise reduction compared to conventional road pavements. Federal subsidies can be claimed for low-noise pavements. In order to receive subsidies, an acoustic reduction of at least 1 dB (final value of the acoustic lifetime) must be taken into account in the noise abatement project (LSP). The acoustic effect of the low-noise pavements must be periodically checked by measurements. If the permissible noise emissions are exceeded, the necessary measures must be taken according to article 37a LSV (e.g. pavement replacement) [13].

2.2 Requirements for low-noise surface courses

The challenge in the development and use of low-noise pavements is to meet the numerous requirements. Constant optimisation of the entire system is required.

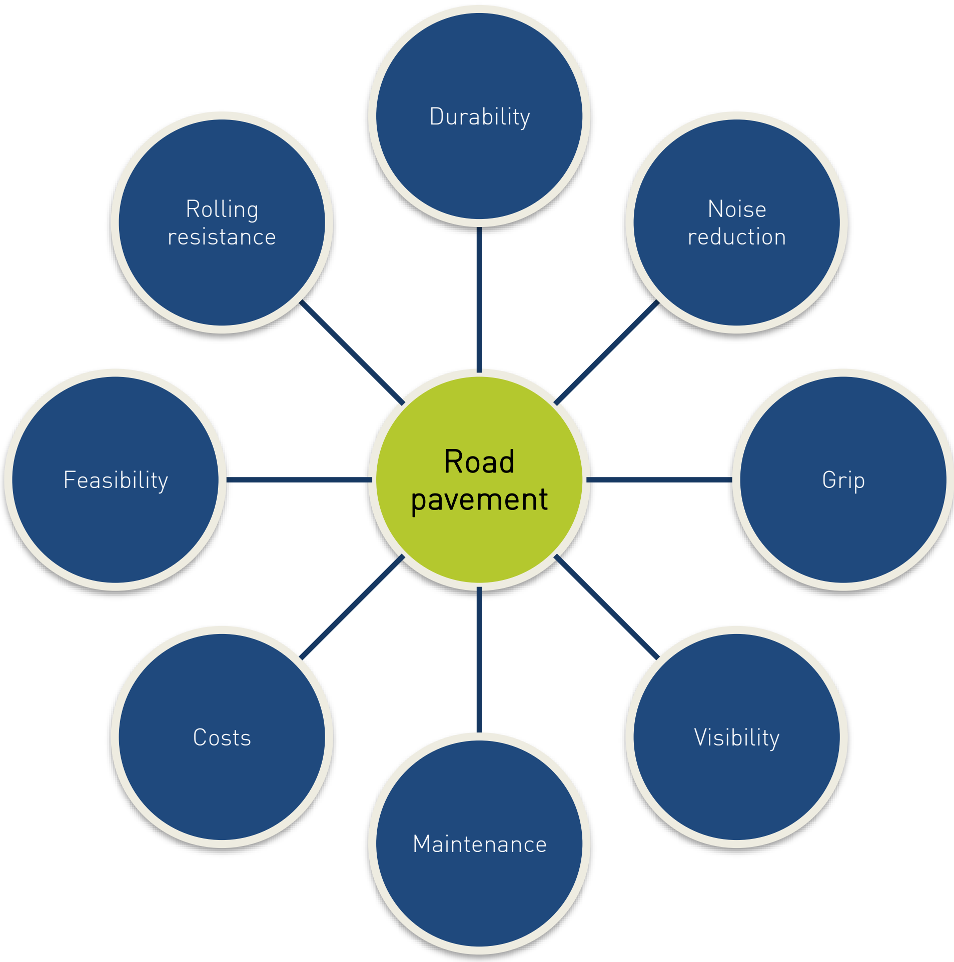


Figure 9: Requirements for low-noise surfaces (not exhaustive) (Source: Grolimund + Partner AG)

- **Durability:** One of the most important requirements for low-noise surface courses is good durability, both in structural and acoustic terms. Today, FEDRO assumes a lifetime of 25 years for conventional pavements, 20 years for SDA 8 and 10-15 years for SDA 4 [14].
- **Noise reduction**: Depending on the type of surface course, a permanent noise reduction is required from low-noise road surfaces. For SDA 8, a noise reduction of at least -1 dB and for SDA 4 of at least -3 dB is expected during the entire lifetime (see chapter 2.5).
- **Grip:** Grip, such as wet grip or cornering grip, is an important general requirement for surface courses with regard to road safety.
- **Visibility:** Visibility requirements, especially in wet conditions, are also key elements in terms of road safety. Visibility depends on the formation of spray plumes on the road surface.

- **Maintenance**: The effort and requirements for winter maintenance (snow removal, etc.), patching, cleaning, etc. should be similar to those of conventional wearing courses.
- **Costs**: The installation costs of low-noise wearing courses should preferably be the same or not significantly higher than those of conventional wearing courses.
- **Feasibility**: Special requirements regarding feasibility (production of mixtures, materials, installation conditions, know-how, etc.) should be as low as possible in order to enable broad use.
- **Rolling resistance**: Reducing the rolling resistance of the vehicle can reduce fuel consumption and pollutant emissions. The surface condition of road surfaces has a strong influence on rolling resistance. The potential for savings through road pavements with low rolling resistance is great, as all road users contribute to this.

2.3 Requirements for the quality of the road surface

In principle, the binder course does not need to be replaced when installing SDA pavements. However, the risk of structural cracking is increased if subsidence is expected (e.g. in shafts). In this case, it is recommended to apply pavement reinforcements.

In the Canton of Aargau, the pavement structure is standardised as follows:

Traffic class		Thickness (mm)	Pavement structure Inside towns	Outside towns
T5 220 mm		30 95 95	SDA 4 - 12 / SDA 8 - 12 [1] AC B 22 H AC T 22 H	AC MR 8 AC B 22 H AC T 22 H
T4b 170 mm		30 70 70	SDA 4 - 12 / SDA 8 - 12 [1] AC B 22 H AC T 22 H	AC MR 8 AC B 22 H AC T 22 H
T4a 150 mm		30 50 70	SDA 4 - 12 / SDA 8 - 12 [1] AC B 16 S AC T 22 S	AC MR 8 AC B 16 S AC T 22 S
T3 130 mm		30 100	SDA 4 - 12 / SDA 8 - 12 [1] AC T 22 S	AC MR 8, AC 8, AC 11 [2] AC T 22 S
Bus stop or roundabout 220 mm		30 95 95	SDA 4 - 12 / SDA 8 - 12 [1] AC B 22 H AC T 22 H	AC MR 8 AC B 22 H AC T 22 H
Cycle or footpath		30 70	AC 8 N AC T 22 N	

[1] first-mentioned type = increased noise exposure according to the «Strategieplan Lärm»
second-mentioned type = average noise exposure according to the «Strategieplan Lärm»

[2] minimal course thickness: 35 mm

Figure 10: Standard of the pavement structure in the Canton of Aargau (Source: [15])

2.4 Low-noise pavements in Switzerland

Currently, the following six main approaches for the development of low-noise road surfaces in Switzerland can be noted, which are applied either in combination or individually, depending on the technology and the objective (see also chapter 1.3):

- Optimisation of the surface texture with regard to tyre stimulation and optimisation of the vibration properties respectively
- Optimisation of the surface texture with regard to the air flow properties through negative texture (concave textures) or very fine positive texture
- Optimisation of the air flow properties through voids near the surface
- Optimisation of sound absorption properties (acoustic impedance) through void structures accessible from the surface
- Reduction of the mechanical impedance by changing the material components and/or properties

The solutions applied in Switzerland are explained in more detail in the following subchapters. In the last decade, there has been a strong increase in the use of low-noise pavements in Switzerland. During the last 10 years, low-noise pavements have been installed on more than 1200 road sections in Switzerland as noise protection measure at the source. This has made low-noise pavements the most important noise protection measure in Switzerland. At that time, approximately 30% of all low-noise pavements implemented in Switzerland were located in the Canton of Aargau.

2.4.1 Porous asphalts PA

The first low-noise pavements were used in Switzerland in the early 1980s. At that time, these were primarily porous asphalts (water-permeable drainage surfaces), some of which are still used today on national roads due to their great noise reduction. Another advantage of porous asphalts is that their water permeability significantly reduces the spray plumes during precipitation and thus leads to better visibility, improved safety and thus to steadier traffic. In Switzerland, porous asphalts are usually produced with maximum grain sizes of 11 mm or 8 mm. Two-layer porous asphalts (as often used in the Netherlands and Japan, for example) are rarely used in Switzerland. Porous asphalts have special requirements for drainage and winter maintenance, have a shorter lifetime and are only effective when they are not contaminated. For successful application, porous asphalts require high speeds (>80 km/h), as only then does a self-cleaning effect occur [9].

2.4.2 Semi-dense asphalts SDA

In order to be able to reduce noise emissions also on municipal and urban roads using low-noise pavements, new solutions had to be sought. First attempts in this regard were made in the mid-1990s [16].

The first tests of low-noise pavements in inner-city areas focused on dense solutions. The noise-reduction effect was mainly achieved by a noise-optimised surface texture. This turned out to be considerably less than that of open-pored asphalt pavements. In

2003, therefore, the FOEN, together with FEDRO, initiated a research project with the aim of developing low-noise pavements specifically for the low speed range [17]. The study showed that semi-dense asphalts with small grain sizes and medium cavity content are most effective in the low speed range [18]. More recently, research in Switzerland has therefore focused on semi-dense asphalts as a compromise between noise reduction and durability.

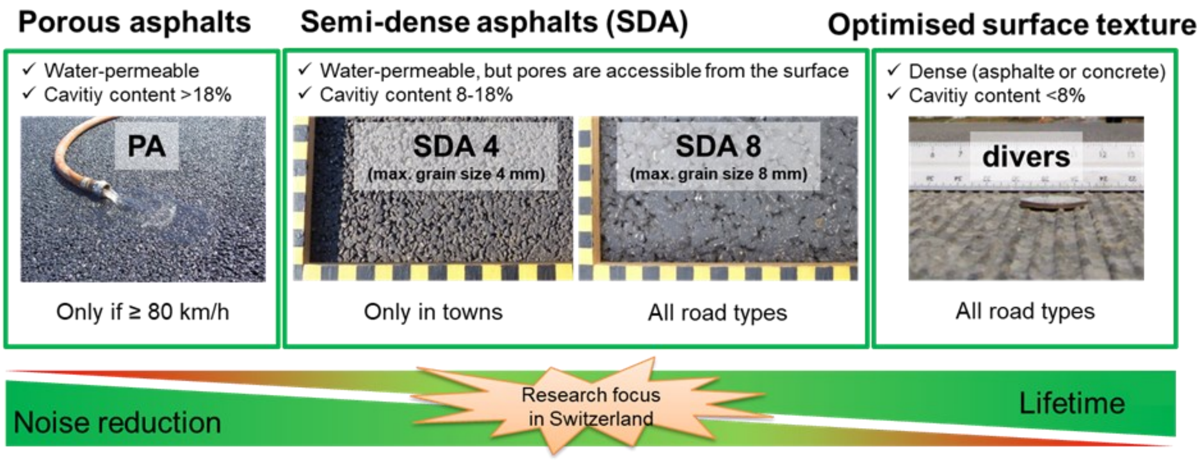


Figure 11: Overview of the main types of low-noise pavements in Switzerland (Source: Grolimund + Partner AG)

In 2010, the FOEN and FEDRO launched a research package in which semi-dense asphalts inside urban areas were extensively tested with 15 test installations. In this context, a Swiss standard was drafted (VSS-40436 [19]), which should allow construction companies to produce and install noise-reducing semi-dense asphalts. The findings on the acoustic effect and the constructional requirements of these test pavements were recorded in the final report of the accompanying long-term monitoring [20]. In the meantime, the mixtures have been tested by various cantons with additional installations. With the additional test results, the most important parameters for the successful implementation of SDA could be obtained. Through data analyses of approx. 150 installations, the following results could be obtained within the framework of studies [21], [22] commissioned by the FOEN and the Canton of Aargau the most important material, manufacturing and installation parameters were identified. With these parameters, the noise reduction and durability of semi-dense asphalts can be further increased. These results are currently being incorporated into the existing VSS standard. SDA 4 pavements have become established in Switzerland as a proven noise protection measure in urban areas.

2.4.3 Texture-optimised construction methods

The following construction methods can be produced in a noise-optimised way. It should be noted, however, that generally lower noise reductions are achieved than with PA and SDA pavements.

Figure 12: Texture-optimised pavements (Source: Grolimund + Partner AG)

Table 5: Summary of texturally optimised construction methods (see also below) (Source: Grolimund + Partner AG)

Type	Scope of applicatioin	Acoustic properties
Mastic Asphalt (GA, MA) scattering 2/4	Brigdes, tunnel, patches	-2 to -3 dB compared to StL-86+ (after 4 years)
Washed Concrete 8mm	Roundabouts	approx. +/- 0 dB compared to StL-86+
Washed Concrete 11mm	Roundabouts	approx. +2 dB compared to StL-86+
OB (Surface Treatment)	Transition pavements	ca. 0 to +2 dB compared to StL-86+ (depending on grain size)
DSAK (Thin Asphalt Layer Cold)	Transition pavements	ca. -2 to +1 dB compared to StL-86+ (depending on grain size)
AC 8 (Asphalte Concrete 8 mm)	Standard pavement, manhole, patches	ca. -1 dB to 0 dB compared to StL-86+ after 8 to 10 years
Small stone paving	For aesthetic reasons	ca. 2 dB louder than sloping paving
Straight paving	For aesthetic reasons	ca. 1.5 to 2.5 dB louder than sloping paving
Sloping paving	For aesthetic reasons	ca. 1.5 to 2.5 dB quieter than straight paving

Mastic asphalts

Due to their composition, mastic asphalts (MA) are relatively more weather-resistant and wear-resistant. Mastic asphalts are therefore often used on bridges and engineering structures.

PA and SDA pavements do not completely seal the structure from water. This is undesirable on bridges due to possible damage to the waterproofing and the bridge structure. Therefore, waterproofing mastic asphalt pavements are usually installed on bridges. Thanks to optimisation of the surface texture, these can nevertheless be designed to reduce noise. The aim of the FEDRO research project "*Low-noise surfaces for mastic asphalt wearing courses on bridges" is to* develop a mastic asphalt wearing course whose surface is designed in such a way (scattering of chippings, treatment with special rollers, etc.) that the greatest possible reduction in traffic noise is achieved [23].

For this purpose, various noise-optimised mastic asphalts with different surface chippings were installed and accompanied by measurements. After 3 to 4 years, some of these still achieve a noise reduction of as much as -3 dB. This significant noise reduction is achieved with pure optimisation of the texture. Long-term experience with noise-optimised mastic asphalts is not yet available. Various research commissions for the investigation and optimisation of mastic asphalts are planned.

Washed concrete

Washed concrete is a concrete construction method in which the aggregate is exposed through a surface treatment. Washed concrete is a noise-optimised concrete construction method, but it is not considered low-noise per se. However, washed concrete surfaces are less noisy than concrete applied using conventional construction methods (with cross broom finishing).

The grain size and, to a lesser extent, the rock shape influence the acoustic properties of washed concrete surfaces. Experience shows that washed concrete road surfaces with a maximum grain size of 8 mm can reduce noise by approx. -2 to 0 dB. Washed concrete with a maximum grain size of 11 mm has similar or up to approx. 0 to +2 dB louder values than a neutral pavement (see Figure 13). Due to its directional and long-lasting texture, washed concrete is particularly suitable for use in roundabouts. Its installation is rather expensive. It should be noted that the amount of experience is relatively small at this point in time.

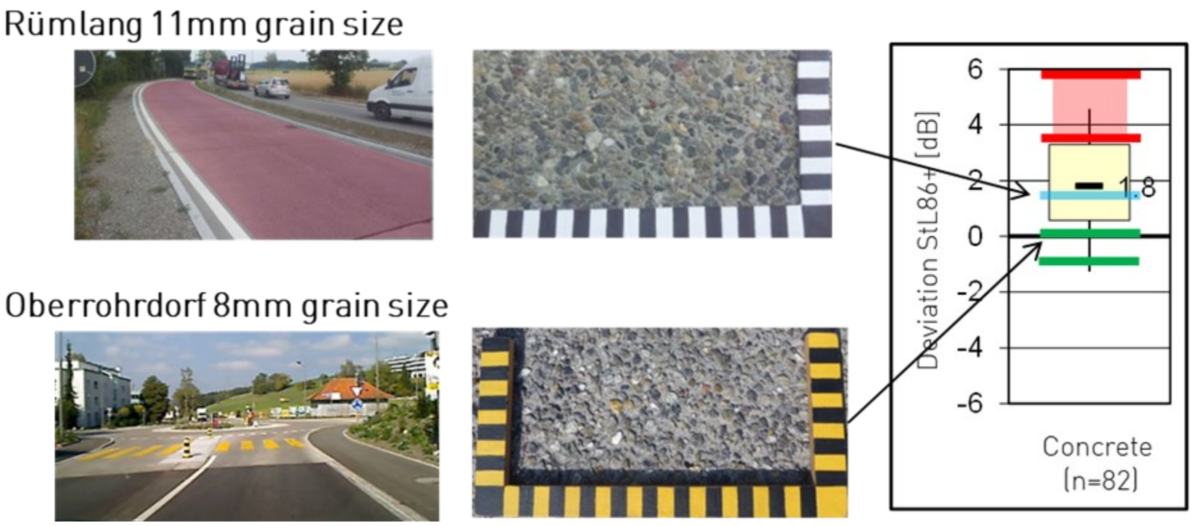


Figure 13: Comparison of washed concrete of different grain sizes with regard to acoustic pavement quality (Source: Grolimund + Partner AG)

Compared to concrete with a with cross broom finishing, washed concrete is able to reduce noise emissions by approx. 4 dB. These reductions are achieved by reducing the vibration sound and the airflow sound.

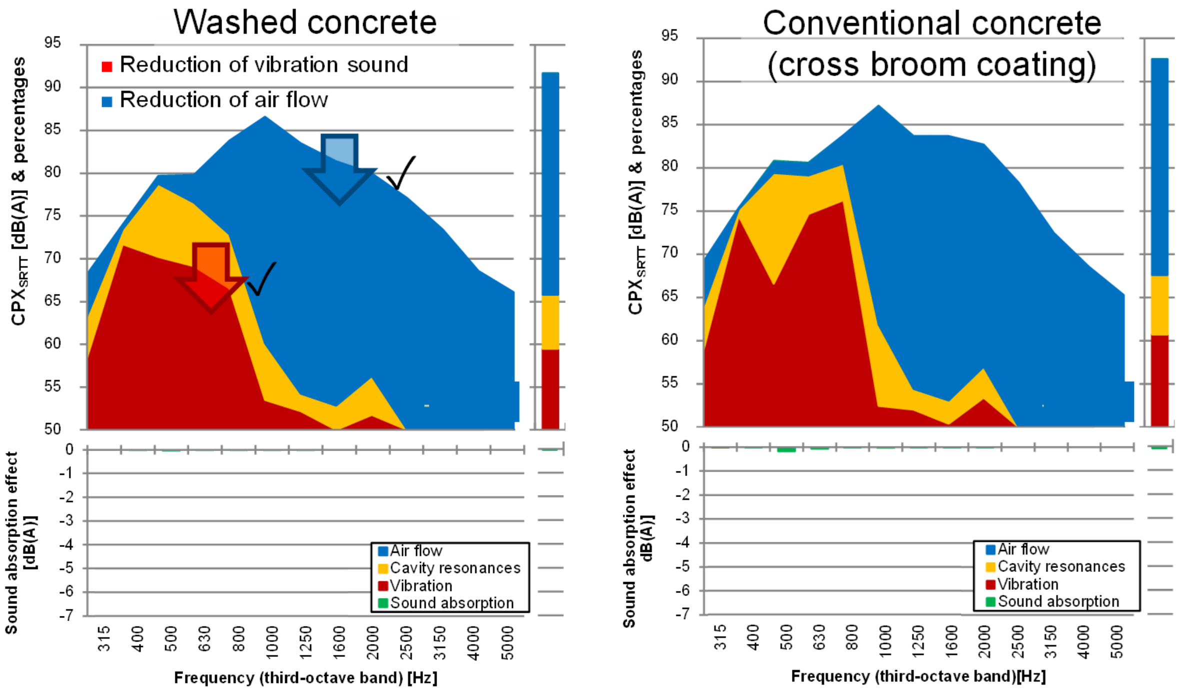


Figure 14: Spectral comparison of tyre/road noise of washed concrete and conventional concrete road surfaces (Source: Grolimund + Partner AG)

Noise-optimized transition pavements

Cold micro surfacing is a good option as a transitional measure (short and medium term rehabilitation measures) where high noise levels occur as a result of the current pavement condition. However, care should be taken to use grain sizes of 4/6 mm or finer to achieve good acoustic properties. Surface treatments should also be applied using the finest possible chipping.

Paving stone

Paving is installed exclusively for aesthetic reasons. When installing paving as a design element, care should be taken to ensure that there are as few or no differences in the level between paving stones as possible. In the following, different types of paving are compared with each other from a noise point of view.

