Influence of environment- and traffic-related factors on acoustic ageing of low-noise road surfaces in Switzerland

Erik Bühlmann
Grolimund + Partner AG – environmental engineering, Bern, Switzerland.

Marlène Dias
Swiss Federal Office for the Environment FOEN, Bern, Switzerland.

Simon Steiner
Swiss Federal Office for the Environment FOEN, Bern, Switzerland.

Summary

Low-noise road surfaces have become a popular and widely used measure in Switzerland to combat road traffic noise at its source. In total, 371 low-noise road surfaces have been constructed in urban areas over the last decade on road sections where traffic noise exceeded the legal limits. As with all conventional road surfaces, low-noise road surfaces become louder and lose some of their initial noise reduction properties over time. Research has shown that the loss of acoustic performance over time can vary substantially on different road sections. The explanations for this, however, remain unclear. Therefore, an extensive dataset of 778 CPX (close proximity) measurements was analysed and correlated with 14 environmental and traffic related variables obtained from spatial analysis to assess their influence on acoustic ageing behaviour of low noise road surfaces. Multivariate statistical analysis revealed that (1) frost has the strongest negative impact on acoustic durability of a low-noise road surface, increasing the risk of strong acoustic ageing (risk of a road surface to lose faster its initial noise reduction properties) importantly. (2) Traffic load also affects acoustic durability adversely, leading to a moderate increase of the risk for strong acoustic ageing. (3) Interestingly, the results suggest that ingress of dirt from agricultural activity does not have a negative impact on acoustic durability of the assessed low-noise road surfaces.

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1. Introduction

Low-noise road surfaces have become a popular and widely used measure in Switzerland to combat road traffic noise at its source. When applied in inner-city environments at low traffic speeds, low-noise road surfaces often have been prone to clogging, which may occur because of depositions of dirt and dust from the road surroundings, or from the wear products from tyres and the pavement itself [1]. To prevent water and dirt from entering the pores and clogging the surface, new types of semi-dense road surfaces and road surfaces with small granulate sizes and very fine pores have been developed. Overall, more than 350 of such low-noise road surfaces consisting of three different types have been constructed in Switzerland over the last decade on road sections where traffic noise exceeded the legal limits.

To determine their long-term performance in terms of noise reduction, most of these surfaces have been subjected to repeated tyre/road noise measurements. Such measurements have shown that the loss of acoustic performance over time can vary substantially on different road sections (see also the companion paper analysing the long-term acoustical performance of low noise road surfaces [2]). Similar variations were also found in the scope of a recent European project, which did not draw clear and consistent conclusions on the reasons behind it [3].

This article aims to fill this gap by shedding light on the reasons for the varying acoustic ageing behaviour of low-noise road surfaces. We, therefore, related the acoustical property changes of 371 low-noise road surfaces to several

environment and traffic related variables obtained from spatial analysis.
The objectives of this study are, firstly, to identify environment and traffic related factors that negatively influence long-term acoustic performance of low-noise road surfaces. Secondly, to quantify the elevated risk for strong acoustic ageing related to such factors. Finally, to determine non-critical factors and non-critical factor ranges regarding the long-term acoustical performance of such surfaces.

2. Materials & Methods

2.1. Road Surfaces

The sample of road surfaces consists of 371 road surfaces and only includes road surfaces which have been measured and evaluated by the environmental engineering company Grolimund + Partner AG - environmental engineering, Switzerland. The sample contains new generation semi-dense and thinlayer road surfaces constructed in urban areas in Switzerland. It consists of various products constructed by different road construction companies. The road surfaces can be divided into three main road surface types: (1) those with a maximum aggregate size of 4 mm and a medium to high void content of 12-22%, (2) those with a maximum aggregate size of 8 mm and a medium void content of 10-16%, and (3) those with a maximum aggregate size of 8 mm and a low void content of 6-10%. Table I lists the road surface types assessed in this study together with their range in void content and their product names. The map in Figure 1 gives an overview of the road surfaces' spatial distribution (see next page).

Table I. Assessed road surface (RS) types.

RS Type	*Void in top layer*	*Product names*	*No.of RS (no. of measurements)*
4 mm	12-22%	Nanosoft, Sapaphone, Famsiphonogrip, SDA 4 B/C	196 (379 meas.)
8 mm	10-16%	ACMR 8 HR, SDA 8 B/C	48 (129 meas.)
8 mm low void	6-10%	ACMR 8, SDA 8 A	127 (270 meas.)