Sloping vs. straight paving

Paving with inclined joints shows 1.5 to 2.5 dB lower rolling noise compared to paving with straight joints. There is less impulse noise when rolling over the sloping joints.

Large stone paving vs. small stone paving

Small stone paving is approx. 2 dB louder than large stone paving with sloping joints. The increase in rolling noise mainly takes place in the low frequency range.

Figure 15: Acoustic comparison of paving (Source: Grolimund + Partner AG)

Due to the increased rolling noise, it is recommended to use paving only on sections with low speeds (speed ≤ 30 km/h).

2.4.4 Trends in research on low-noise pavements

PERS (Pore Elastic Road Surfaces)

PERS (Pore Elastic Road Surfaces) were developed within the European project PERSUADE (2009-2015). The aim of the project, carried out by 12 research participants, is to develop a cost-effective poro-elastic road surface using old pneumatic material. For this purpose, individual test sections were installed internationally. The noise reduction of PERS is achieved through voids as well as through the mechanical impedance of the rubber fraction.

Recycled pavements with noise-reducing properties

Research is currently being conducted in Switzerland on recycled pavements. These are also being tested and optimised for their acoustic properties.

Cool road surfaces with noise-reducing properties

According to international studies, road pavements with a cooling effect can reduce the surface temperature by up to 10°C. The cooling effect is mainly achieved by a higher albedo of the pavement surface compared to conventional asphalts. Currently, ongoing studies are testing and investigating cooling road surfaces with regard to their long-term effect, their noise effect and various other parameters.

2.4.5 Potential for further optimisation

The following list contains aspects for further optimisation potential (not finite):

- Use of high-quality bitumen to extend lifetime and reduce rutting
- Optimisation of mastic properties (interaction of bitumen and filler)
- Use of alternative materials and additives (optimised granulates e.g. for chipping, rubber additives in the asphalt mix in the "dry" and "wet" process, etc.).
- Improved structural resistance through additions with fibres
- Reinforcements
- Extremely fine-grained coatings (SDA 2)
- Use of non-standard grain sizes such as SDA 6

2.5 SDA as preferred road noise reduction practice in the Canton of Aargau

In the interplay between noise reduction, void content and lifetime, it can be assumed that:

- The greater the void content, the shorter the lifetime
- the lower the void content, the longer the lifetime

The aim is to determine the optimum range (lowest possible void content with the greatest possible noise reduction) and to design the formulations accordingly. This can be done either with performance-oriented proprietary products, for which the pavement companies guarantee performance in the work contracts. Or composition-oriented: e.g. according to VSS-40425 (procedure Canton of Aargau). Table 6 shows the expected acoustic effect after installation and after 5 years, as well as the final effect.

Table 6: Expected acoustic effect of SDA coverings (Source: Grolimund + Partner AG)

Type	Scope of application	Initial effect	Effect after 5 years	Final effect
SDA 8	All road types including motorways	-5 to -3 dB	-2 dB	-1 dB
SDA 4	All road types in urban areas	-6 to -9 dB	-4 dB	-3 dB

2.5.1 Sub-types according to standard

In "VSS-40436 2019 Semi-dense mixes and wearing courses", the requirements for the new generation of low-noise pavements were specified. The following Figure 16 describes the designation. Table 7 contains the designations and limit values for the void content of the Marshall test specimens in the standard. The Marshall tests carried out for all SDA pavements in the Canton of Aargau.

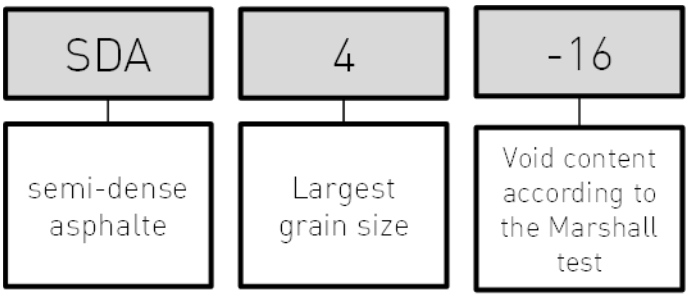


Figure 16: Designation of SDA coverings (Source: Grolimund + Partner AG)

Table 7 below shows the target void contents of SDA formulations with the permissible void content range of the mix according to VSS-40436 [24].

Table 7: Characteristic void content and limits of Marshall test specimens according to VSS-40436 [24]

Characteristic void content of Marshall test specimens [Volume-%]			
SDA 4	12	16	20
SDA 8	12	16	-
Limits for the void content of Marshall test specimens [Volume-%]			
SDA 4	10...14	14...18	18...22
SDA 8	10...14	14...18	-

2.5.2 Implementing regulations to ensure acoustic performance

The aim of SDA semi-dense pavements is to ensure good acoustic performance with the lowest possible void content (reducing the negative effects of void content on durability). The VSS standard "VSS-40436 Semi-dense mixes and wearing courses" successfully laid the foundation for the widespread use of low-noise pavement in urban areas.

The experience gained in the federal research project on *low-noise pavements in urban areas as* well as practical experience within the framework of impact analyses on low-noise pavements in various cantons show that the acoustic performance of semi-dense asphalts can vary greatly, even within the same maximum aggregate and void content class. The reason for the variability of the long-term acoustic performance of individual SDA formulations is often due to constructional differences.

The study *Implementation Regulations Acoustics for Semi-Dense Asphalts (2017)* [21] shows that, in a consistent manner, those pavements with high acoustic quality three years after paving are all characterised by deep airflow noise and thus by surface-accessible voids. The results also show that the surface-accessible voids are dependent in part on the filler and sand content of the formulation. If these voids are blocked by loose filler and sand, the pavement can have substantial void contents that are not accessible from the surface and thus, not acoustically effective. A maximum was determined for both the filler and the sand components in order to guarantee that the void contents are accessible from the surface. However, to achieve a permanent noise reduction, the interaction of filler and sand contents is decisive: If a formulation contains a rather high sand content, the accessibility of the voids can still be achieved with a reduced filler content. Conversely, formulations with filler contents close to the maximum can also be promising with rather lower sand contents at the same time. To take this into account, an acoustic factor was determined in addition to the individual maxima, which considers the correlation between filler and sand content, and which acts as a further prerequisite for voids accessible from the surface. Due to its larger surface area, the filler content is given a greater weight in the acoustic factor than the sand content. Limiting ranges for SDA 4 and SDA 8 pavements with acoustically effective void contents are shown in Figure 17.

In practice, it is important to ensure that the acoustic limit between semi-dense and dense formulations is not exceeded and that the accessibility and degree of connectivity of the voids are not restricted or lost altogether due to excessive filler and sand content through bonding. The proposed acoustical implementation provisions of VSS 40436 represent an essential step in the effort to minimise the void content with semi-dense asphalts while ensuring acoustic performance, and thus to achieve the greatest possible durability of low-noise road pavements [21].

To ensure effectiveness, maximum values for filler, sand and the acoustic factor have been set. Minimum values are currently not given. However, the aim is to select a void content for the semi-dense pavements that is below that of PA pavements in order to achieve improved properties in terms of durability.

In order to complete the optimum sieve curve for acoustics, the following supplementary analyses were carried out for sieves 1 mm (for SDA 4 and SDA 8) and 4 mm (SDA 8). The following emerges from the detailed analyses of sieves 1 and 4 mm:

- Sieve 1 mm has only little influence on acoustics (SDA 4 and SDA 8) and is sufficiently explained by sand content but can play a role in extreme cases with SDA 4.
- Sieve 4 mm has hardly any influence on acoustics with SDA 8

An adjustment of the acoustic designs is therefore not necessary. It should be noted, however, that strong scattering with sieve 1 mm should be avoided.

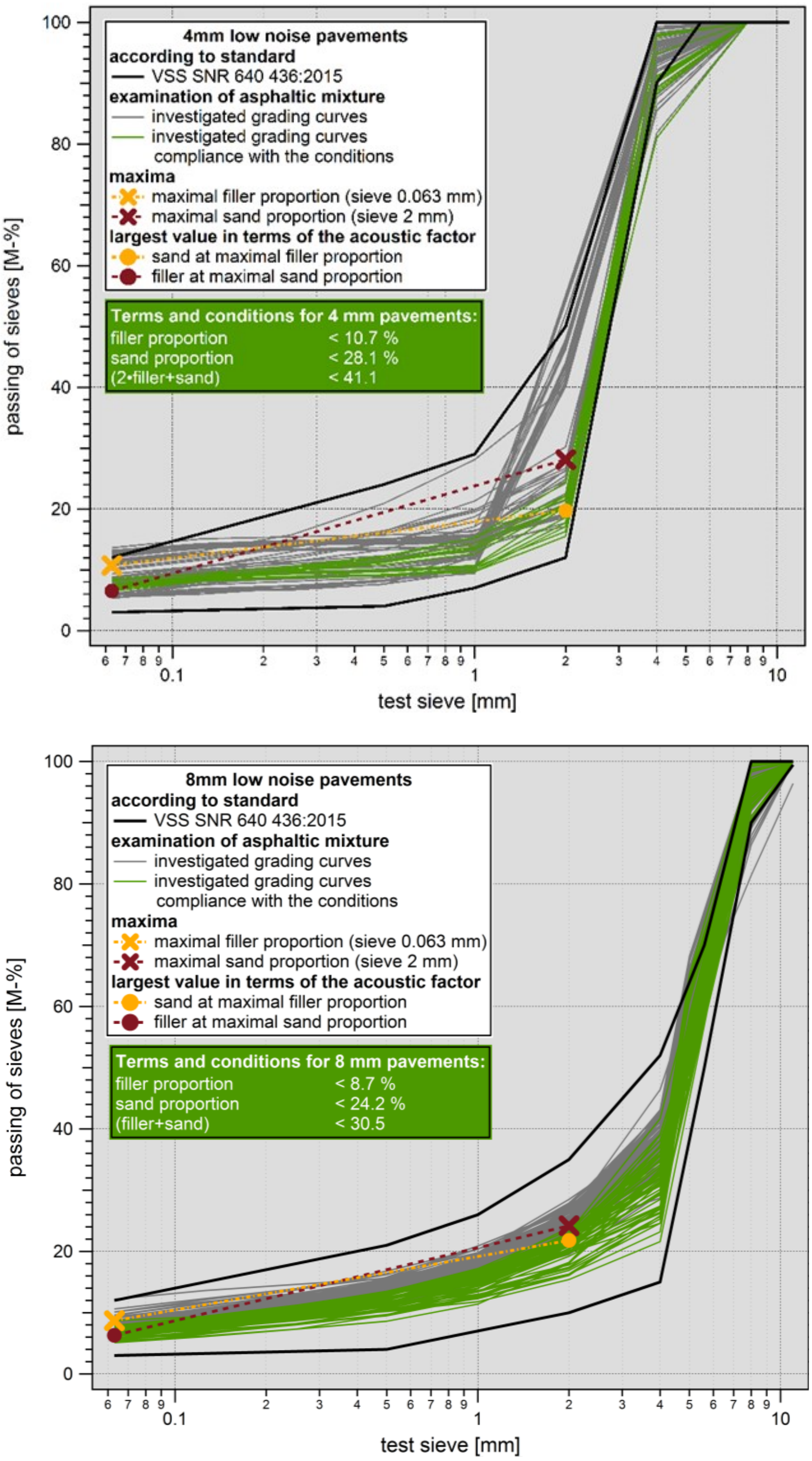


Figure 17: Recommended implementation regulations for acoustics for the standardisation of semi-dense asphalts (Source: [21])

Experience has shown that the acoustic quality of SDA pavements can be improved by complying with the above-mentioned implementation regulations. It should be noted, however, that in addition to the ratio of filler to sand, other important factors such as binder content, mix transport, mix temperature, compaction, etc. are decisive for a successful application (see chapter 2.7).

2.6 Additional factors for lower-noise

2.6.1 Design of non-pavement elements

One factor for the successful realisation of low-noise road surfaces is the design of manhole covers, concrete elements (e.g. at bus stops and roundabouts) and road markings. These elements can cause disturbing impulse noises or annoying frequency shifts. These phenomena also occur with conventional road surfaces. However, they are much more perceptible with low-noise road surfaces, as they are masked to a lesser extent by vehicle noise. In a study, the disturbing effect of such influences was investigated in more detail, and recommendations for practical implementation were elaborated (see chapter 2.6.2) [25].

2.6.2 Position of the transitions to the adjacent pavement

The difference in noise emissions between low-noise and conventional pavements can be up to 10 dB. Although residents in the transition area also benefit from a noise reduction, abrupt level changes occur at the transition, which can be perceived as very annoying. A noise propagation model was used to estimate the distance up to which these abrupt level increases are perceptible [25]. This is illustrated in the schematic sketch in Figure 18.

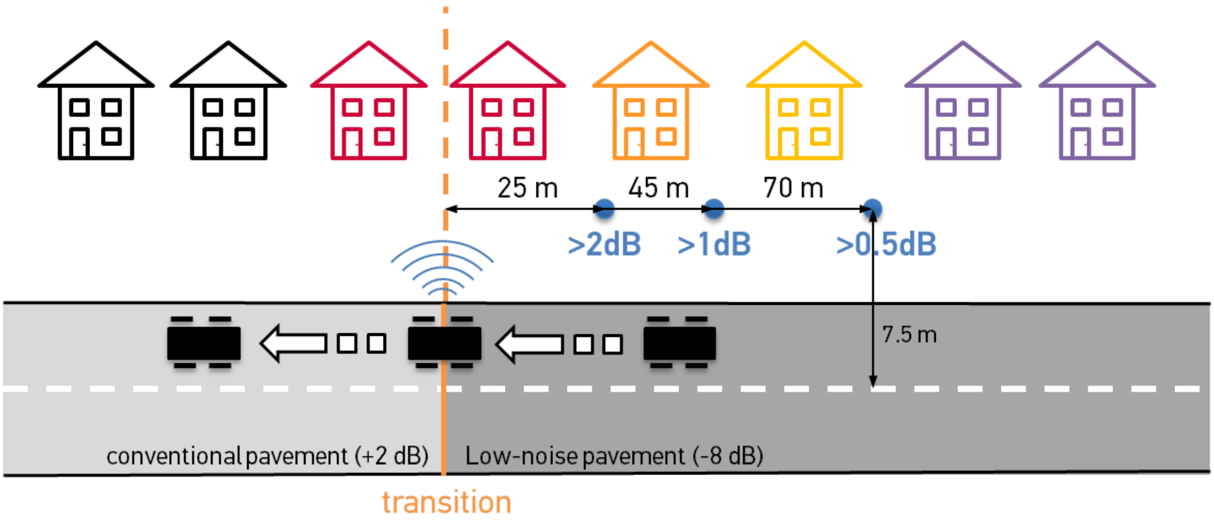


Figure 18: Acoustic effect on the emission side of a road transition from a low-noise to a conventional pavement. With >2 dB, the effect is very clearly perceptible for residents at a distance of 25 m to the roadway transition. (Source: [25])

As shown in the figure above, perceptible level increases are to be expected up to approx. 45 m from the transition. As a rule, level differences of >1 dB are considered perceptible. Since frequency shifts, which increase annoyance, also occur at the same time, the distance between the transition and the property should be at least 70 m if possible. Where this is not feasible, a transition area with a surface of medium noise impact (e.g. AC 8) should be implemented despite lower noise reduction in order to mitigate these effects.

The following procedure currently applies in the Canton of Aargau:
The low-noise road surface is extended over the border of urban areas and overland. The transition from the low-noise pavement to the conventional pavement is therefore at least 30 m from the last property or the building zone boundary.

2.6.3 Concrete elements in the roadway

Concrete pavements are often significantly louder than conventional asphalt pavements. The acoustic quality of concrete pavements can vary by up to 6 dB depending on the design (see also the section on washed concrete in chapter 2.4.3).

Concrete carriageways with longitudinal broom finish have the quietest acoustic values (see Figure 19). From an acoustic point of view, the installation of concrete pavements with transverse broom finish is not recommended.

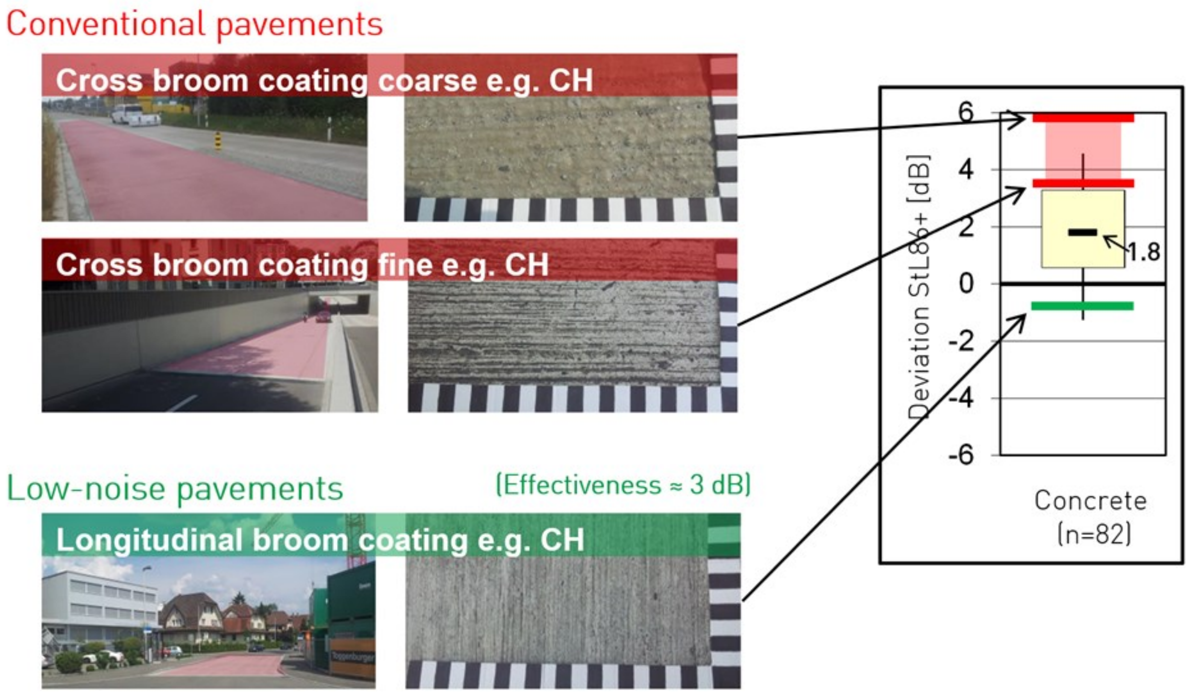


Figure 19: Acoustic quality of concrete structures, (Source: Grolimund + Partner AG)

2.6.4 Impulsive sounds

When rolling over transitions and joints with level differences, impulsive noise can occur and thus lead to additional annoyance. On the one hand, this problem can be mitigated by noise-optimised surface textures (fine and regular broom coating textures). On the other hand, the joints between individual concrete elements can be designed to be low-noise if they are sufficiently filled with joint compound and realised at the same level [25].

Figure 20: Concrete elements at a bus stop (left) and close-up of a joint between two noise-optimised concrete elements (right) (Source: [25], modified by Grolimund + Partner AG)

Figure 21: Transition from concrete pavement to adjacent pavement with difference in level (left) and at the same level (right) (Source: [25], modified by Grolimund + Partner AG)

2.6.5 Application of road markings

Another potential source of disturbance is road markings. Experience has shown that textured markings (textured markings with quartz sand), especially on new SDA 4 pavements, can lead to complaints from residents, as they cause audible level increases and frequency shifts. Measurements with the CPX method show that tyre-road noise can increase by up to 6 dB. Pure colour markings on the other hand, hardly lead to a change in the tyre-road noise. On SDA 4 pavements, coloured markings should therefore be preferred to textured markings (see Figure 22) on SDA 4 pavements, if the safety requirements allow this. It must be emphasised that pure colour markings have disadvantages in terms of visibility and adhesion in wet conditions.

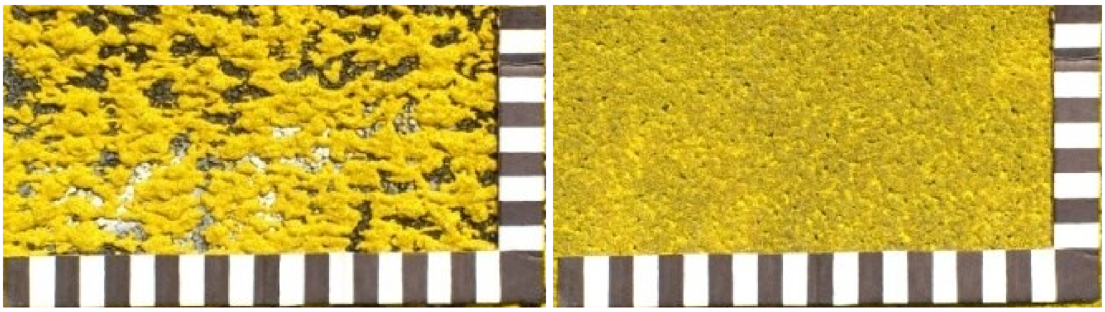


Figure 22: Image of a texture marking (left) and a colour marking (right) on a quiet road surface in the Canton of Aargau (Source: [25])

In the Canton of Aargau, the following regulation applies:

- Core lane→ Colour marking
- Centre marking and pedestrian crossing→ Structure marking

2.6.6 Design of manhole covers

Measurements show that due to manhole covers, impulse noise can occur that differs from tyre-road noise by up to 10 dB. Where possible, manhole covers should not be placed in the wheel lane. Since the position of manhole covers can usually no longer be changed in existing road infrastructures, manhole accesses should be raised level with the road surface and the manhole covers should be provided with a noise-optimised texture.

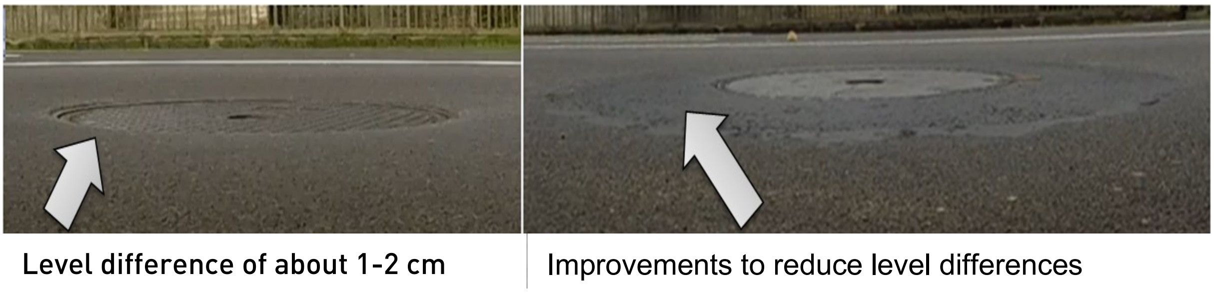


Figure 23: Design of a manhole cover before (left) and after the improvement (right). With the levelling measure as well as a low-noise texture of the shaft cover, the level increases during rollover could be reduced by approx. 5 dB. (Source: Grolimund + Partner AG)

In the case of the manhole cover in Figure 23 on the left, the position of the manhole access had to be corrected shortly after the roadway was reopened. As the manhole access was located in the middle of the wheel track and 1-2 cm below the road level, the vertical offset led to clearly perceptible impulse noises during vehicle rollovers. During the rehabilitation, the low-noise road surface was removed within a radius of 10 to 15 cm around the manhole access and filled with a fine asphalt mixture at the same level. In addition, the manhole covers were replaced with a textured type (fine and uniform texture, see Figure 7 right). Through these measures, the impulse noise could be reduced by approx. 5 dB on average.

In the Canton of Aargau, the following regulation applies:

- BEGU lids, no anti-grip cast lids

2.6.7 Traffic lights with detectors

Provided that no level differences occur due to the installation of the detectors, these do not lead to disturbing impulse noises and thus have no influence on the noise emissions and noise pollution. If the detectors are attached to the surface, they could lead to stronger impulse noises due to the difference in level. In the Canton of Aargau, the detectors are only installed on the surface for temporary measures. Otherwise they are cast into the pavement.

2.6.8 Tram rails

Driving over tram tracks in longitudinal direction has no significant influence on noise emissions. If necessary, there is a slight frequency shift into the high frequency range.

On the other hand, impulse noise can occur when crossing tram tracks in the transverse direction. It should be noted that in the Canton of Aargau, the rails mainly run on their own track and thus have no influence on road noise emissions.

2.7 Factors influencing acoustic ageing

All road surfaces become a little louder over time. The factors influencing the acoustic ageing behaviour can be summarised in a simplified way as follows:

Structural	- Material, formulation, installation (compaction, finishing) - Quality of the road surface
Climatic	- Altitude (choice of binder, special stress) - Climatic influences (frost, heat)
Use-related	- Mechanical stress due to traffic - Mechanical loads maintenance - Dirt ingress (agriculture, construction sites etc.)
Intervention	- Maintenance measures

Figure 24: Overview of factors influencing acoustic ageing, not conclusive (Source: Grolimund + Partner AG)

The statistical analyses of a study conducted in 2015 [26] revealed three main factors influencing acoustic ageing:

1. A high number of frost cycles increases the risk of loss of effect the most due to the heavy stress.

2 With increasing traffic load, low-noise pavements also lose their effect faster due to the heavy load. Here, however, the share of heavy traffic is more relevant than the total traffic load.

3. High dirt ingress, such as due to agriculture or construction activity, has an influence. According to new results from a study on dirt and cleaning carried out in the Canton of Aargau, dirt ingress (and the associated loss of effectiveness) is part of the normal acoustical ageing of low-noise pavements.

2.8 Measures to extend the acoustic lifetime

2.8.1 Cleaning of SDA pavements

The noise-reducing effect of SDA pavements decreases due to the incorporation of dust particles and external dirt input (e.g. from construction sites, agriculture) in the voids [26]. Whether and to what extent the acoustic effect of low-noise pavements can be restored or improved with different cleaning measures has been investigated in various studies [27] [28] [29].

Studies carried out in the Canton of Aargau are currently investigating the extent to which regular cleaning of SDA pavements is worthwhile in order to maintain acoustic quality [27]. Interestingly, the influence of dirt is greater for SDA 8 pavements than for SDA 4 pavements. This supports the hypothesis that water and dirt can penetrate less well in semi-dense asphalts with 4 mm maximum grain size due to their finer pore structure. Initial findings regarding cleaning measures show that cleaning can effectively remove dirt in the pavement, especially near the surface (acoustic effect up to 2.5 dB). Once the dirt has penetrated deep into the voids of the semi-dense asphalt, it can only be partially removed (effect 0.5 to 1 dB). During cleaning, the suction power seems to be of central importance. The water pressure must not be set too high to avoid damage to the pavement surface [27]. Note: The investigations on cleaning will be continued in the coming years.

2.8.2 Micromilling of SDA pavements

Various milling methods are currently being tested to improve the macrotexture and acoustic performance of SDA pavements with clogged pores. Additionally, investigations into milling of SDA 4 pavements are currently taking place in the Canton of Aargau. In Zofingen on the K 104 cantonal road, milling was carried out on approx. 300 m of the SDA 4 pavement from 2012 using different methods (milling depths). By means of CPX and sound absorption measurements (see chapter 3), the improvements in the acoustic quality of the SDA 4 pavement achieved by the milling work were recorded. The measurements show that the acoustic quality of the pavement improves significantly with increasing milling depth. The sound absorption properties of the SDA 4 pavement were also improved compared to previous measurements [30]. The durability of the effects produced by the milling work under traffic load will be shown by future measurements.

In principle, milling for the recovery of the acoustic quality of low-noise road surfaces can be described as a promising approach on the basis of the initial findings. However, open questions such as the milling depth, the milling speed, removal of the material without stressing the pores, dust formation, subsequent cleaning, etc. still need to be clarified. Future tests and investigations will show the advantages and disadvantages of micro-milling of SDA pavements as a measure to extend the lifetime.

Figure 25: Milling of SDA coverings (Source: Hans Weibel AG)

2.8.3 Other measures

In the Netherlands, products to extend the life of a pavement have been used since 2010, mainly as a preventive measure at the time of the first appearance of grain outbreaks, approximately 5 to 7 years after installation. However, the pavement surface must not yet be seriously damaged. The lifetime of the surface courses can subsequently be increased by 2 to 4 years. Only one treatment per surface course is recommended. The treatment is cold bitumen emulsion containing bitumen rejuvenator or a warm applied polymer modified bitumen. The products are applied with a pressure blower (PA overlays) or with a spray bar (thin overlays) where they penetrate 10 to 20 mm into the layer through depressions and pores [31]. Furthermore, international research, or rather ideas, regarding biological or chemical dirt degradation are underway.

3. Acoustical performance control

3.1 Standards and basic documents on acoustic measurement methods

All standards can be ordered from the respective institution. In principle, the latest standards are always to be applied.

Table 8: Overview of standards and basic documents on acoustic measurement methods (Source: Grolimund + Partner AG)

Document	Designation	Year of publication	Contents	Validity
CPX standard	ISO 11819-2 [32]	2017	Requirements measurement systems, requirements measurement procedure and measurement process, correction procedure, uncertainty estimation	international
CPX specification test tyre	ISO/TS 11819-3 [33]	2017	Requirements for commissioning, storage and lifetime, requirements for documentation, shore hardness correction	international
CPX temperature correction	ISO/TS 13471-1 [34]	2017	Pavement category and speed-dependent temperature correction	international
SPB standard	ISO 11819-1 [35]	2022	Requirements measurement location, measurement and evaluation	international
SPB measurements	Leitfaden Strassenlärm Anhang 1c [36]	2013	Requirements for measurement and evaluation Leq	national
SEM measurements	Leitfaden Strassenlärm Anhang 1c [36]	2013	Requirements measurement location, measurement and evaluation	national
Conversion CPX-SPB	Leitfaden Strassenlärm Anhang 1c [36]	2013	CPX conversion model reference speed 50 km/h and 80 km/h Vehicle categories passenger cars (N1) and trucks (N2)	national
Acceptance measurements	VSS Nationaler Anhang zur ISO 11819-2	Expected to be published at the end of 2020	Requirements for the performance and evaluation of acceptance measurements	national

3.2 Acoustical characteristics of road surfaces

To determine the acoustical effect of road pavements, different methods are used depending on the country, such as CPX pavement quality measurements (close proximity), statistical pass-by (SPB), emission measurements and emission measurements. The international standards for the measurement methods of acoustic pavement properties ISO 11819-1 (SPB method [35]) and ISO 11819-2 and ISO 11819- 3 (CPX method [32], [33], [34]) regulate the performance and evaluation of measurements. In addition, the corresponding Swiss standard SN ISO 11819-2 specifies the performance and evaluation of acceptance measurements with increased accuracy requirements (e.g. for the verification of acoustic requirements in work contracts). However, these standards leave open how the determined standard levels are converted to a national pavement quality value. Thus, the determination of pavement quality values is not covered by CEN or ISO. The determined acoustical measurement data are converted into an acoustic pavement quality value on a country-specific basis. The pavement quality values are decisive for the description of the acoustic quality of road pavements. Using these measurement methods, a verification of the acoustic quality of road pavements over time and among each other is guaranteed.

Switzerland

In Switzerland, a methodology has been used so far, which is described in the Road Noise Guidelines - Appendix 1c [36]. This resulted in pavement quality values that are issued in deviation from the previously valid standard model StL-86+ and characterise the effect of a pavement in relation to the total noise emissions (consisting of rolling and driving noise) for two speed ranges. Since StL-86+ will soon lose its validity, the development of a new methodology for determining the pavement quality values is imperative. An analogous procedure with reference to the new noise emission model SonROAD18 is not expedient, as this model is to be continuously adapted to new trends. These questions are currently being further clarified by the responsible standardisation commission of the VSS.

International:

To enable comparisons between data of international origin, the effects must be related to a uniform reference. As part of the research pact on *low-noise pavements in urban areas EP 7: Innovative low-noise pavements for potential use in Switzerland, ASTRA 2013/002, 2016* [31] a reference was made to the conventional road pavement SMA 11, as this pavement is often used as a standard road pavement worldwide. In Figure 26 the different national references are compared. The acoustic value for the SMA 11 pavement in the respective national model is also plotted.

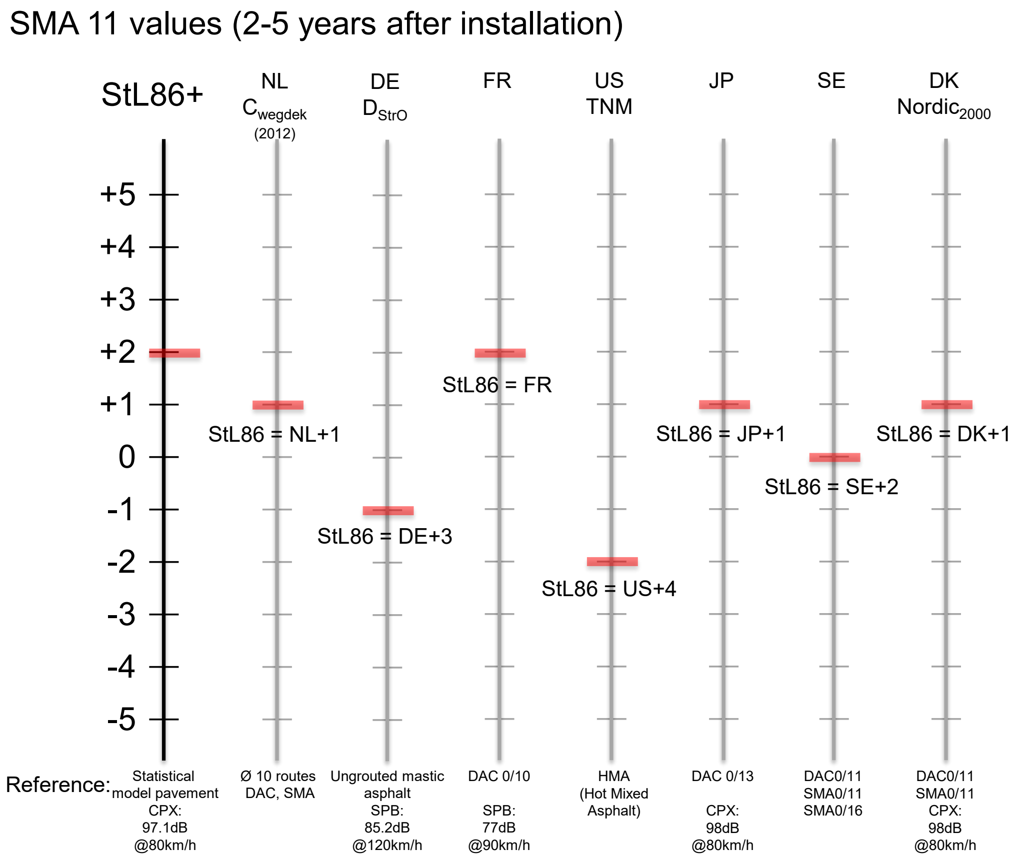


Figure 26: SMA 11 and conversion to StL86+ (Source: [31])

3.3 Measurement method

In the following, the different measurement methods, as well as their advantages and disadvantages, are outlined. Chapter 3.3.5 shows a proposal for the selection of the most suitable measurement method depending on the problem. This is based on the advantages and disadvantages of the different measurement methods. The standards applicable to the measurement methods are described in Chapter 3.1.

3.3.1 Near-field trailer measurements - close-proximity (CPX)

In the CPX (close proximity) measurement method, the acoustic properties of road surfaces are determined by continuous and direct measurement of tyre-road noise with a measurement trailer.

With the CPX measuring system, the sound level is measured in two separate sound-insulated chambers inside the measuring trailer in the immediate vicinity of the tyre, each with two microphones. The trailer used must meet the requirements specified in ISO 11819-2:2017 [32] regarding the influence of the device's own sound reflections as well as internal and external sound noise on the measurement results.

The test tyre sets used are shown in Figure 27 (left: test tyre P1 for passenger cars, right: test tyre H1 for trucks).

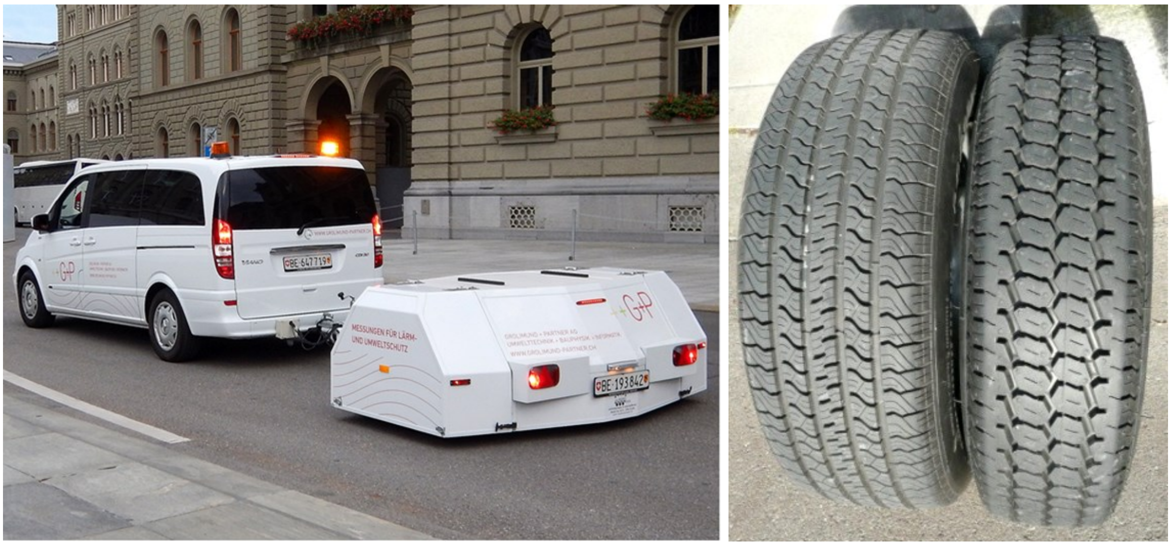


Figure 27: Example measuring trailer and CPX test strips P1 (left) and H1 (right) (Source: Grolimund + Partner AG)

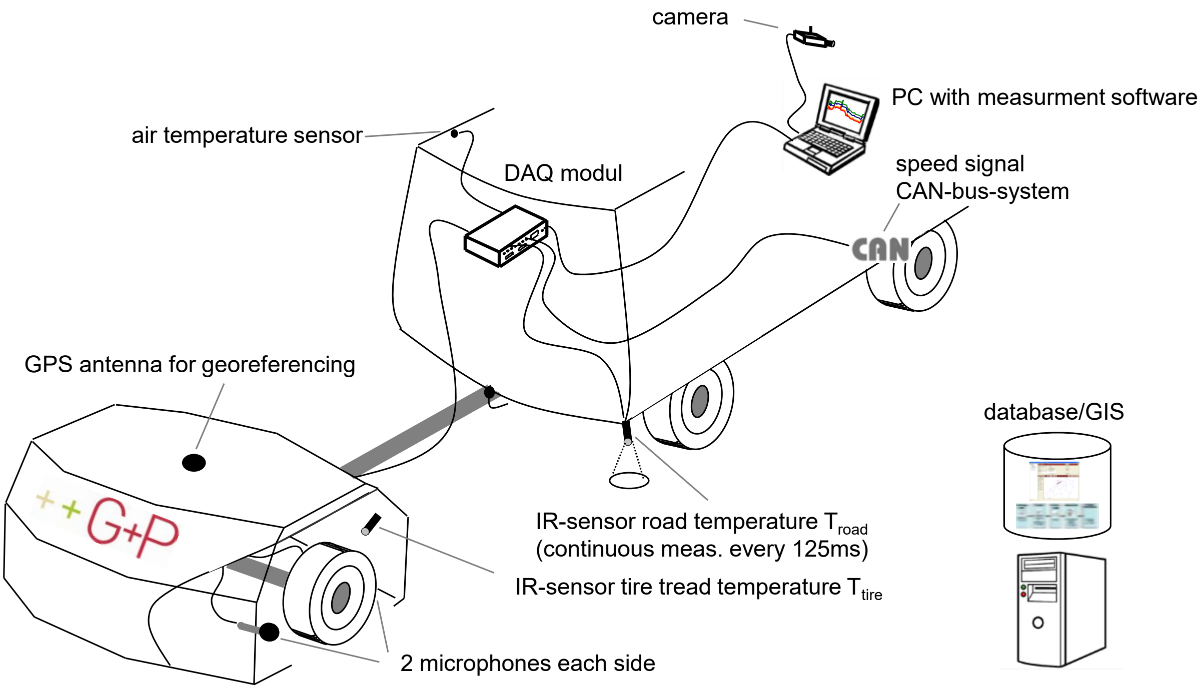


Figure 28: Schematic overview of a measuring system (Source: Grolimund + Partner AG)

The signals from the 4 measuring microphones (2 measuring microphones per side), the speed signal from the calibrated CAN bus system of the towing vehicle, the GPS signal for georeferencing the measurement data, as well as the signals from the temperature sensors are processed in the central data module and recorded by the measurement software. The immediate graphical display of the measurement signals enables constant monitoring of the entire measurement process while driving. One camera each on the front and rear of the vehicle continuously photographs the road surface for interpretation and control purposes.

For each tyre, the A-weighted sound levels are continuously recorded along the entire measuring section. The microphone signals are recorded at a frequency of 8 Hz (1 value every 0.125 seconds) and averaged energetically per measuring segment (length 20 m). The measurement run takes place at as constant a speed as possible (reference speed of 50 km/h or 80 km/h).

Explanations:

Measurement tyres: The reference tyres specified in the standard are test tyres that represent specific tyre-road noise characteristics and have been selected for use in this procedure with specified and reproducible standard characteristics. Depending on the purpose of the measurement, one or both sets of test tyres are used.

The measuring tyres must be run in (mounted on the measuring system) for at least 400 km before commissioning (from production) in accordance with the standard so that there are no more possible knobs on the tyres. Before each CPX measurement, the measuring tyres are also run in so that the tyres are warmed up.