2.2. Determining acoustic ageing

As with conventional road surfaces, low-noise road surfaces become louder over time (see [4]). We call this phenomenon *acoustic ageing*: it is expressed in dB and determined by comparing a road surface's acoustic state with its initial noise reduction properties (a measurement was typically made roughly three months after construction).To quantify acoustic ageing, we analyse a database comprising 778 tyre/road noise measurements carried out between 2008 and 2014 on 371 different road surfaces. All measurements are performed using the CPX measurement method as specified in [5], with sets of reference tyres which correspond to passenger cars (Standard Reference Test Tyre SRTT of dimensions 225/60R16) mounted in a closed two-wheeled trailer owned and operated by Grolimund + Partner AG. Variation of speed (reference speed 50 km/h) was kept to a minimum using automatic speed control. On all road surfaces tyre/road noise levels were obtained by averaging a minimum of four measurement runs.
The high standardisation of the CPX measurement method and the elaborated correction schemes for ambient temperature influences (see [6]) allow for direct comparison of measurements carried out in different years.

2.3. Looking for causes of ageing

To take into account possible stresses which may have been responsible for a road surface's acoustic ageing behaviour, we derived sets of environment and traffic related variables for each specific road section from national datasets using spatial analysis. This includes the following variables:

- climatic stress: average number of days with ground frost in the period between 2003 and 2013;
- ingress of dirt from agriculture: presence of farmland adjacent to the road section, agricultural activity within a certain distance of the road section, employment in the 1st sector;
- mechanical stress due to ordinary traffic: daily traffic load, percentage of heavy vehicles, number of heavy vehicles per day;
- mechanical stress due to snow chains: mean altitude (meter asl) of nearby population, mean altitude of nearby population multiplied by the daily traffic load, population above an altitude of 800 m asl;
- other factors: population density, altitude, slope, maximum allowed speed.