Measuring tyre P1: Passenger car (SRTT)
Measuring tyre H1: Truck (AVON AV4)

Shore hardness / rubber hardness: The shore hardness of tyres changes over time and with stress. These changes in the material have a direct influence on the acoustics. Therefore, the measuring tyres must be monitored by measuring the shore hardness so that deviations from a reference hardness can be taken into account. A corresponding shore hardness correction (shore hardness coefficient in dB/ShoreA) is taken into account in the evaluations of the CPX measurements.

As a general rule:

The tyre becomes harder with use. The harder the tyre, the louder the tyre-road noise.

The shore hardness effects determined by various studies for the test tyres are shown in Figure 29. In the corresponding study [37] data from 12 studies were compiled. The existing standard ISO11819-3 [33] is currently being adapted with regard to these latest findings:

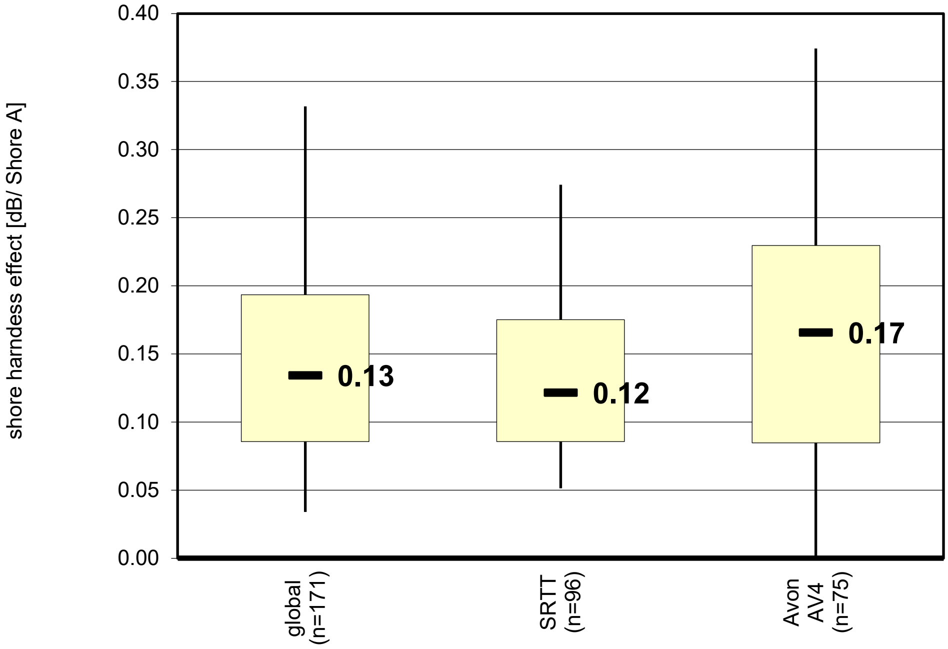


Figure 29: Shore hardness effect based on 12 studies and a total of 171 data sets (Source: [37])

Temperature: Temperature has a significant influence on tyre road noise. Basically, the tyre temperature is decisive, which is also defined by the air and pavement temperature. However, as an overall system, tyre temperature does not react to changes as quickly as air and pavement temperature. In order to identify the most suitable temperature variables for correcting temperature influences, all measured temperatures (air temperature at 150 cm (T_air150), 35 cm (T_air35) and 15 cm (T_air15) above the road surface, pavement temperature (T_tyre) and tyre temperature (T_road)) were correlated [38].

This study shows that the air temperature which is least influenced by the surface (measured 150cm above the road surface) is best suited for temperature correction. This is especially true for situations with different solar radiation and pavements with different surfaces [38].

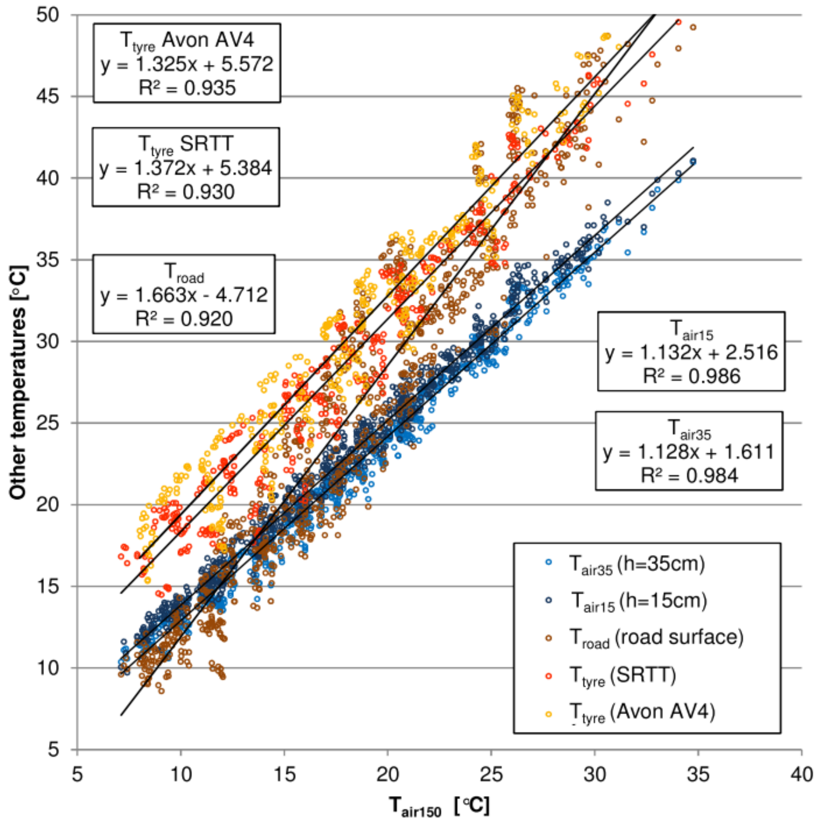


Figure 30: Dependence of the measured temperatures (pavement temperature, tyre temperature, air temperature H=15cm, air temperature H=35cm) from the least surface-affected temperatures (air temperature H= 150cm) [38] during approx. 10 measurement days in September in Switzerland. (Source: [39])

During the measurements, the temperature is recorded continuously so that the CPX levels can be corrected accordingly. According to the CPX standard, CPX measurements are permissible in temperate and continental climate zones between 5 and 30°C. The permissible temperature range depends on the local road construction materials. In colder zones, bitumen viscosity is adapted to lower temperatures. In warmer climates, the same viscosity can lead to bitumen seepage. This is known to cause additional sticking/cracking noise from the rolling tyre.

The temperature coefficient is velocity-dependent [40] and is given in decibels per degree Celsius. The reference temperature is 20 °C. The values are negative for P1 and H1.

As a general rule:

The higher the temperature, the quieter the tyre-road noise.

Experience outside the norm

Measuring tyres: Experience shows that the number of 400 running-in kilometres specified in the standard is not sufficient. To minimise the probability of errors, 1,000 km is recommended.

To ensure comparability at all times, it is recommended to replace the test tyres every measuring season in case of heavy use.

Shore hardness / rubber hardness: Experience has shown that the rubber hardness measurements every 3 months specified in the standard are not sufficient. To minimise the probability of error, monthly measurements of shore hardness are recommended.

3.3.2 Statistical Pass-by Method (SPB)

Statistical pass-by (SPB) measurements are measurements of individual vehicles on a lane according to ISO 11819 1 [35]. The maximum pass-by level (L_AFmax) and average level (L_Aeq) are recorded for individual passenger cars and trucks, as well as the actual driving speed and vehicle category (N1 or N2). From this, the emission values L_Amax and L_Aeq/h at 1 m from the lane axis are calculated for each pass-by and compared with the reference values of the EMPA model StL-86+.

With the pass-by measurements, statements can be made about the pavement effect, taking into account the current vehicle mix. The vehicle categories of cars and trucks are surveyed separately. The measurements include only one lane (point-by-point survey) and are dependent on the current and local vehicle mix, e.g. the predominant truck type. Depending on the local conditions (e.g. high traffic volume, influences of the subsoil, shielding/reflections from crash barriers, buildings and obstacles near the source), the high demands of the SPB measurement method on the measurement conditions often cannot be completely fulfilled.

The new international standard on SPB measurements is expected to be published in 2020.

3.3.3 Sample emission measurements (SEM)

The SEM measurement is a simplified determination of the pavement quality. For at least 30 minutes, the L_Aeq is determined close to the road for all vehicles travelling on all lanes with simultaneous traffic counting. The measured immission level is compared with the immission level calculated using the StL-86+ model.

With the SEM method, the total noise emissions are recorded in addition to the acoustic pavement effect, taking into account near-source sound propagation effects for the current situation. The entire fleet of vehicles is recorded. However, a subdivision into cars and trucks is not possible (only mixed traffic across all lanes). The measurements depend on the number of noisy vehicles and the speeds driven. Therefore, this type of noise measurement is unsuitable for determining pavement quality values, especially for monitoring measurements.

3.3.4 Advantages and disadvantages of measurement methods

	Advantages	Disadvantages
CPX	▪ Highly standardised procedure ▪ Good repeatability ▪ Comprehensive survey ▪ Survey over all tracks ▪ Separate survey of the vehicle categories passenger car and truck ▪ Calculation of mixed traffic possible ▪ Independent of changes in the vehicle mix ▪ Local pavement characteristics identifiable ▪ Use in projects (LSP, etc.)	▪ Possible limitations in forecasting for vehicle mix ▪ The pavement properties of PA pavement in advanced age vary laterally→ Dependence of the measured lane ▪ Escort vehicle necessary for measurements on overtaking lanes ▪ Complex measuring equipment: tractor vehicle, measuring trailer, multi-channel technology required and measuring tyres necessary
SPB	▪ Statement on pavement effect possible with regard to current vehicle mix ▪ Separate survey of the vehicle categories passenger car and truck ▪ Calculation of mixed traffic possible ▪ Effect in relation to total noise emissions	▪ Survey cross-section on one lane ▪ Depending on the current and local vehicle mix→ ≠ Monitoring ▪ Dependence on the measurement engineer (vehicle selection and classification) ▪ Description of ideal passages ▪ Measurement associated with more effort than with SEM methods ▪ High demands on measuring conditions ▪ Individual pass-bys on heavily loaded section difficult to survey ▪ Accuracy limitation due to the dimension of the distances to the source ▪ Measurement can be associated with hazards (keeping the measurement engineer at a small distance from the road)
SEM	▪ Estimation of the pavement effect for the current situation ▪ Survey of the total noise emission ▪ Survey of the entire vehicle fleet ▪ Survey of acoustic pavement effects taking into account near-source sound propagation effects ▪ Simple implementation ▪ Cost-efficient implementation	▪ Depending on the current and local vehicle population→ ≠ Monitoring ▪ Survey only mixed traffic across all lanes ▪ Site-specific ▪ Not suitable for determining pavement quality values ▪ Dependence on the amount of noisy vehicles ▪ Dependence on the driving speed ▪ Traffic normalisation only works to a limited extent

3.3.5 Selection of measuring method

The selection of the measurement methods is based on their specific suitability for answering the question. The individual measurement methods, as well as their advantages and disadvantages, are described in the chapters 3.3.1 to 3.3.4.

The acoustic properties of road surfaces often vary greatly along the route. Therefore, a comprehensive survey using the CPX method often offers advantages. If a specific cross-section is decisive for answering the question, an SPB measurement can be carried out instead of CPX measurements. The CPX method has the highest degree of standardisation and is therefore especially suitable for determining acoustic changes over time, as well as for comparing the acoustic properties of pavements with each other.

If new construction methods are implemented, the acoustic effect of the road surface in relation to the statistical vehicle mix is to be checked by means of an additional SPB measurement. If the effect of a road surface is to be checked in the case of a special dispersion situation, it is recommended to additionally carry out a sample emission measurement (SEM).

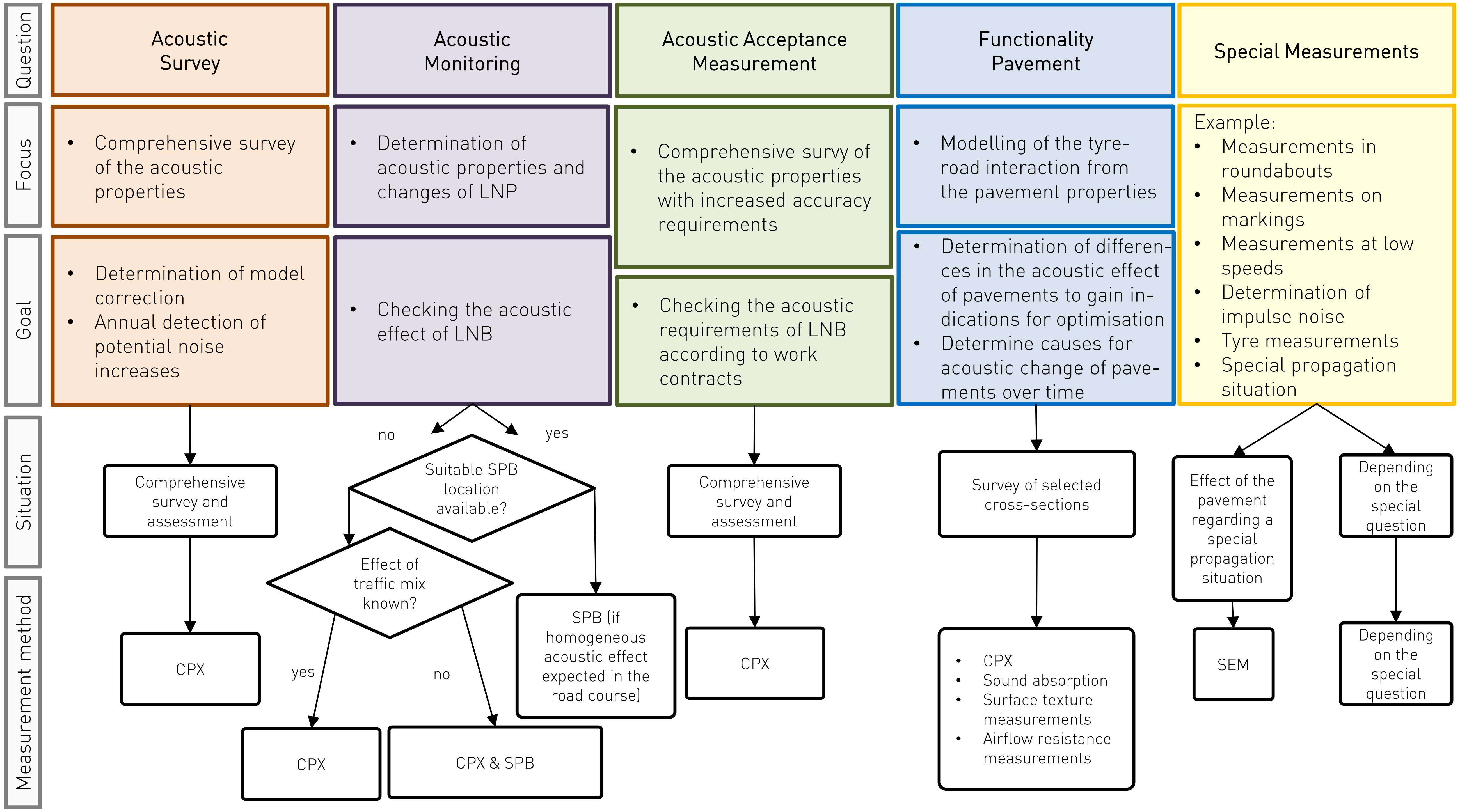


Figure 31: Selection of the appropriate measurement method for the initial situation (Source: Grolimund + Partner AG)

3.4 Analysis and identification of optimisation potential

The following chapter explains the acoustic analyses used to determine the optimisation potential of low-noise road surfaces. Acoustic analyses are always overlaid with structural engineering investigations (see chapter 3.3.4).

3.4.1 Acoustic impact analyses

Supposedly identical or similar formulations sometimes result in very different noise reductions. Other pavements, on the other hand, only behave very differently over time, without this being easily explained. G+P has therefore developed the service "acoustic impact analyses". By means of acoustic impact analyses, the real causes for such differences are revealed in order to find necessary answers for a future acoustic improvement of the pavements.

Goals

- Modelling of the tyre-road interaction from the road characteristics using SPERoN (Statistical and Physical Explanation of Rolling Noise)
- Understand effectiveness in reducing vibration and airflow noise.
- Quantification and possible prediction of the sound-absorbing effect
- Investigation of the differences between road pavements with regard to their acoustic effect Determine the causes of the acoustic change of the pavements over time
- Analysis of the pores accessible from the surface by incorporating the drill core and mix tests

Acoustic pavement impact analyses thus provide important information for sustainable acoustic optimisation of low-noise road pavements.

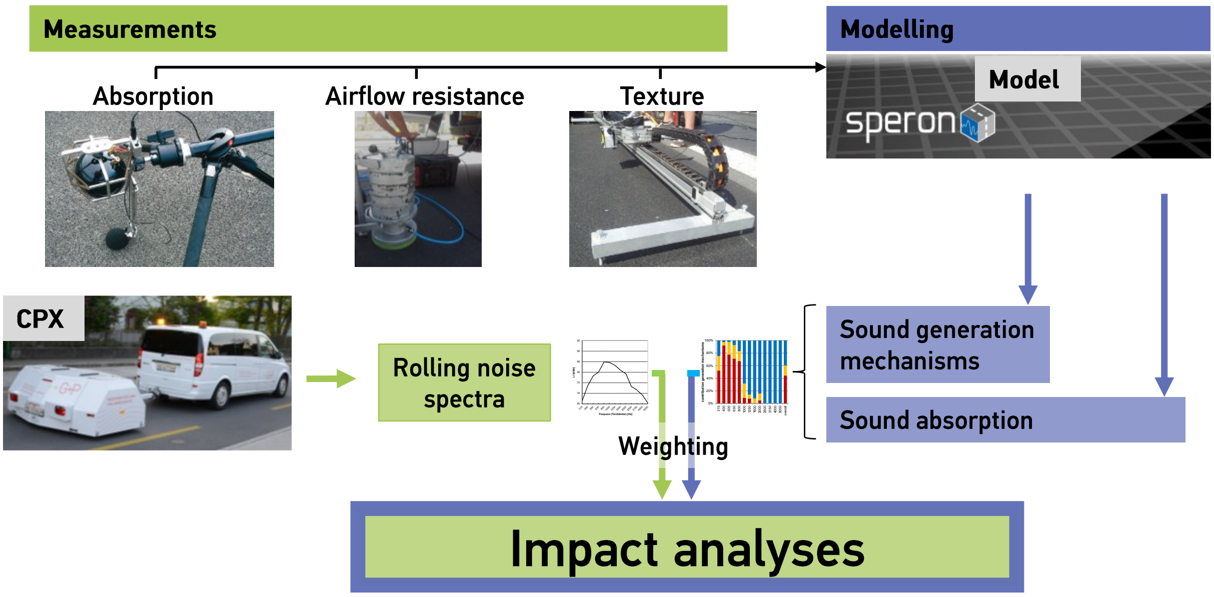
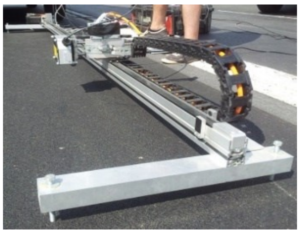
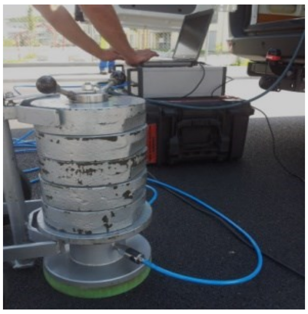


Figure 32: Procedure acoustic impact analysis (Source: Grolimund + Partner AG)

Methods

CPX-measurements 	Continuous survey of tyre-road noise. At least two measurement runs per direction and per test tyre (passenger car and truck).
Sound absorption measurement 	The sound absorption properties are measured in-situ using the PU method. In this measurement method, a sound signal is emitted onto the test surface. In addition to the sound pressure, the sound velocity is also recorded. The impulse response of the emitted signal and its reflection are calculated from this and the sound absorption coefficient of the test surface is determined from this. Compared to the determination of the absorption coefficient with the impedance tube method, the PU method can be used to determine the sound absorption coefficient for a wider range of the noise spectrum. Furthermore, it is possible to determine relatively low sound absorption characteristics in-situ with high accuracy.
Surface texture measurements with laser profilometer 	The surface texture of a pavement has a decisive influence on sound generation. The surface of the road surface is scanned with a laser and a 2D profile is created. The surface profile is recorded according to EN ISOL 13473-1. At least 20 profile cross-sections of at least 2 m length (spacing 1 cm) are recorded. The resulting pseudo 3D profile is then used as an important import variable in SPERoN.
Airflow resistance measurements with air pot 	By measuring the air flow resistance on the surface of the pavement, it is possible to determine how "easily" the air can escape from the contact zone during tyre-pavement contact, which in turn provides information about the sound generation in the tyre-pavement contact zone. For this purpose, a compressor is used to generate a uniform airflow via an air duct in the "air pot", which is measured again in a second air duct. The overpressure in the chamber is measured as a function of the regulated flow of the incoming air. Both measured variables are theoretically linearly dependent, with the slope depending on the speed at which the air can escape through the pavement. This gives the measure of the air escaping in the tyre-pavement contact zone.
Tyre-road interaction model SPERoN	The tyre-road interaction model SPERoN (Statistical and Physical Explanation of Rolling Noise) is used to interpret the measured noise reducing effect of pavements in terms of sound generation mechanisms and sound absorption. Based on surface texture, airflow resistance and sound absorption measurements, SPERoN models the noise levels for the individual sound generation mech-