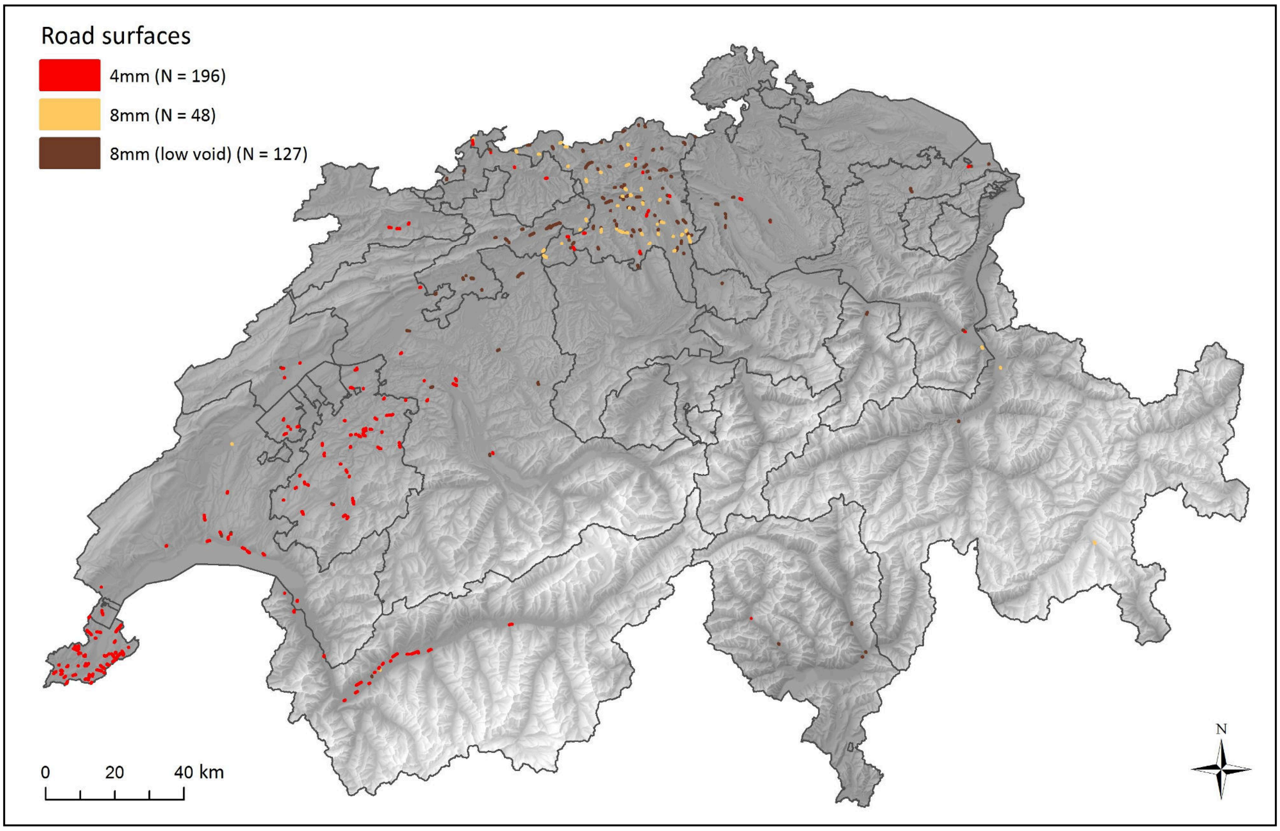

Figure 1. Location of road surfaces.

Some of these variables may be directly linked to causes of ageing (e.g. traffic load) while some other variables may not in themselves be directly relevant, but serve in place of a variable of interest as proxy variables (e.g. mean altitude of nearby population as a proxy for the likelihood of the use of snow chains on the road section). For the variables obtained by buffer searches in the vicinity of a road surface (e.g. presence of farmland, mean altitude of nearby population etc.), the buffer distance was varied as follows: 500 m, 1000 m, 2000 m and 5000 m. The variables with the most suitable buffer search radius were selected for analysis.

2.4. Reducing complexity for analysis

After discarding the variables with less suitable buffer distances, altogether 14 environment and traffic related variables were selected to be included in the statistical analysis (see below). In order to reduce the complexity of the analysis, principal component analysis (PCA) was used as a data reduction technique with standardised variables. It can be assumed that some of the studied variables are highly correlated and, are therefore describing the same type of stress on the road surface. With PCA, the variables of the original dataset are transformed and grouped to a new set of uncorrelated principal components. These new variables (components) are linear combinations of the original variables and are derived in decreasing order of importance, so that the first principal components account for the greatest part of the variance in the original multidimensional dataset [7].

2.5. Determining the main influences on acoustic ageing

Multivariate linear regression analysis was used to assess the reasons behind the acoustic ageing behaviour of low-noise road surfaces. The dependent variables considered in the analysis represent the change in overall tyre/road noise levels obtained for the different road surface states i.e. for the different surface age (number of years a road surface was exposed to different stresses). To obtain information about the main influences on acoustic ageing, the principal components (see section 3.1) were entered into the models as normalised independent variables, each one representing a group of influencing variables.
The approach allows us to assess the causes of acoustic ageing by comparing the standardised partial coefficients in the multivariate ageing models. This is repeated for each road surface type and age. Focus is made on comparing the partial coefficients obtained for the different models.

2.6. Assessing the risk of strong acoustic ageing

To estimate the elevated risk of strong acoustic ageing (i.e. risk of a road surface to lose its initial noise reduction properties faster than 2/3 of its type) which may occur with the use of a road surface type in certain environments, it was calculated how different environment and traffic related variables may alter this risk. For each surface type and age therefore, the sample was divided into three equally sized categories of weak, medium and strong acoustic ageing. According to this definition, the risk for a road surface to show strong acoustic ageing is exactly 1/3. For some, easy to measure, variables the risk offset is estimated for the road surface to exhibit strong acoustic ageing. This information may help road owners taking a decision about using a particular road surface type in a certain environment, taking into account possible additional risk for strong acoustic ageing.

3. Results & Discussion

3.1. The influencing variables' principal components

The first five principal components were obtained accounting together for 75% of the total variance of all influencing variables. These five principal components are shown together with their main contributing variables and their partial correlation coefficients in Table II. Principal component analysis also produced 9 more components. These components, however, showed low eigenvalues of equal or less than 1. They only contributed little to the total variance and, therefore, were not considered for statistical analysis.

The following groups of influences (principal components) were obtained (the same colour codes are used throughout the paper):

- influence of altitude/frost (blue): represented by component 1, accounting for 24% of the total variance;
- influence of traffic load (red): comprising components 2 (total traffic load) and 3 (heavy vehicles), accounting together for 32% of the total variance;
- influence of agricultural activity (yellow): including components 4 (presence of adjacent farmland) and 5 (high agricultural activity), accounting together for 19% of the total variance.

3.2. Main influences on acoustic ageing

Multivariate statistical analysis was performed to determine the main reasons behind the acoustic ageing behaviour of the assessed low-noise road surface types. The partial correlation coefficients obtained for the five principal components *altitude & frost, traffic load, heavy vehicles, farmland adjacent* and *high agricultural activity* are displayed in Table III (see next page).