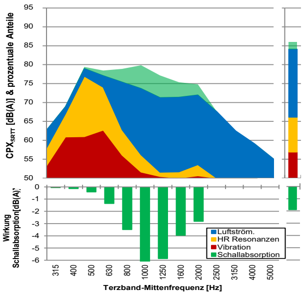
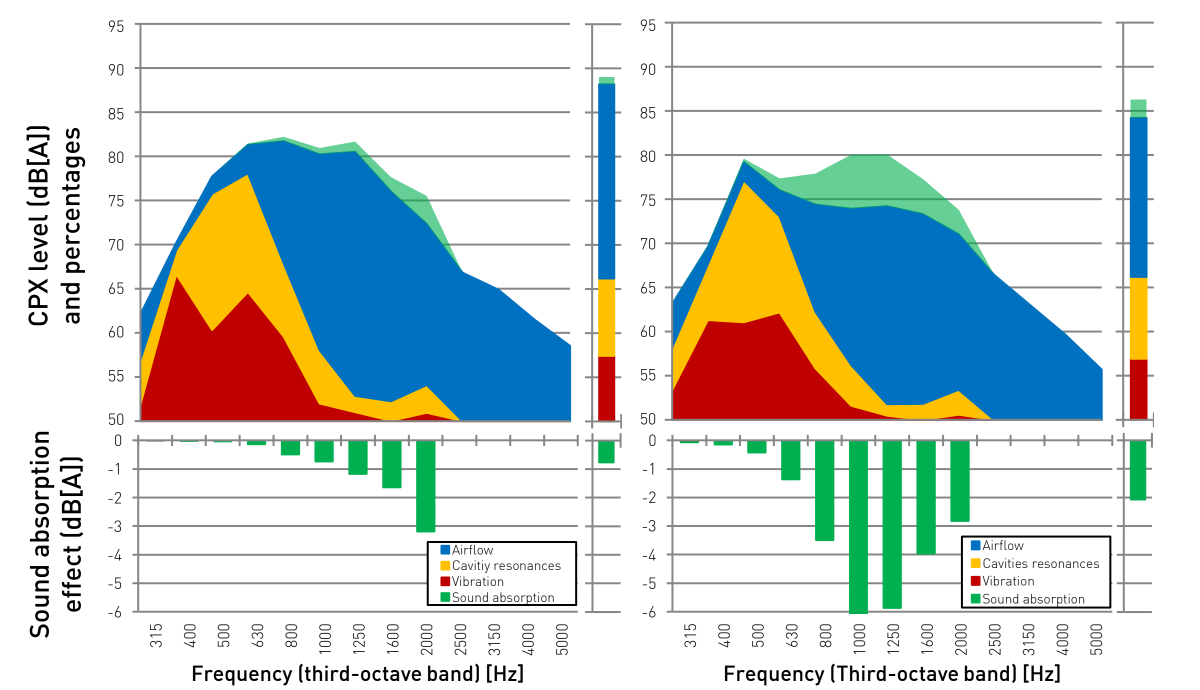
	anisms for car and truck tyres at different speeds. The physical part of the model calculates the contact forces between the pavement surface and the tyres. The pavement surface is simulated by a 3D profile. A standard model is chosen for the tyre. The statistical part of the model builds a virtual noise spectrum based on the modelled tyre vibrations, air flow mechanisms, friction, tyre profiles and the aerodynamically generated sound. SPERoN also includes a module for sound propagation taking into account the horn effect, which allows an estimation of the noise-reducing effect due to sound absorption. As a simulation result, the model provides a noise spectrum (L_max) of the rolling noise for the microphone positions of the CPX and SPB procedures [42].
Acoustic impact analyses 	For the interpretation of the measured rolling noise spectra CPX with respect to noise generation and effect sound absorption, the noise components are weighted with the sound generation mechanism-specific noise components modelled by SPERoN [43]. In this way, statements can be made about the effectiveness of the pavements with regard to the reduction of vibration and airflow noise, the containment of cavity resonances, and the sound-absorbing effect of a pavement. Such acoustic effect analyses are used to explain differences in the acoustic effect between individual pavements. They also make it possible to find causes for the acoustic change of the pavements over time.

Figure 33 shows the results of an impact analysis. As an example, an acoustically poor (left) and an acoustically good (right) pavement of the same design are shown.

By means of acoustic impact analyses, the shares of the different noise generation mechanisms can be collected and identified in detail. This makes it possible to explain the real causes of different acoustic effects and different acoustic ageing behaviour. Impact analyses provide answers and a basis for acoustic improvements of future mixes and installations.



Moderate sound absorption	Very good sound absorption
Increased vibration (tyre stimulation)	Low vibration (tyre stimulation)
Increased airflow noise	Low airflow noise
➔ Acoustically rather poor pavement	➔ Acoustically very good pavement

Figure 33: Example of results of impact analyses (Source: Grolimund + Partner AG)

3.4.2 Analysis of dirt input in low-noise road pavements

To achieve long-term noise reduction through low-noise road pavements, the void content should be reduced to a minimum while maintaining pore accessibility. This delicate optimisation process requires a detailed understanding of the pore structure of each pavement. With older pavements, one wants to know the exact location of contamination (from tyre wear, agriculture, construction sites, etc.) in order to increase the number of active pores again with suitable measures. G+P has developed the AVCA methodology (Acoustic-Void-Content-Analysis), which allows to determine the active pore volume of PA and SDA pavements based on computer tomography (CT) scans of drill cores. Emphasis is placed on the effect of dirt ingress. Image classification algorithms have been developed to separate stones, putty, dirt and void volume. A subsequent path analysis calculates the amount of active and clogged pores. The resulting 3D model of the active pore structure is used to investigate its impact on acoustics. This methodology provides detailed insights into the acoustically effective development of asphalt mixtures, serves as an ideal basis for their optimisation and enables the quantification and localisation of contamination. Based on this, the expected effect of various measures can be predicted in a cost-efficient manner, so that the dirt horizon can be adequately removed with suitable measures (see Figure 34).

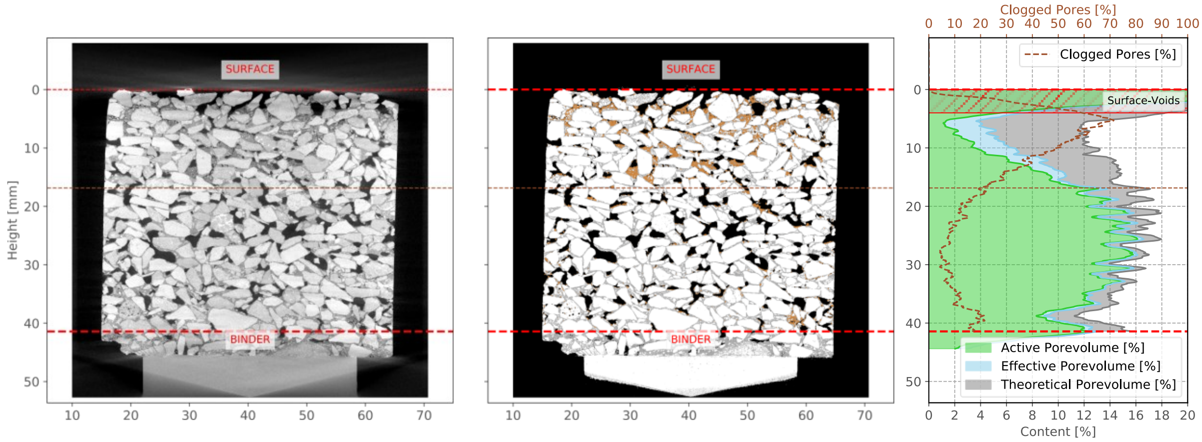


Figure 34: Debris and cavity analyses (Source: [44])

The CT method produces slice images generated from a cone beam X-ray. The analysis consists of imaging the shadow image of the sample to be examined onto a flat panel detector. From the image data, an image recognition algorithm is then used to determine the void content and dirt content for each 0.03 mm thick layer. ([45], [46])

Using a model developed by G+P, the height-dependent void contents (results of com-

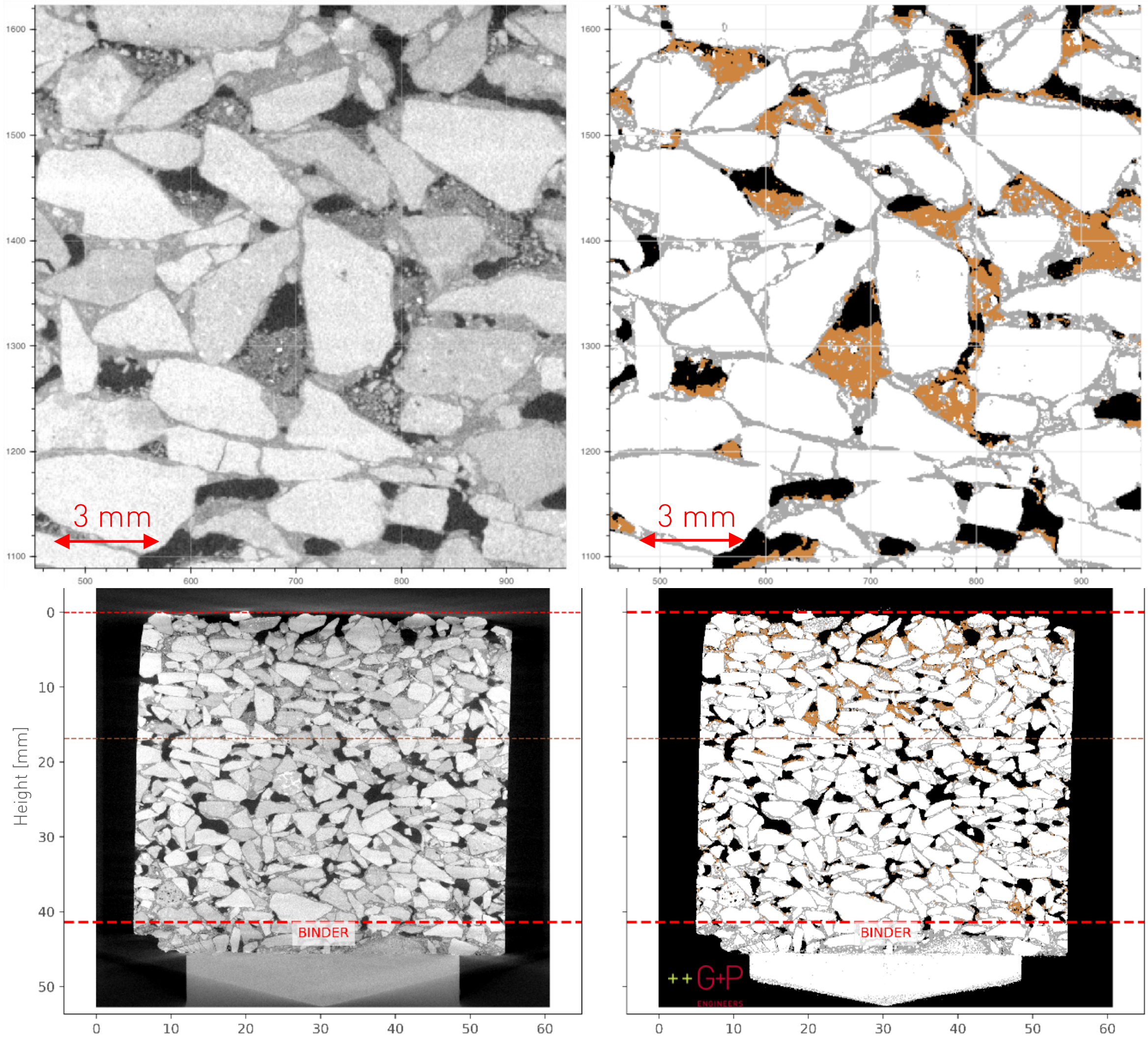


Figure 35: Classification of accessible void content (black), debris (brown), rock aggregates (grey) and bitumen (light grey) in drill core (Source: [44])

puted tomography) are quantified as paths of the voids accessible from the surface by means of 3D particle analyses. The dirt input can be shown separately in the same analysis. The volume of the cavities accessible from the surface is used directly as the assessment variable.

When determining the void content accessible from the surface, the type of dirt is decisive. For example, dirt can have different consistencies and compositions. Through the CT analyses and the downstream algorithms, dirt is distinguished from the mastic or rock by its structure and its grey values. This can lead to certain uncertainties in the case of highly compacted dirt, as no colour differentiation is possible. The classification of the developed method was successfully tested using existing 2.5D methods [48].

When investigating the active pore volume, the handling of small pores is important. This is because the acoustic efficiency depends on the pore size, and its 3D structure. Thus, the influence of small pores on acoustic performance is the subject of research.

3.4.3 CPX to classify the acoustic performance of semi-dense asphalts

Experience shows that cavities accessible from the surface are of central importance for durable acoustic performance. Even with a fine texture, good acoustic quality can be achieved when new. However, the fine surface particles are removed by the mechanical stress, so that the acoustic quality quickly decreases due to the rougher texture. Accordingly, semi-dense asphalts cannot be characterised exclusively by measurements of noise levels in the new condition. Following on from the approach described in chapter 2.5.2 further assessment methods were developed with the aim of characterising newly paved semi-dense asphalts more reliably with regard to the expected long-term acoustic effect already in their new condition. In the following, the acoustic factor CPX developed in the study of the Canton of Aargau by Saurer et al., *Establishment of an acoustic factor for assessing the acoustic performance of semi-dense asphalts* (2018) [47] is presented. In this study, multivariate statistical analyses were used to determine which CPX frequencies (in the range of 315 to 5000 Hz) are significant for long-term good acoustic performance. From the statistical analyses, it was found that the vibration frequency (500 Hz) and the airflow frequency (3,150 Hz) are the most suitable for characterising SDA pavements.

Acoustic factor CPX = -2.5 Lp500Hz + 2.3 Lp3150Hz + 98.5

A limit value of 41.1 is assumed. Below this, the presence of accessible cavities can be expected. The two highly significant frequencies lie in areas of the rolling noise spectrum that are strongly characterised by individual sound generation mechanisms. The frequency 3150 Hz characterises the airflow noise. It can be assumed that with lower airflow sound there are more accessible cavities. The frequency 500 Hz characterises the generation of vibration sound [47]. This method can be used to estimate the long-term acoustic effect. The basis for this is the data of the acoustic measurements CPX shortly after installation of the SDA pavement.

3.4.4 Forecasting of acoustic maintenance effectiveness (FAME) analysis

FAME (Forecasting of Acoustic Maintenance Effectiveness) is a forecasting tool developed by G+P to support decision-makers in the economic and effective use of low-noise pavements. The acoustic effect of quiet pavements gradually decreases over time. This acoustic change can often be attributed to one or more ageing processes (e.g. partial loss of void structure due to dirt ingress, texture change, grain outbreaks, etc.). The acoustic ageing of pavement, which leads to increased noise exposure, can shorten its acoustic lifespan. This necessitates earlier replacement to avoid surpassing the maximum allowable noise levels. Instead of replacing the overlay completely, it may be profitable to apply micro-milling or cleaning to restore previous effects and thus extend the acoustic lifetime. To ensure cost-effective use of low-noise pavements, it is important for the design to have a specific prediction for the end of the acoustic life for each low-noise pavement. Secondly, there is a need for early information on the most promising treatment method and when this method should be applied in order to be economical and effective. FAME relies on large data sets and time series of spectral tyre-road noise profiles (CPX measurements) and analyses and categorises the underlying mechanisms of sound generation. The categorisation as well as the derived current state of the pavement allow to specifically predict the expected ageing processes and the associated acoustic effect loss for each pavement and to indicate options for intervention. These fundamentals provide an important basis for a cost-benefit analysis and an objective decision as to whether maintenance measures or complete replacement should be carried out.

4. Construction success control

4.1 Mixture and drill core investigation

The following chapter provides information on the production and composition of mixes, as well as information on the incorporated layer.

4.1.1 Methods for porosity determination

EN 12697 provides various methods for determining the bulk density of asphalt test specimens. In the immersion method, the specimen volumes necessary for calculating the bulk density are calculated by underwater weighing. In the geometrical measurement method, the bulk density is determined geometrically using an average of the height and diameter of the specimen.

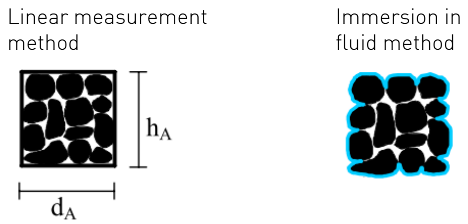


Figure 36: Linear measurement method and immersion in fluid method (Source: [49]

The immersion method offers greater precision for dense samples, since minor errors in linear measurements can significantly affect volume and, consequently, density calculations. The problem with the immersion method is that the water penetrates into the test specimen. Particularly in the case of porous and semi-dense pavements, the immersion method is therefore not sufficiently precise, as the water penetrates the test specimen and then runs out again. The immersion method is therefore only useful for dense pavements with a void content of up to about 6% [50]. In the Canton of Aargau, the geometrical measurement method is the definitive method for determining voids.

Figure 37 shows the correlation of the two measurement methods. This is based on a total of 72 drill core measurements from pavements with a maximum grain size of 4 mm and 8 mm from the Canton of Aargau.

The correlation proves to be very strong (slope 1.0). It can also be seen that there is a relatively low scatter (R^2 = 0.9). On average, the void contents are 3% higher with the geometrical measurement method than with the immersion method (a = 3.0). The mean error is +/- 0.6% [21].

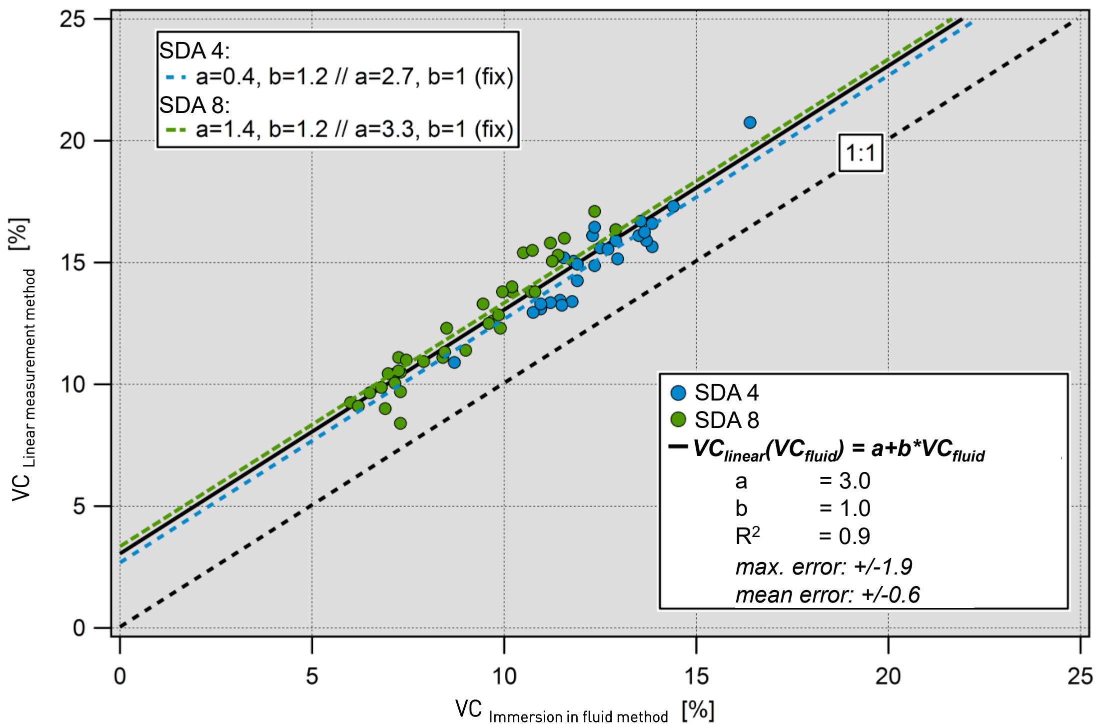


Figure 37: Correlation between immersion and geometrical measurement method for the determination of void content in drill cores and Marshall specimens (Source: [21])

4.1.2 Analysis of the particle size distribution of the mix – Acoustic factor recipe

Within the framework of a research project of the FOEN and the Canton of Aargau, the decisive physical parameters for the long-term acoustic performance of SDA pavements were determined [21]. The results show that acoustically good SDA pavements in the long term are characterised by deep airflow noise and thus, by voids accessible from the surface. In addition, it is apparent that construction and material parameters are secondary. Mix parameters in the formulation are decisive, because the voids accessible from the surface depend strongly on the proportions of filler and sand in the formulation (see also chapter 2.5.2).