From the results presented in Table III a set of hypotheses were formulated describing the causes of acoustical ageing. The qualitative estimation of the probability of a hypothesis to be true (!! = highly probable, ! = probable, ? = unclear) is given together with a list of supporting evidence.

Table II. Principal components with their main contributing variables (colour codes: blue = altitude & frost related; red: = traffic load related; yellow = agricultural activity related).

Component	Variables[b]	Details	Range (mean)	Comp.corr.[a]
1 (blue)		*Altitude & frost (explaining 24% of total variance)*		
	population height	av. altitude of population within 5 km of road [m asl]	248 to 1774 (443)	0.94
	altitude	av. altitude of road section [m asl]	234 to 1808 (436)	0.88
	frost	no. of days p. year with ground frost 2000-2013	64 to 223 (86)	0.87
2 (red)		*Traffic load (explaining 18% of total variance)*		
	traffic ˙ pop. height	traffic load multiplied by population height	0.01E+6 to 27.1E+6 (3.3E+6)	0.92
	traffic load	av. no. of vehicles per day on road section	381 to 22961 (6624)	0.89
3 (red)		*Heavy vehicles (explaining 14% of total variance)*		
	traffic load heavy veh.	av. no. of heavy vehicles per day on road section	2 to 2321 (505)	0.98
	heavy vehicles	percentage of heavy vehicles on road section	0.1 to 17.5 (5.4)	0.97
4 (yellow)		*Farmland adjacent (explaining 10% of total variance)*		
	farmland adjacent	presence of farmland adjacent to road section [no. of fields]	0 to 25 (2.3)	0.76
	speed	maximum allowed speed on road section [km/h]	30 to 100 (57.2)	0.69
5 (yellow)		*Acricultural activity in area (explaining 9% of total variance)*		
	agricultural activity	presence of farmland within 5 km of road [no. of fields]	3 to 4867 (1852.3)	0.70

[a] Linear correlation coefficient with component

[b] Variables *population above altitude of 800m*, *employment in the 1st sector*, *slope* and *population density* were dropped as they did not singnificantly contribute to any of the five principal components

Table III. Causes of acoustic ageing: partial coefficients of principal components from multivariate analysis. Coefficients in bold represent significant relationships with p<0.05, also non-significant relationships are displayed for relative interpretation

surface age [years]	4mm road surfaces – components & component groups: altitude/frost 1	traffic load 2	agriculture 3	agriculture 4	agriculture 5	*n*
1	**0.48**	0.20	≤ 0	≤ 0	≤ 0	*60*
2	**0.38**	0.11	0.03	≤ 0	≤ 0	*54*
3	0.23	0.11	≤ 0	≤ 0	≤ 0	*50*
4	0.16	0.05	≤ 0	≤ 0	≤ 0	*29*
5	0.26	0.08	≤ 0	0.05	≤ 0	*13*
6						*4*
7						*0*

surface age [years]	8mm road surfaces – components & component groups: altitude/frost 1	traffic load 2	agriculture 3	agriculture 4	agriculture 5	*n*
1	0.25	**0.45**	≤ 0	≤ 0	≤ 0	*36*
2	≤ 0	0.36	≤ 0	≤ 0	0.09	*24*
3	≤ 0	0.58	≤ 0	≤ 0	0.53	*11*
4						*2*
5						*1*
6						*1*
7						*0*

surface age [years]	8mm road surfaces (low void) – components & component groups: altitude/frost 1	traffic load 2	agriculture 3	agriculture 4	agriculture 5	*n*
1	0.26	≤ 0	≤ 0	**0.35**	≤ 0	*41*
2	0.11	0.08	≤ 0	0.11	0.07	*39*
3	≤ 0	0.42	≤ 0	≤ 0	0.31	*17*
4	≤ 0	0.05	≤ 0	0.20	≤ 0	*21*
5	0.46	**0.57**	≤ 0	0.35	≤ 0	*18*
6	0.22	**0.65**	≤ 0	0.08	≤ 0	*17*
7	≤ 0	**0.65**	0.39	≤ 0	≤ 0	*16*

Colour codes: strong influence of… (the stronger the influence, the darker the colour)
altitude/frost — traffic load — agricultural activity

Acoustic ageing of 4mm road surfaces:

!! Primarily influenced by the component altitude/frost (highly probable: significant and strong relationships, consistent picture).

! Secondary influence can be attributed to component traffic load. Overall traffic load seems to be more important than the number of heavy vehicles (probable: consistent picture).