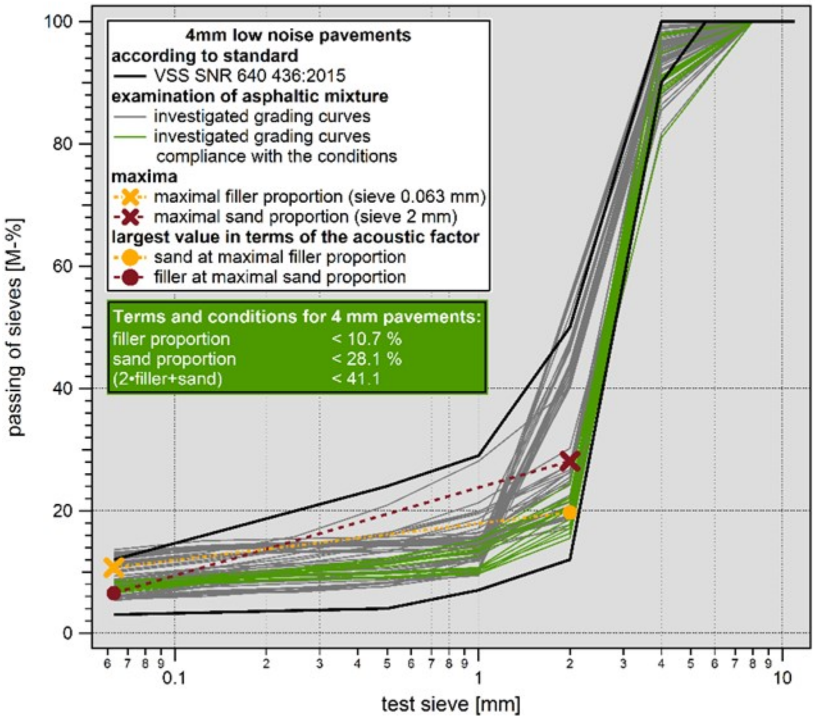


Figure 38: SDA 4 filler and sand contents for long-term acoustical performance (Source: [21])

In order to guarantee good long-term acoustic performance of SDA pavements, a factor was determined which includes the relationship between filler and sand content and is considered a condition for voids accessible from the surface [21].

Acoustic factor recipe SDA 4 = 2*Sieve0.063+Sieve2.0 < 41.1
whereby the proportion of filler is < 10.7% and the proportion of sand is < 28.1%

Note: Sieve = percentage passing for respective sieve size

4.2 Polishing resistance

Experience has shown that skid resistance and thus safety on roads is significantly (but not solely) influenced by the polishing resistance of aggregates. Polishing resistance describes the resistance of aggregates to the polishing action of vehicles on the road. The PSV method (Polished Stone Value) and the WS method (test method according to Wehner/Schulze) are available. The development of both test methods aimed at simulating the polishing stress of road traffic on samples in the laboratory. The PSV method is commonly used in Switzerland [51].

Aggregates with minerals that behave differently in the face of polishing stress are favourable for polishing resistance, so that the fine roughness of the aggregates necessary for skid resistance is regenerated again and again. The aggregate properties of polishing resistance, strength and frost resistance are often not optimally present in one aggregate at the same time. Aggregates with very good polishing resistance may have comparatively unfavourable strength behaviour, and sometimes unsatisfactory frost resistance. Aggregates with favourable resistance to polishing may be: certain greywackes, quartzites, granites or quartz porphyries, depending on the extraction site [52].

4.3 Bitumen properties

Bitumen properties are of great importance in road construction and in relation to the mechanical durability of low-noise pavements. In this chapter, the bitumen properties and their test methods are roughly explained. All procedures are defined in the DIN standards for bitumen and bituminous binders.

The following Figure 39 shows an overview of the three parameters for characterising bitumen that are explained in more detail, as well as their test methods.

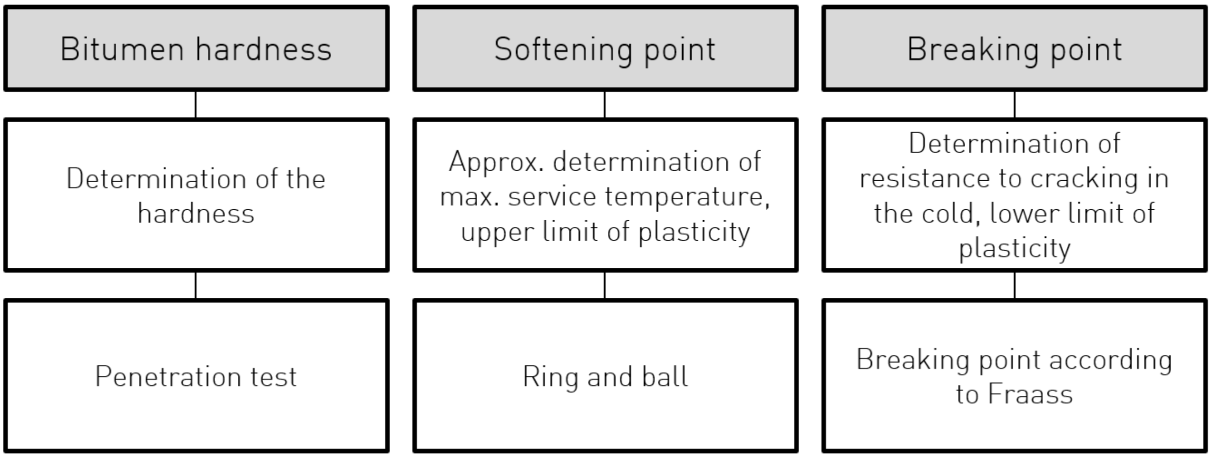


Figure 39: Bitumen properties, , non-exhaustive (Source: Grolimund + Partner AG according to [53])

The plasticity range is used to characterise and test bitumen. This is defined as the temperature range between the softening point ring and ball (indicator for the melting point) and the breaking point according to Fraass (temperature at which a defined binder film breaks under cyclic bending) [53].

Penetration test (EN 1426)

The penetration test allows statements to be made about the hardness of the bitumen. A standardised needle is loaded with a weight and the penetration depth of the needle is determined in 0.1 mm. The requirements for temperature, time and weight specified for the procedure are laid down in the standard.

Penetration values are indicated in the classification of bitumen. For example, the designation bitumen 50/70 means that the bitumen has penetration values (penetration depth of the needle) in the range of 50 to 70 [53].

Softening ring and ball test (EN 1427)

The ring-and-ball test is used to determine the upper service temperature at which the transition from solid/elastic to liquid/plastic takes place. For this purpose, a steel ball (3.50 g) is placed on a bitumen layer in a ring. The bitumen is heated uniformly. The softening point is the temperature at which the steel ball has formed (pressed down) a 25mm long bitumen bag [53].

Breaking point according to Fraass in EN 12593

The Fraass breaking point shows the temperature at which a bitumen film cracks under cyclic bending. A film of binder is applied to a sheet of spring steel. The temperature is then lowered and the sheet is cyclically compressed and relaxed. The temperature at the first crack is considered the breaking point according to Fraass [53].

Polymer modified binders PmB

Polymer-modified binders are essentially determined by their structural composition and by the micro- and nanostructural interaction between polymer and bitumen. Polymer-modified bitumen can have different properties in terms of elasticity, oxidation and temperature sensitivity [53].

Example designation:

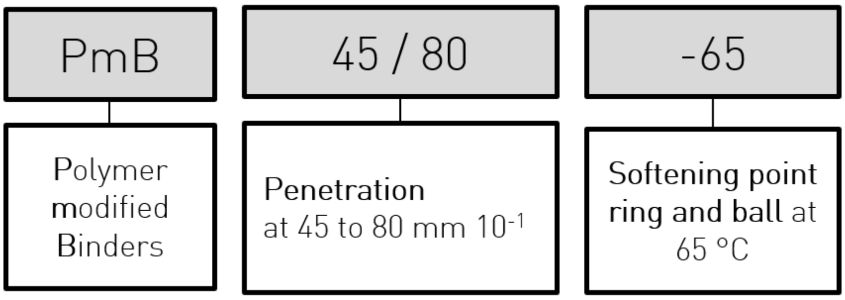


Figure 40: Bitumen designation (Source: Grolimund + Partner AG)

Properties of polymer-modified bitumen depend on the type and amount of polymer, as well as the freedom from dispersion. Reasons for using polymer bitumen are shown below: [53]

- Softer binders at low service temperatures (few cracks)
- Stiffer binders at high temperatures (little rutting)
- Reduction of viscosity at installation and application temperatures (easier compactability)
- Reduction of the required installation and application temperatures
- Increasing the durability and strength of road surfaces
- Increasing the abrasion resistance on the surface of road pavements
- Increasing the fatigue strength of coverings
- Reducing the thickness of road surfaces
- Increasing the weather resistance
- Increase in binder film thickness
- Realisation of special road surface concepts (porous asphalt)

4.4 Mastic properties

The mastic quality is an important factor for the service life of the road surface. The characterisation of mastic is done, for example, by the "Module-de-Richesse method". In this chapter, the characterisation of the mastic properties by this method is roughly explained (not conclusive).

The "Module de Richesse" characterises the thickness of the binder film that coats the aggregate in the asphalt mix (VSS 640 431) [54], [21]. In order to prevent grain breakout, the binder film is of great importance for good bonding of the aggregates, especially in the case of precipitated aggregates.

The "Module de Richesse" M_R is defined as follows [21]:

$$M_R = \frac{B_{AGG}}{A \cdot \sqrt[5]{\frac{0.25 \cdot (100 - a) + 2.3(a - b) + 12 \cdot (b - c) + 150 \cdot c}{100}}}$$

with:

B_{AGG}: Dosed binder content related to the mass of the aggregate

A: Adjustment coefficient for the actual bulk density of the aggregate

a: Sieve passage at 4.0 mm [mass %]

b: Sieve passage at 0.25 mm [mass %]

c: Sieve passage at 0.063 mm [mass %]

5. Collection of basic acoustic data in the Canton of Aargau

5.1 Area-wide acoustic condition recording with CPX

Objective:
- Area-wide survey of acoustic pavement quality (entire road network)
- annual detection of any noise increases

5.1.1 Carrying out the measurement

The requirements for the measurements are summarised in Table 9.

Table 9: Requirements for performing CPX measurements - acoustic condition recording with CPX (Source: Grolimund + Partner AG according to [32])

Standard, basics and corrections	ISO 11819-2 [32], ISO/TS 11819-3 [33], ISO/TS 13471-1 [34]
Measuring speed	50 km/h
Tolerance range for measuring speed	±10 km/h (for individual segments)
Perimeter	Entire road network or road sections
Measuring temperautre (air)	5°C to 30°C
Meteo	Precipitation-free and dry pavements
Number of measurement runs	1 run per lane with car tyres, mounted on both sides 1 run per lane with truck tyres, mounted on both sides
Measured lanes	Measurements always in the wheel lane
Setting electronic markers matching the acoustic signals	Start/end of measuring section, noise, lane shifts, bridges, tunnels, construction sites
Measurement runs must be repeated until valid measurements can be carried out	e.g. in case of high traffic volume during the day, measurements can be shifted to the evening/night hours

5.1.2 Data evaluation and conversion to StL-86+/ SonRoad18

The data analysis and evaluation is carried out according to the specifications in ISO 11819-2:2017 [32], ISO TS 11819-3:2017 and ISO 13471-1:2017 [34] described procedure. The measurement results are corrected according to the measurement speed as well as with regard to the device's own sound reflections, the air temperature measured in-situ at a height of 1.5 m above the ground and the specific tyre hardness. A schematic representation of the procedure for data evaluation and correction is shown in Figure 41 is shown. The requirements for the data evaluation are shown in Table 10 summarised.

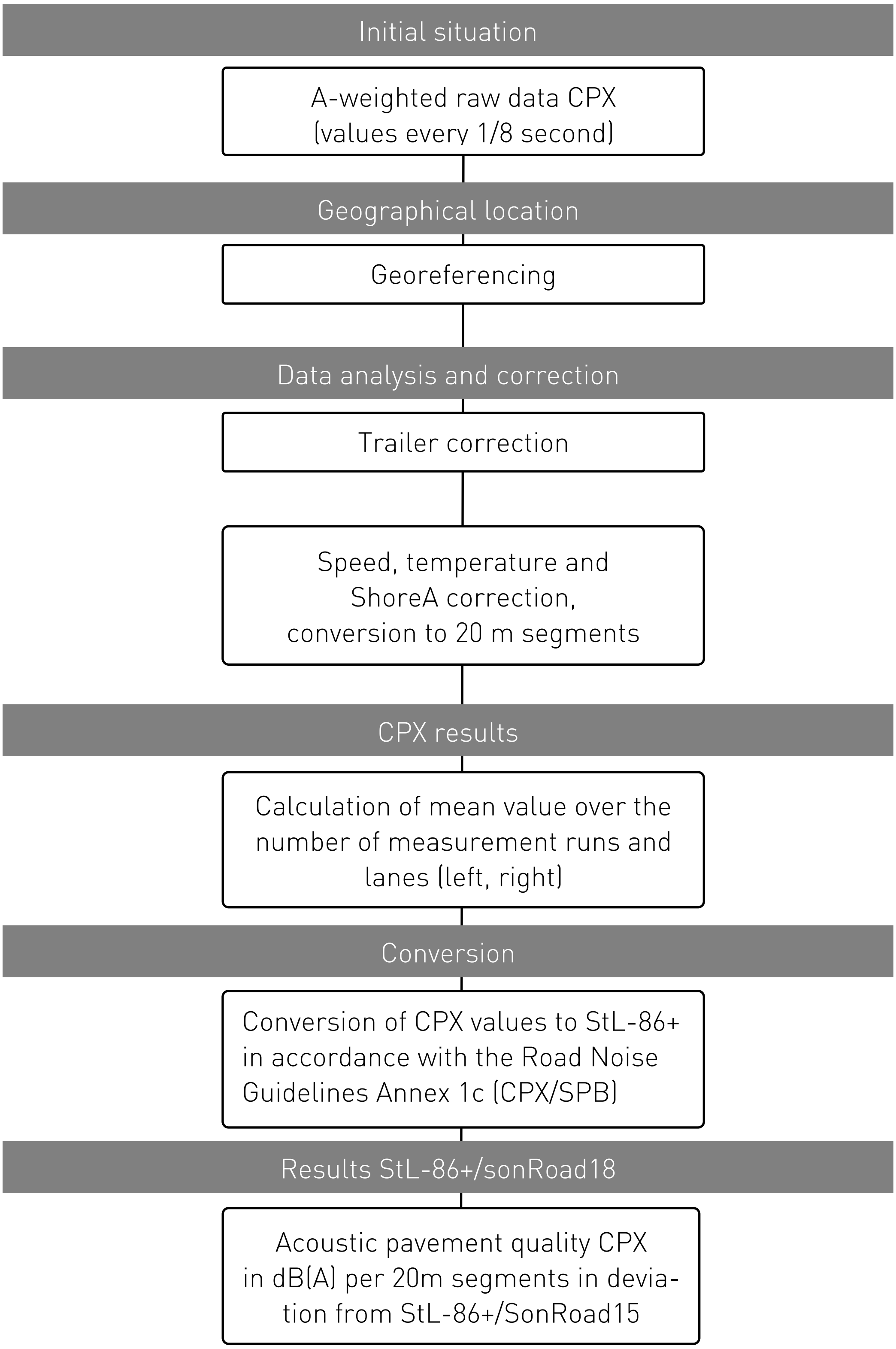


Figure 41: Scheme for data evaluation and correction - acoustic condition recording with CPX (Source: Grolimund + Partner AG according to [32], [33], [34], [36])

Table 10: Requirements for the evaluation of CPX measurements (Source: Grolimund + Partner AG according to [32], [33], [34], [36])

Standards, basics and corrections	ISO 11819-2 [32], ISO/TS11819-3 [33] , ISO/TS 13471-1 [34]
Georeferencing	Lanes parallel to each other
CPX system correction	ISO: 11819-2 [32]
Speed correction	ISO 11819-2 [32]
Temperature correction	ISO/TS 13471-1 [34]
Rubber hardness correction	ISO/TS11819-3 [33]
20 m segments	ISO : 11819-2 [32]
Conversion model CPX values to StL-86+	Leitfaden Strassenlärm, Anhang 1c [36]
Exclusion of segments with non-standard measurement results (if necessary) and documentation	E.g. speed deviations, noise interference

5.1.3 Data preparation and submission

In the following chapter, the most important steps for data preparation and submission are explained. These refer to the applicable standards and the specific requirements of the Canton of Aargau.

Results of the 20 m segments, which are influenced by disturbing elements (e.g. speed deviations, disturbing influences, etc.), are excluded from the assessment. Since the acoustic assessment of the entire road surface is in the foreground during the condition assessment measurement, "non-pavement" influences in the wheel lane are not excluded from the assessment. If available, the pavement information such as pavement type or year of installation is assigned to the 20 m segments. Based on the pavement information, the mean values of the Acoustic Pavement Quality CPX in dB(A) are calculated per pavement segment (over the entire consecutive length of the same pavement type and the same year of installation) in deviation to StL-86+. This results in acoustic mean values for cars, trucks, and mixed traffic with a certain percentage of heavy traffic (usually 8 %). For longer sections without pavement information, acoustically homogeneous sections are formed (according to the method described in [55]). This means that if there are statistically significant changes in the acoustic properties along the road, and taking into account a minimum mean value difference, the sections are divided into acoustically homogeneous sections. The Standard Normal Homogeneity Test (SNHT) according to Alexanders-son & Moberg [56], which is often used to identify significant changes in mean values in data series, is suitable for this purpose. The results of the CPX measurements are then processed so that they can be visualised in plans using shapefiles (file format for vector geodata). The following figure shows the most important delivery formats and their contents.

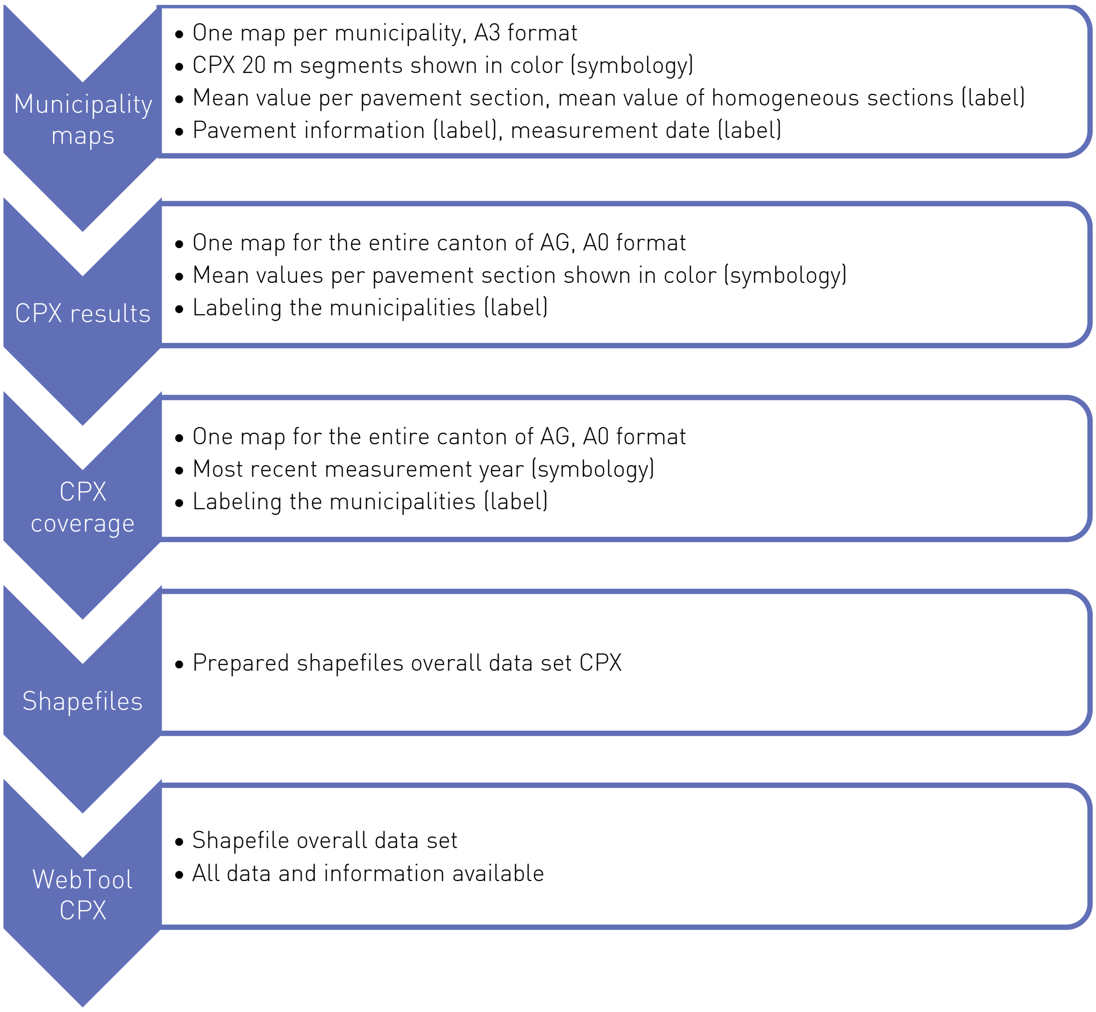


Figure 42: Delivery formats and contents of acoustic quality recording (Source: Grolimund + Partner AG)

5.1.4 Use of data in projects

The use of CPX data in projects is described in detail in the working instructions for the implementation of noise abatement project (integral management system (IMS) document of Kt Aargau 403.201).

5.2 Acoustic monitoring of low-noise pavements with CPX

Objective:
- Monitoring of the acoustic pavement quality of routes with low-noise pavements
- Annual monitoring of the acoustic performance.

5.2.1 Carrying out the measurement

The requirements for the measurements are summarized in Table 11.

Table 11: Requirements for performing CPX measurements - acoustic monitoring of low-noise pavements with CPX (Source: Grolimund + Partner AG according to [32])

Standards and corrections	ISO 11819-2 [32], ISO/TS 11819-3 [33], ISO/TS 13471-1 [34]
Measuring speed	50 km/h
Tolerance range of the measuring speed	+/-5 km/h (for individual measuring segments)
Perimeter	Individual pavement sections
Measuring temperature (air)	5°C to 30°C
Number of measurement runs	Precipitation-free, dry pavements
Measured lanes	2 runs per lane with car tyres, mounted on both sides 2 runs per lane with truck tyres, mounted on both sides
Measurement procedure for multiple lanes	Measurements always in the wheel lane
Setting electronic markers matching the acoustic signals	Start/end of measurement section or LNP, noise, bridges, tunnels, construction sites, all influences outside the pavement such as manhole covers, markings, patches, etc.
Measurement runs must be repeated until valid measurements can be carried out	E.g. in case of high traffic volume during the day, the measurements can be shifted to the evening/night hours

5.2.2 Data evaluation and conversion to StL-86+/SonRoad18

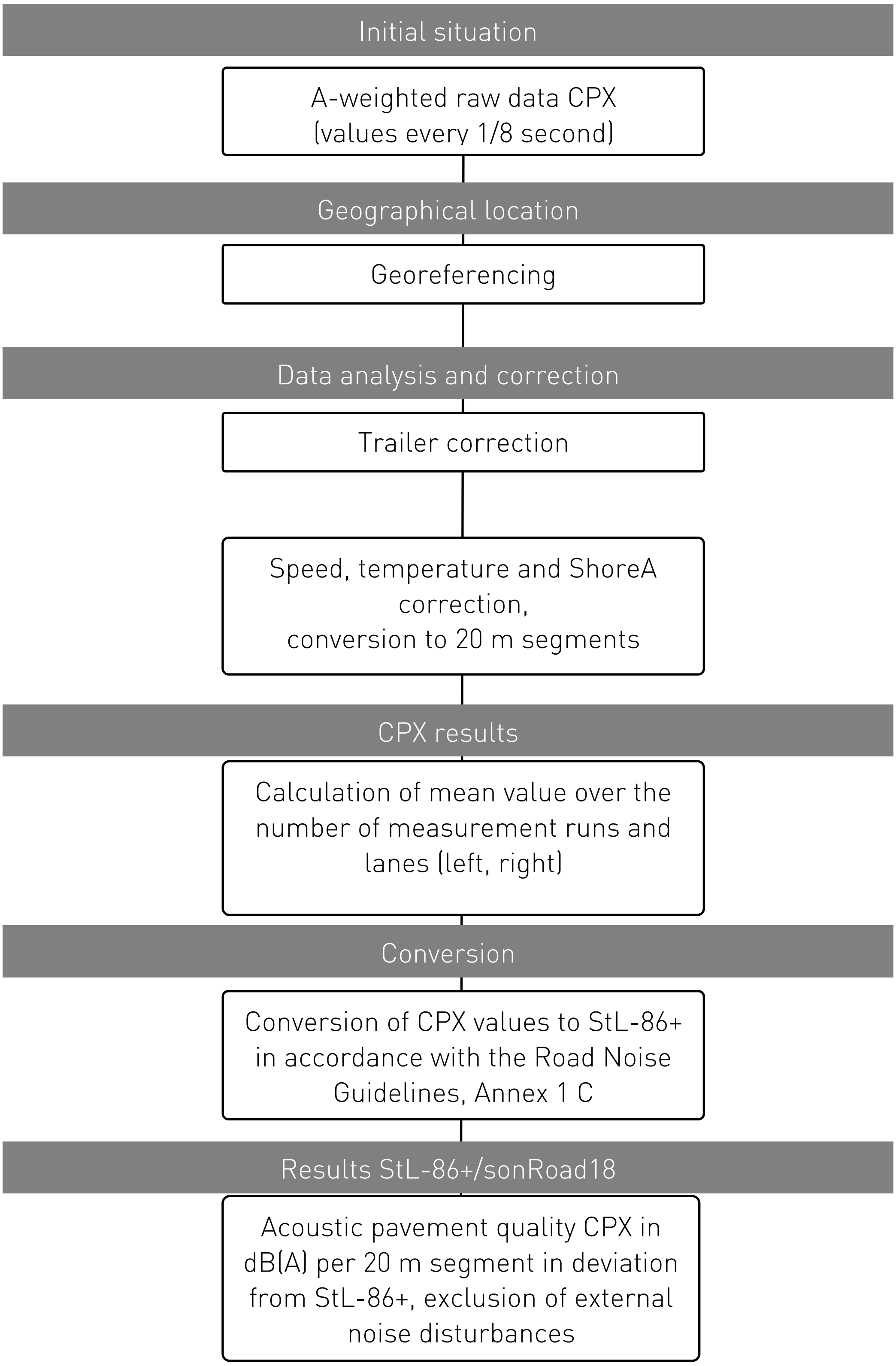


Figure 43: Scheme for data evaluation and correction - acoustic monitoring of low-noise pavements with CPX (Source: Grolimund + Partner AG according to [32], [33] , [34], [36])

In the following chapter, the most important steps for data preparation and submission are explained. These refer to the applicable standards and the specific requirements of the Canton of Aargau.

Results of the 20 m segments that are influenced by disturbing elements (e.g. speed deviations, disturbing influences, etc.) and "non-pavement" elements (manhole covers, markings, patches, etc.) are excluded from the assessment. Monitoring measurements focus on assessing the acoustic properties of the pavement. The pavement information (type of pavement, year of installation) is assigned to the 20 m segments. Based on the pavement information, the mean values of the acoustic pavement quality values CPX in dB(A) are calculated for each pavement segment in deviation to StL-86+. This results in acoustic mean values for cars, trucks and mixed traffic with a certain heavy traffic share (usually 8 %) per section with LNP. Figure 44 shows the most important delivery formats and their contents.

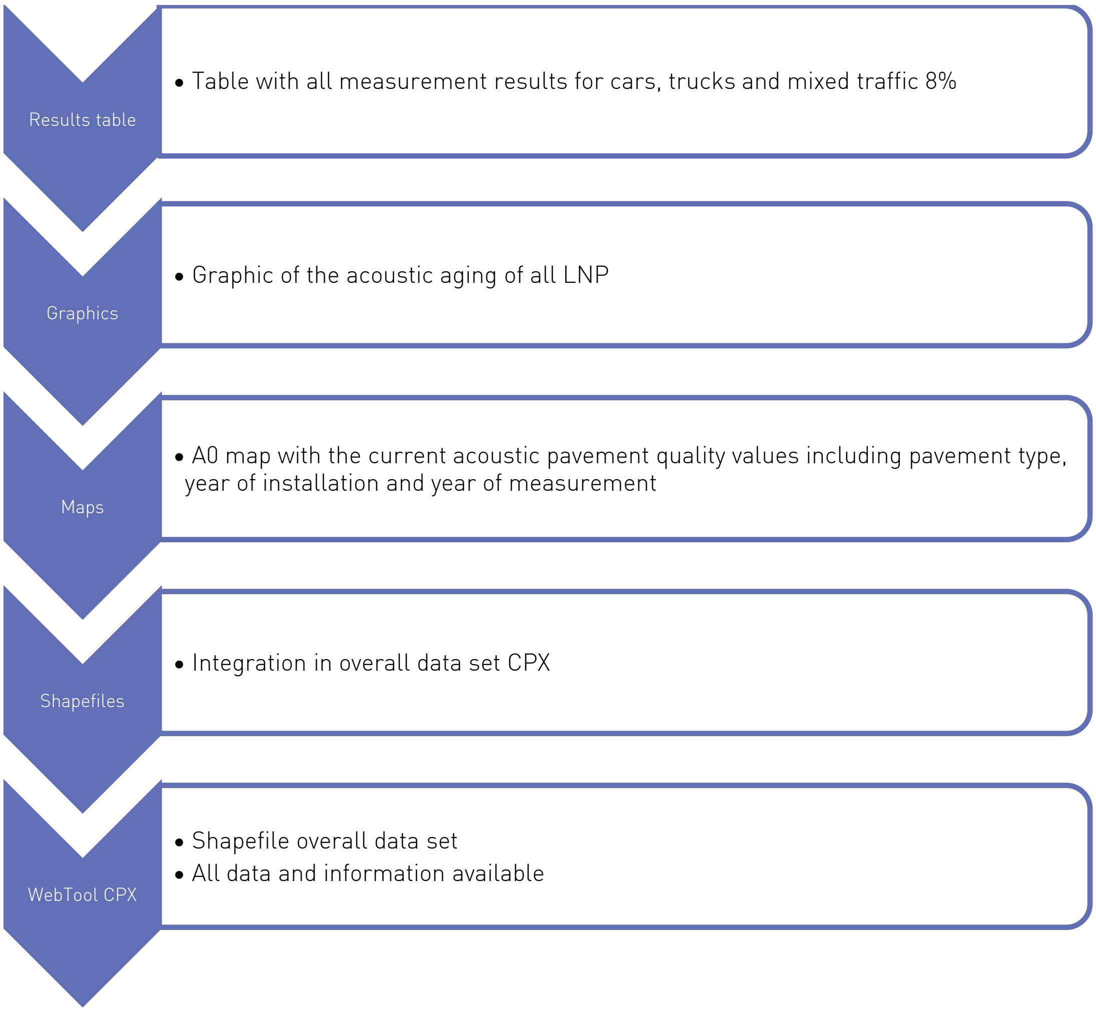


Figure 44: Delivery formats and content of acoustic monitoring (Source: Grolimund + Partner AG)

5.3 Checking the road asset value

The data described in chapter 5.1 and 5.2 are a basic element for the verification of the asset value of the roads.

The acoustic quality of the road surfaces is measured every three years across the entire cantonal road network of the Canton of Aargau using the CPX method (see chapter 5.1). These data represent a central means of monitoring the changes in noise emissions caused by street noise. In order to verify the requirements of the federal subsidies, the acoustic quality of the installed low-noise pavements is also periodically surveyed and assessed (see chapter 5.2). The measurements also serve as an early warning system, on the one hand to detect possible defects during manufacture or installation, and on the other hand to provide a basis for the continuous optimisation of the road surfaces [57]

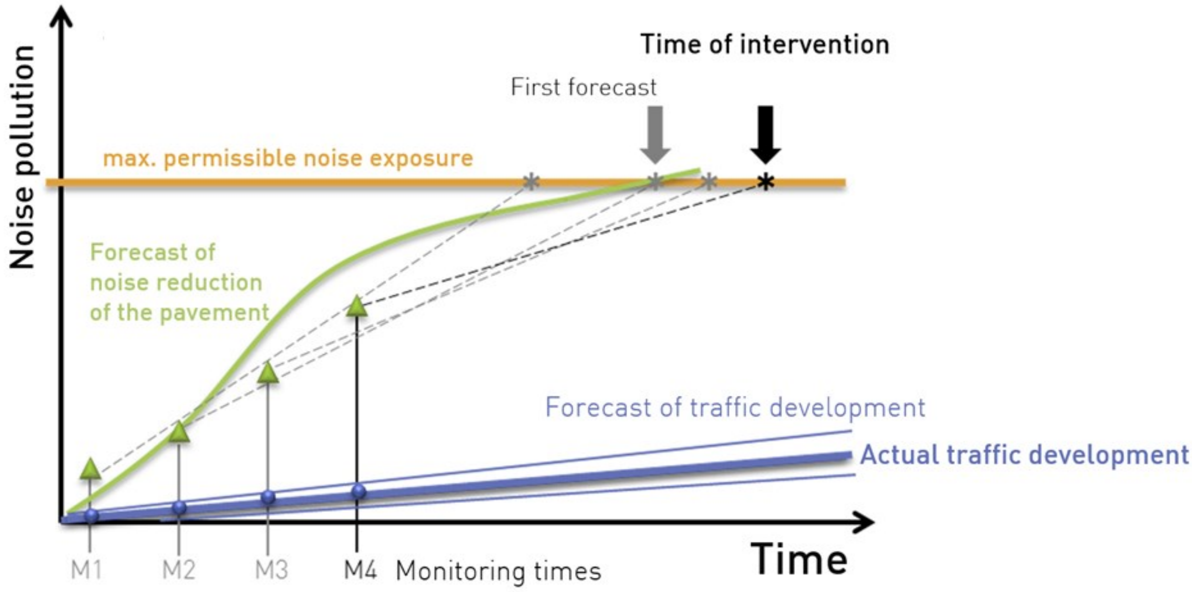


Figure 45: Determination of the intervention time for low-noise pavements (Source: Grolimund + Partner AG)

Noise emissions are monitored at regular intervals using the forecasting tool described above. The time at which pavement replacement is required (time of intervention) can thus be determined at an early stage and included in the planning accordingly.

The time of intervention, or the change in noise emissions, depends on various factors:

- From the deterioration of the acoustic quality of the pavement
- From the development of traffic

The survey of the current acoustic condition of the installed low-noise pavements and the entire road network allows long-term and efficient planning of road maintenance. On the other hand, the surveys enable monitoring and compliance with noise protection requirements and the required effectiveness of low-noise pavements [57]. In order to pursue a targeted and successful strategy, it is of great importance to monitor the acoustic condition of the roads in the long term.

6. Insights from practice

6.1 Acoustic effect of SDA pavements in the Canton of Aargau

The Canton of Aargau has the acoustic quality of the SDA pavements checked annually. The following two figures show the acoustic effects depending on the age of the pavement.

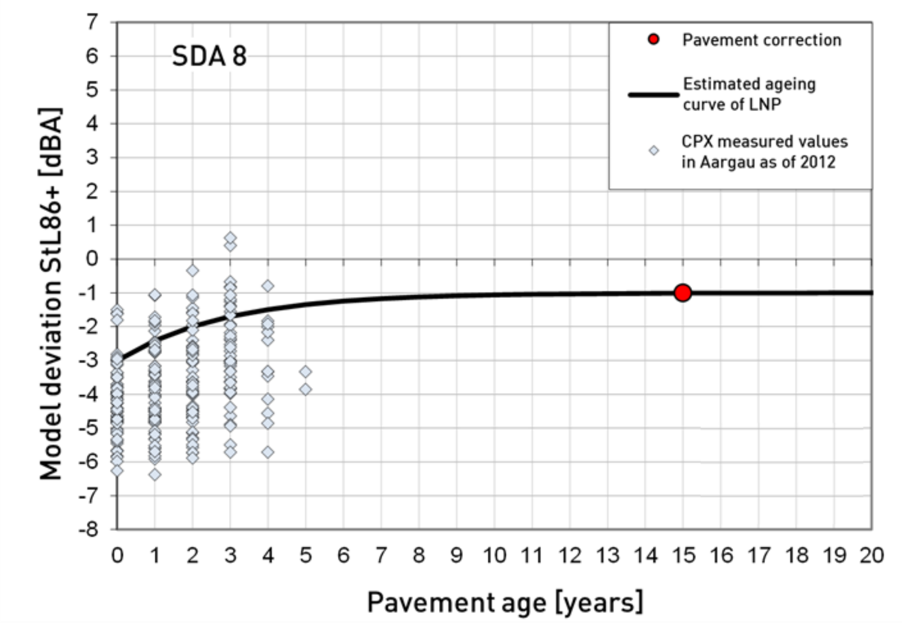


Figure 46: SDA 8 – CPX measurements in Canton of Aargau from installation year 2012 (as at end of 2018, mixed traffic values 8 %) (Source: Grolimund + Partner AG)

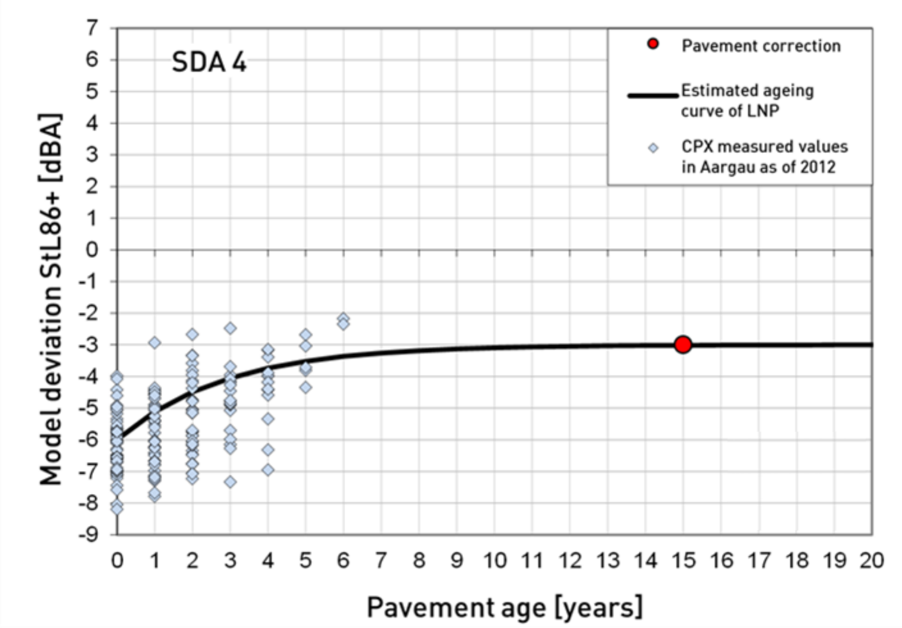


Figure 47: SDA 4 – CPX measurements in Canton of Aargau from installation year 2012 (as at end of 2018, mixed traffic values 8 %) (Source: Grolimund + Partner AG)

6.2 Acoustic effect of road surfaces at junctions and roundabouts

In the implementation guideline 3.21 of the Cercle Bruit *Lärmtechnische Beurteilung von Knoten und Kreiseln* (*Noise assessment of junctions and roundabouts*) shows, among other things, the emission-side pavement effects to be taken into account [58].

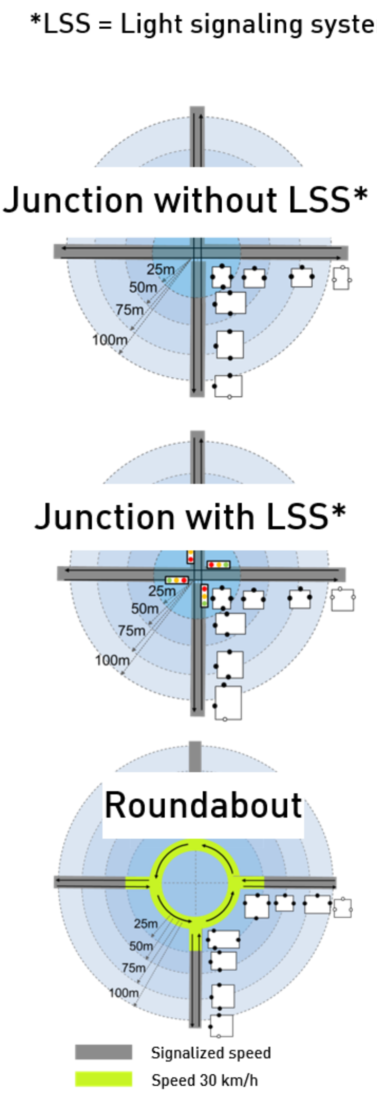
Pavement effect on the emission side

The pavement effect in the vicinity of junctions and roundabouts is listed in the following Table 12 as a percentage value of the pavement characteristic value on the straight stretch [58].

Table 12: Pavement effect in the vicinity of junctions and roundabouts (Source: [58])

	Distance to junction/roundabout	Pavement effect
Straight stretch	>25 m	100 %
Junction/roundabout	≤25 m	60 %

Example: Concrete free section → +4 dB
Concrete junction and roundabout → +2.4 dB



Emission-side correction of the pavement effect

Scenario	Distance	SDA 4	SDA 8	SMA 8	Low-noise washed concrete	Concrete with broom finish
Junction without LSS*	straight	-3 dB	-1 dB	+1 dB	+2 dB	+4 dB
	< 25m	-1.8	-0.6	0.6	1.2	2.4
	25 - 50m	-3.0	-1.0	1.0	2.0	4.0
	50 - 75m	-3.0	-1.0	1.0	2.0	4.0
	75 - 100m	-3.0	-1.0	1.0	2.0	4.0
Junction with LSS*	straight	-3 dB	-1 dB	+1 dB	+2 dB	+4 dB
	< 25m	-1.8	-0.6	0.6	1.2	2.4
	25 - 50m	-3.0	-1.0	1.0	2.0	4.0
	50 - 75m	-3.0	-1.0	1.0	2.0	4.0
	75 - 100m	-3.0	-1.0	1.0	2.0	4.0
Roundabout	straight	-3 dB	-1 dB	+1 dB	+2 dB	+4 dB
	< 25m	-1.8	-0.6	0.6	1.2	2.4
	25 - 50m	-3.0	-1.0	1.0	2.0	4.0
	50 - 75m	-3.0	-1.0	1.0	2.0	4.0
	75 - 100m	-3.0	-1.0	1.0	2.0	4.0

Figure 48: Emission-side corrections for the pavement effect in various scenarios (Source: [58])

The standardised measurement procedures CPX, SPB and SEM cannot be applied to a roundabout in accordance with the standards, as these are based on straight stretches with constant speed. In order to determine changes in noise emissions in the context of roundabout renovations, an adapted measurement concept is recommended. Note: An associated report will be published shortly.