!! No negative influence due to agricultural activities and the presence of farmland adjacent to the road section (highly probable: significant relationship, consistent picture).

! With time, other factors than the assessed principal components seem to be of increasing importance (probable: more or less consistent picture of decreasing strength of assessed relationships with increasing surface age).

Acoustic ageing of 8mm road surfaces:

!! Primary influence comes from component traffic load. Again, the presence of heavy vehicles seems not to be an aggravating factor (highly probable: significant relationships, consistent picture).

? Both components altitude/frost and agricultural activity seem to be less important (unclear: generally low coefficients, but with a few exceptions).

Acoustic ageing of 8mm road surfaces with low void content:

!! Primary influence comes from component traffic load. Again, little of this influence seems to be attributed to the presence of heavy vehicles (highly probable: significant relationships, more or less consistent picture).

! Of secondary importance seems to be component altitude/frost (probable: several cases of medium to strong influence).

! Less clear was the component agricultural activity, which seems to be of increasing importance (probable: significant relationship, more or less consistent picture).

3.2. Risk of strong acoustic ageing

To help road owners make a decision about whether a low-noise road surface should be applied in a specific environmental or traffic condition, we estimated the risk for a road surface to show strong acoustic ageing for a range of easy to measure variables. The resulting estimate of elevated risk is given in Table IV (see next page). For example Table IV shows that if a 4 mm low-noise road surface is applied on a busy road section with more than 10,000 vehicles passing per day, the additional risk for it to show strong acoustic ageing is 18%. A cumulative risk may be calculated when more than one variable are considered (except for the variables altitude and frost which are interrelated).

4. Conclusions

This first study investigated the influence of environmental and traffic related factors on acoustic ageing behaviour of low noise road surfaces by carrying out multivariate statistical analyses on extensive datasets. It revealed the following: (1) Frost has probably the largest impact on acoustic ageing of a low-noise road surface, increasing the risk of strong acoustic ageing by up to 50%. (2) Traffic load also affects acoustic ageing adversely, leading to an elevated risk for strong acoustic ageing of between 10 to

Table IV. Elevated risk for strong acoustic ageing (risk of a road surface to lose its initial noise reduction properties faster than 2/3 of its type).

influence (variable) ***[unit]***	***elevated risk for strong acoustic ageing per road surface type*** *4mm*	*8mm*	*8mm low void*
altitude [meter asl]	≤400: 0%; >400: +1%; >500: +23%; >600: +32%	≤400: 0%; >400: 0%; >500: 0%; >600: 0%	≤400: 0%; >400: 0%; >500: 0%; >600: 0%
frost [days/y with ground frost]	≤80: 0%; >80: +24%; >90: +34%; >100: +48%	≤80: 0%; >80: +4%; >90: +38%; >100: n.a.	≤80: 0%; >80: +0%; >90: +9%; >100: +50%
traffic load [vehicles/day]	≤5000: 0%; >5000: +13%; >7500: +13%; >10000: +18%	≤5000: 0%; >5000: +17%; >7500: +22%; >10000: +27%	5000: 0%; >5000: +8%; >7500: +5%; >10000: +10%
farmland [no. of adjacent fields]	0: 0%; >0: 0%; >5: 0%; >10: +2%	0: 0%; >0: 0%; >5: 0%; >10: 0%	0: 0%; >0: +7%; >5: +27%; >10: +34%
not or less critical	- agricultural activity	- altitude - agricultural activity	- altitude - traffic load

30%. In the case of 4 mm road surfaces, the risk increase is acceptably low even when traffic load is doubled. (3) The results suggest that ingress of dirt from agricultural activity had no negative impact on acoustic durability of a low-noise road surface (true for types 4mm and 8mm) i.e. agricultural dirt does not increase the speed of clogging of such surfaces. This finding is of particular interest, since a major focus was made on the impermeability of water (and hence dirt) when designing low-noise road surfaces for low-speed roads. The pores of such low-noise road surfaces, though, may still be clogged by the wear products from tyres and the pavement itself. Moreover, the results suggested that with time, other factors than the assessed factors seem to be of increasing importance with respect to acoustic ageing: A possible factor may be differences in a road surface's specific chemical and mechanical resistance. This may be a result from the interaction of the components used in the mixture or due to properties of the top layer (e.g. void content) which originate from construction. It should be noted, however, that the here presented numbers may shift as more data is added. Future work is planned to apply refined statistical approaches. Also, the analysis will be extended to cost/benefit threshholds.

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