6.3 Quiet tyres on low-noise pavements

The potential for reducing noise emissions across the board holds opportunities to reduce the costs of noise abatement measures in the future. In the study *Lärmminderungspotential leiser Reifen auf gängigen Schweizer Strassenbelägen* (Noise reduction potential of quiet tyres on common Swiss road surfaces), G+P was commissioned by the Federal Office for the Environment (FOEN) and the cantons of Aargau, Graubünden, Solothurn and Zurich to measure the rolling noise level of 14 commercially available summer tyres on 10 different conventional road surfaces and on a low-noise pavement. The aim of the study was to determine the noise reduction potential of "quiet" tyres on the most common Swiss road surfaces. In addition, the most important tyre-related influencing variables were identified and quantified in order to be able to create scenarios for future trends. The following is a summary of the most important findings from this study:

- The difference between the loudest and quietest tyres measured in this study is relatively large. With 100 % use of quiet tyres, this would correspond to up to a halving of traffic [59].

Tire width	185 mm	205 mm	225 mm	295 → 155 mm
common Swiss road surfaces	3.5 dB	1 dB	1.5 dB	4 dB

Figure 49: Noise reduction potential of quiet tyres (Source: [59])

- The noise reduction potential determined is almost identical on all conventional pavements investigated.
- Interestingly, the noise reduction potential on low-noise pavements is not lower.
- The most important influencing variables for the noise reduction potential are: Tyre width, tyre radius, tyre rubber hardness (tread and sidewall) and rolling resistance label.
- Due to recent tyre trends (increase in tyre width and tyre radius), it must be assumed that tyre-related noise emissions will increase slightly to moderately in the future.
- If the noise reduction potential of the tyres can be exploited more in the future, noise emissions could be reduced by a few decibels.
- With one hundred percent use of quiet tyres, a noise reduction potential of up to 3.5 dB was determined [59].

Remarks:

In September 2019, an EU project of the CEDR (Conference of European Directors of Roads, project management G+P) started with the following objectives:

- Developing and testing variants for further tightening of tyre approval values
- Optimisation labelling procedure
- Ensure reliability and representativeness on roads in Europe

7. Strategy - optimal use of low-noise pavements

7.1 Involvement of the main stakeholders

A fundamental challenge for the successful application of low-noise pavements is the cooperation between road construction, road maintenance, maintenance planning and noise protection. In order to be able to coordinate these specialist areas, an overarching strategy of the civil engineering office is of great importance. Furthermore, current relevant data and information should be available at all times. A constant exchange and comparison between the stakeholders and projects is necessary. Since continuous monitoring enables forward-looking planning and noise protection to be taken into account, it is desirable that noise protection be integrated into the maintenance strategy and maintenance planning.

The unification of all stakeholders involved and their interests leads to a constant updating of the state of knowledge and know-how, which is of great importance for the further development and optimisation of technologies. The success of the application of low-noise pavements as a noise abatement measure depends on the unification of all stakeholders and all interests and an existing and functioning overarching strategy. The strategy and its successes should be communicated to the public as broadly as possible [57].

7.2 Selection of technologies and road sections

In the Canton of Aargau, the first priority is to implement noise protection measures at the source. These include low-noise pavements, speed reductions and traffic control measures. In order to protect the affected properties from excessive noise in the future, the installation of low-noise pavements should therefore be the primary focus, as they have an effective and area-wide effect without hindering traffic flow.

According to the concept of low-noise pavements in the Canton of Aargau, only pavements with noise-reducing properties are installed in urban areas. On the acoustically less heavily polluted network, this is the semi-dense pavement SDA 8-12 and on the more heavily polluted network an SDA 4-12 in accordance with VSS-40436 (with the exception of zones with noise sensitivity level ES IV).

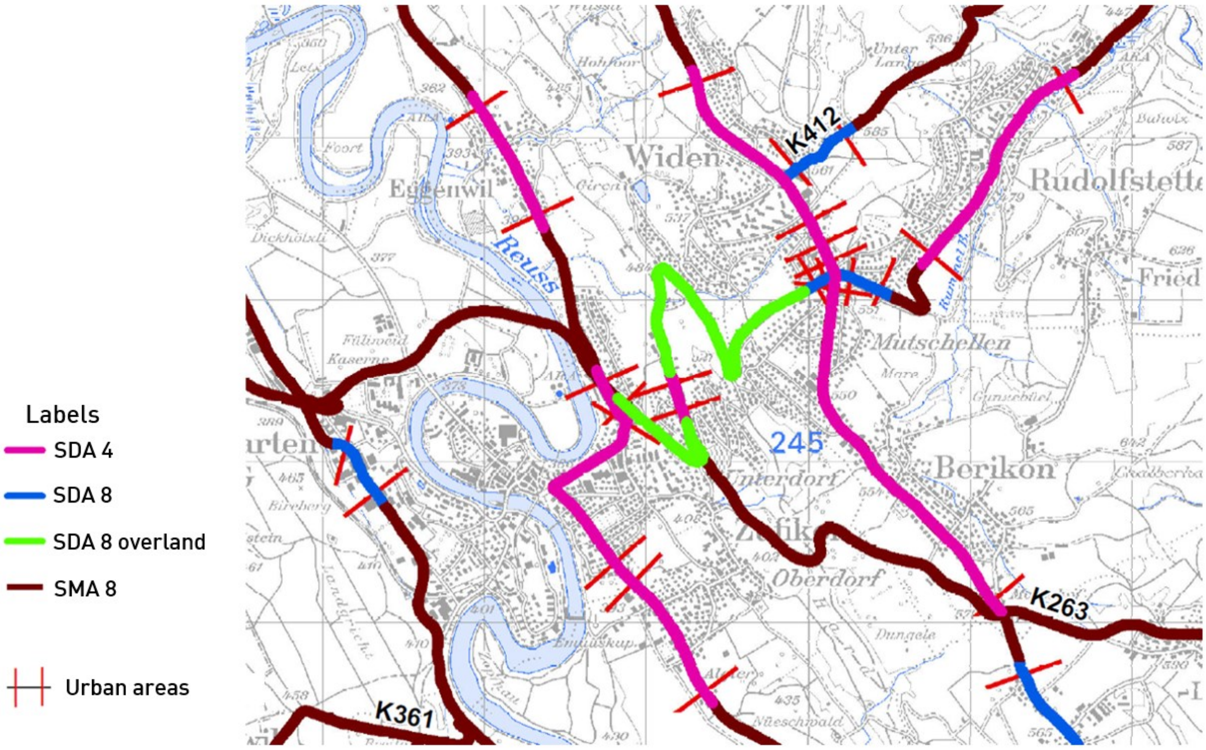


Figure 50: Excerpt from the Canton of Aargau low-noise pavement strategy plan (Source: ATB, Canton of Aargau)

7.3 Monitoring of road surfaces and planning of replacement

At present, it is assumed that the surface course of SDA 8 pavements will have to be replaced after 20 years. For SDA 4 pavements, the replacement of the surface course is assumed to take place after approx. 10 years and the combined replacement of the surface course and base layer after 20 years. However, it is quite possible that the longevity of SDA pavements may be higher than assumed.

It should be possible to take noise protection interests into account as early as possible in road construction, maintenance and repair planning. For this purpose, noise data must be processed and made available in a suitable form. Monitoring of the pavements and monitoring of the noise abatement projects (LSP) ensure that information is available as a basis for decision-making (e.g. early replacement of the surface course, preference for subsequent remediation of the LSP). In order to monitor and include the change in noise emissions caused by the pavement, an acoustic condition survey of the road surfaces is also carried out using the CPX method with the periodic survey of the road condition.

8. Conclusions

Low-noise pavements reduce noise generated at the source and are suitable as an effective noise protection measure in typical situations in urban and overland areas and under most traffic regimes. With the technologies known today, permanent noise reductions can be achieved. Suitable acoustic and structural measurement and analysis methods are available to monitor success. However, it must be noted that long-term experience with low-noise pavements with the technologies used in Switzerland is still lacking in some cases. For example, at the time of writing this document, only a time series of a maximum of eight years was available for SDAs. The present document highlights the knowledge gained on the planning, manufacture and installation of low-noise pavements. As it is a snapshot showing the current state of knowledge, both positive and negative experiences must continue to be collected and analysed, and the measurement procedures and analysis methods must be continuously developed. The present documentation is intended as a working aid and will be periodically supplemented with new findings. Further research is needed, for example, to optimise the bitumen and mastic properties of SDA in order to achieve improved durability and better behaviour in heat and frost. Furthermore, specific further developments are desirable for their application in special locations. With the network-wide use of low-noise pavements, further questions arise on how to further optimise the efficiency and the cost-benefit ratio.

The Canton of Aargau wants to continue to play a leading role in the application and further development of low-noise pavements. To this end, systematic monitoring measurements (acoustic pavement quality measurements CPX) and targeted evaluations are carried out. The data collected serves as a basis for planning the maintenance and replacement of surface courses. This periodic survey is enriched with targeted monitoring measurements on rehabilitation pavements eligible for subsidies to fulfil the basic requirements for applying for federal subsidies. The acoustic monitoring measurements serve as an early warning system to identify possible defects during production or installation in good time. It is planned to further investigate particularly good and bad cases in order to optimise the technology of low-noise pavements to the conditions of the Canton of Aargau and thus achieve an improved cost-benefit ratio. The synergies between noise protection and maintenance planning are to be further developed. The Canton of Aargau is keen to exchange experiences among experts.

9. List of figures

10. Bibliography

[1] Bundesamt für Umwelt BAFU, “Lärmbelastung in der Schweiz,” Umwelt-Zustand, 2018.

[2] E. Hammer, S. Egger, T. Saurer, and E. Bühlmann, “Traffic noise emission modelling at lower speeds,” in Conference Proceeding ICSV 2016, 2016, pp. 1–8.

[3] K. Heutschi and B. Locher, “sonROAD18 Berechnungsmodell für Strassenlärm,” 2018.

[4] Bundesamt für Umwelt BAFU, “Leise Strassen,” 2012.

[5] S. Egger, T. Saurer, E. Hammer, and E. Bühlmann, “A new method for reliable determination of the acoustic performance of low-noise road surfaces at speeds below 50 km/h,” pp. 6942–6951, 2016.

[6] Grolimund + Partner AG, “Nachschlagetabelle für Wirkungsprüfung T30 und laB,” in Bearbeitung., 2020.

[7] S. Egger, E. Bühlmann, E. Hammer, and T. Ziegler, “Grundlagen zur Beurteilung der Lärmwirkung von Tempo 30,” Forschungsprojekt VSS 2012/214 auf Antrag des Schweizerischen Verbands der Strassen- und Verkehrsfachleute, 2017.

[8] A. Kuijpers and G. Van Blokland, “Tyre / road noise models in the last two decades : a critical evaluation,” 2001 Int. Congr. Exhib. Noise Control Eng., 2001.

[9] U. Sandberg and J. A. Ejsmont, Tyre/Road Noise Reference Book. Sweden: Informex, 2002.

[10] Z. Mohamed, X. Wang, and R. Jazar, “A survey of wheel tyre cavity resonance noise,” Int. J. Veh. Noise Vib., vol. 9, no. 3–4, pp. 276–293, 2015.

[11] B. Peeters, I. Ammerlaan, A. Kuijpers, and G. Van Blokland, “Reduction of the Horn Effect for Car and Truck Tyres By Sound Absorbing Road,” Imagine, pp. 1–10.

[12] VSS, VSS-40425 Lärmmindernde Decken - Grundlagen. 2019.

[13] ASTRA und BAFU, “Leitfaden Strassenlärm,” 2006.

[14] H. Beyeler, “Lärmmindernde Strassenbeläge,” Präsentation Forum Bauen - November 2014.

[15] Kanton Aargau Departement ür Bau Verkehr und Umwelt, Norm Belagsaufbau – Konzeption und Anforderungen Verkehrsklasse Kanton Aargau. 2020.

[16] R. Attinger and A. Meister, “Akustische Eigenschaften von Fahrbahnbelägen im niederen Geschwindigkeitsbereich, Stand der Erkenntnisse 1996,” 1997.

[17] H. Pestalozzi, H.-J. Grolimund, and C. Angst, “Lärmarme Strassenbeläge innerorts Statusbericht 2003,” Bundespublikationen, vol. Bundesamt, 2004.

[18] C. Angst, F. Beltzung, D. Bosshardt, H.-J. Grolimund, and H. Pestalozzi, "Lärmarme Beläge innerorts. Schlussbericht 2007 – Kurzfassung," Bundesamt für Umwelt und Bundesamt für Strassen, Bern, 2008.

[19] VSS, "VSS 640436 - Semidichtes Mischgut und Deckschichten." 2015.

[20] E. Bühlmann, P. Bürgisser, T. Ziegler, C. Angst, and Beckenbauer Thomas, "Forschungspaket lärmarme Beläge innerorts Teilprojekt (TP 3): Langzeitmonitoring," 2017.

[21] E. Bühlmann, E. Hammer, N. Bueche, and J. Perret, "Ausführungsbestimmungen Akustik für semidichte Asphalte - Auswertung physischer Parameter (in German and French)," Bern, 2017.

[22] E. Bühlmann and E. Hammer, "Towards semi-dense asphalt mixtures that guarantee acoustic performance and durability," INTER-NOISE NOISE-CON Congr. Conf. Proc., no. 4, pp. 1559–1568, 2017.

[23] Bundesamt für Strassen (ASTRA) 2009/007, Lärmarme Oberflächen bei Gussasphalt-Deckschichten auf Brücken. 2016.

[24] VSS, "VSS-40436 Semidichtes Mischgut und Deckschichten, Festlegungen, Anforderungen, Konzeption und Ausführung." 2019.

[25] S. Egger, E. Bühlmann, and H. Gloor, "Kritische Faktoren für den erfolgreichen Einsatz lärmarmer Beläge im Innerortsbereich Kritische Faktoren," Conf. Proc. DAGA 2017, pp. 619–622, 2017.

[26] E. Bühlmann, M. Dias, and S. Steiner, "Influence of environment- and traffic-related factors on acoustic ageing of low-noise road surfaces in Switzerland," Conf. Proc. EuroNoise Maastricht, pp. 1321–1326, 2015.

[27] V. Roth, H. Gloor, D. Milo, and E. Bühlmann, "Reinigung von semi-dichten Asphalten zur Erhaltung der akustischen Leistung," 2019.

[28] E. Hammer, E. Bühlmann, and T. Ziegler, "Forschungspaket : Lärmarme Beläge innerorts EP 8 : Akustische Wirkung betrieblicher Reinigungsmassnahmen bei Lärmarmen Belägen," 2016.

[29] A. M. Delaby, J. Perret, A. E. Bühlmann, and V. Roth, "Nettoyage des revêtements phono- absorbants du canton de Fribourg : Bilan Campagnes 2018 et 2019," 2020.

[30] Grolimund + Partner AG, "Schleifarbeiten Zofingen , Zwischenbericht," 2019.

[31] T. Saurer, E. Bühlmann, and T. Ziegler, "Research Package: Low-noise Pavements in Urban Areas EP7: Applicability of Low Noise Asphalt in Switzerland (in German)," Bern, Switzerland, 2016.

[32] ISO 11819-2: 2017, Acoustics - Measurement of the influence of road surfaces on traffic noise - Part 2: The close-proximity method (ISO 11819-2:2017). .

[33] ISO/TS 11819-3:2017, Acoustics — Measurement of the influence of road surfaces on traffic noise — Part 3: Reference tyres. .

[34] ISO/TS 13471-1:2017, Acoustics — Temperature influence on tyre/road noise measurement — Part 1: Correction for temperature when testing with the CPX method, vol. 2017. 2017.

[35] ISO 11819-1:2022, "Acoustics – Measurement of the influence of road surfaces on traffic noise – Part 1: Statistical Pass-By method," 2022.

[36] Bundesamt für Strassen (ASTRA) & Bundesamt für Umwelt (BAFU), "Leitfaden Strassenlärm Anhang 1c : Technisches Merkblatt für akustische Belagsgütemessungen an Strassen," 2013.

[37] E. Bühlmann, S. Egger, P. Mioduszewski, and U. Sandberg, "An in-depth look at the tire rubber hardness influence on tire/road noise measurements," INTER-NOISE 2018 - 47th Int. Congr. Expo. Noise Control Eng. Impact Noise Control Eng., 2018.

[38] E. Bühlmann and G. van Blokland, "Temperature effects on tyre / road-noise – A review of empirical research," in Conference Proceedings Forum Acusticum, Kraków, 2014, vol. 43.5, p. 6.

[39] E. Bühlmann and T. Ziegler, "Temperature effects on tyre/road noise measurements," 40th Int. Congr. Expo. Noise Control Eng. 2011, INTER-NOISE 2011, vol. 1, pp. 557–564, 2011.

[40] E. Bühlmann, U. Sandberg, and P. Mioduszewski, "Speed dependency of temperature effects on road traffic noise," 2015.

[41] Y. Pillonel, M. Trocmé, E. Bühlmann, and T. Saurer, "CPX-Messungen auf Nationalstrassen - ASTRA 88010," pp. 1–48, 2017.

[42] B. Peeters, I. Ammerlaan, and a Kuijpers, "Noise reduction by absorbing road surfaces : destroying the horn effect," Isma, pp. 4053–4064, 2010.

[43] E. Bühlmann and T. Ziegler, "Interpreting measured acoustic performance on Swiss low-noise road surfaces using a tyre / road interaction model," pp. 1–6, 2012.

[44] F. Schlatter and E. Bühlmann, "Acoustic optimization of asphalts using Acoustic Void Content Analysis AVCA on drill cores," Conf. Proc. Internoise 2020, 2020.

[45] BAM, "CT-Messungen und Hohlraumanalyse von Asphaltbohrkernen," 2017.

[46] D. Meinel, A. Staude, and K. Ehrig, "Analyzing Microstructure and Damage in Construction Materials with 3D Micro CT," Proc. 2nd Int. Congr. 3D Mater. Sci., pp. 23–28, 2014.

[47] T. Saurer, H. Gloor, E. Bühlmann, and E. Hammer, "Etablierung eines Akustik-Faktors zur Beurteilung der akustischen Leistung von semidichten Asphalten," pp. 2–5, 2018.

[48] T. Balmer and F. Steiner, "Akustische Alterung lärmarmer Beläge durch Verschmutzung – Grundlegende Mechanismen," VSS-Strasse und Verkehr, pp. 22–30, 2018.

[49] B. Wallner, “Bewertung von Asphalt mit dem Gyrator,” 2003.

[50] M. Hugener and S. Hean, “Bituminöse Baustoffe,” 2009.

[51] V. Rosauer and C. K. Schulze, Widerstand gegen Polieren : Kritische Bewertung PSV / PWS, vol. 2012. .

[52] Deutscher Asphaltverband, “Asphaltdeckschichten Griffigkeit,” 2006.

[53] P. M. N. Partl, “Asphalt und Bitumen Geschichte-Bitumen-Asphalt,” pp. 1–27, 2011.

[54] VSS, “SN 640 431-1-NA - Asphaltmischgut, Mischgutanforderungen - Teil1: Apshaltbeton.” VSS Schweizerischer Verband der Strassen- und Verkehrsfachleute, 2017.

[55] M. Merki, R. Schibli, S. Schulze, and E. Bühlmann, “Statistical methods to determine acoustically homogeneous sections and predict road surface type changes using tyre / road noise data,” Proc. Forum Acusticum, Kraków, Pol., pp. 1–6, 2014.

[56] H. Alexandersson and A. Moberg, “Homogenization of Swedish temperature data.,” . Int. J. Clim. 17, vol. 17, 1997.

[57] T. Saurer, H. Gloor, D. Milo, and E. Bühlmann, “Strategie zur erfolgreichen Anwendung von leisen Straßenbelägen im Innerortsbe- reich Einleitung Leise Straßenbeläge als Lärmschutzmaßnahme Auswirkungen auf Planung und Prozesse,” 2019.

[58] Cercle Bruit, “Lärmtechnische Ermittlung bei Knoten und Kreiseln,” pp. 1–12, 2016.

[59] E. Hammer and E. Bühlmann, “Lärmminderungspotential leiser Reifen auf gängigen Schweizer Strassenbelägen,” Bundesamt für Umwelt BAFU, 2018.