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ACOUSTIC SIMULATION OF NOISE BARRIERS AND PREDICTION OF ANNOYANCE FOR LOCAL RESIDENTS

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Road traffic is the most widespread environmental noise source in Europe, proven to affect human health and well-being adversely. Noise barriers can be a very effective way to objectively reduce the noise levels to which the population is exposed, leading to positive effects on noise perception and quality of life. In this paper, surveys were used to assess subjective noise level indicators (annoyance and quality of life) from residents of the vicinity of a highway where obsolete noise barriers were to be replaced. %HA before the barrier replacement was measured from the surveys (26.8%) and estimated based on the acoustic simulation and two existing exposure/response relationships (14.6 and 18.8% before and 13.6 and 8.3% after). The difference in the measured %HA to those calculated from the ERRs shows that those models might not estimate %HA fairly for small samples or particular situations where high L_{den} is reported. Noise annoyance correlated differently with the quality of life indicators: a weak link was observed with health problems, while a strong correlation was found with the comfort level to perform activities outdoors. Objective noise measurements gave $L_{A,eq,(15\ min.)}$ reductions of 4.1dB(A) due to the new barrier, while in acoustics models, calculated as L_{day}, expected this reduction to be 5.2 dB(A). After replacing the noise barriers, a second survey could still not be distributed due to the unknown effect of the COVID-19 measures that are still active.

Keywords: Noise intervention, social survey, acoustic simulation, health effects, quality of life

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1. Introduction

According to the World Health Organization (WHO), in 2011, 50% of the population living in large urban areas in Europe were exposed to A-weighted day-evening-night equivalent sound pressure level (L_{den}) caused by road traffic noise exceeding 55 dB. In 2018, a new environmental noise guideline endorsed by the WHO strongly recommended public policies to limit L_{den} of road traffic noise to 53dB [1].

The long-term exposure to high environmental noise levels triggers physiological responses that, over time, can adversely impact the sympathetic nervous and endocrine systems of affected populations. "Noise annoyance" is an indicator that captures the susceptibility of individuals' internal state to these somewhat unconscious behavioural responses caused by noise exposure. Therefore, the subjective indicator noise annoyance, rather than actual noise levels, best correlates with the decrease in quality of life and the build-up of health disorders [2,3].

Understanding the causal relations between objective noise, perceived noise, and potential adverse health effects is essential for creating action plans for noise exposure mitigation [3]. Many studies have previously attempted to establish links between objective noise levels and subjective annoyance in so-called exposure-response relationships (ERR) or functions (ERF), as [2].

Noise mitigation can be performed at the source by, for example, introducing stricter speed limits or using noise-reducing road surfaces. These methods are proven to be the most effective solution for road traffic noise mitigation, although not often feasible to implement due to economic or political reasons. Noise barriers are a path-to-receiver solution that has been widely implemented for decades; they work by creating an acoustic shadow zone for the receiver behind it. Noise interventions such as noise barriers lead to lower noise levels which, in turn, results in reductions in noise annoyance [4].

This work aims to support the policy on dealing with the annoyance caused by traffic noise in an area where an obsolete noise barrier was replaced with a new one. Objective noise levels were obtained via acoustic measurements and simulations. The subjective impact of noise exposure was measured using written surveys before installing the noise barrier, and the percentage of highly annoyed residents (%HA) was determined. The %HA after the installation was calculated via existing ERRs, and based on the acoustic simulation. Those results were compared to a group of control streets, considered quiet, where no noise intervention was applied.

2. Methodology

Figure 1 shows the processes and respective data collected from each step and case study in this work, as further described in the following subsections.

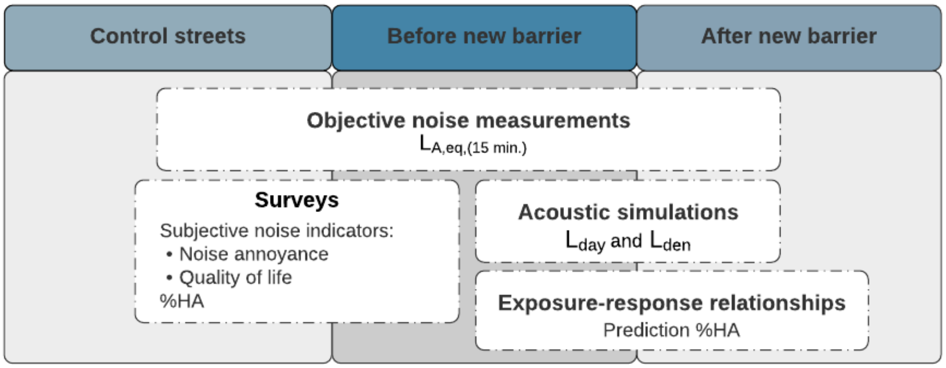

Figure 1: Flowchart of the data collection process and respective outcomes.

2.1 Sites

The sites investigated are located across the municipality of Antwerp, Belgium, and were divided into two groups, as described below.

2.1.1 Borgerhout (noise barrier site)

The "Garden District (Tuinwijk)", in the district of Borgerhout, consists of two streets in the vicinity of the E313 highway. The road surfacing of the A13/E313 at the measurement location was 2x5 lanes in SMA-C with a double New Jersey in the central reservation. The maximum allowed speed is 100 km/h.

A lightweight concrete noise barrier (max. height 3 m) was built in 1985-1986 to mitigate the road traffic noise emanating from the highway. The Flemish Road Agency (*Agentschap Wegen en Verkeer* – AWV) designed this barrier taking into account the allowed exposure to environmental noise levels at that time and traffic intensity of 4000-4500 vehicles/day. After regular complaints of inhabitants from Tuinwijk, acoustical measurements performed in August 2013 by AWV indicated that the current barrier was obsolete as the volume of traffic doubled during the 27-year time window and the allowed environmental regulation for noise exposure became stricter.

In the summer of 2020, the old noise barrier (2.5 – 3m high) along the E313 close to Tuinwijk was replaced by a 6m high aluminium noise barrier. As there was yet no legal standards for road traffic noise in Flandres, Belgium, the design of the new noise barrier by AWV aimed to decrease the A-weighted long-term average sound level over day-time (L_{day}) to less than 65 dB(A) for all residences exposed to road traffic noise from the E313 in that area and at least a few points with noise levels below 60 dB(A).

2.1.2 Control streets

A control group was defined as a single group comprising five streets located in different districts of Antwerp, relatively quiet compared to the noise barrier site, where no noise intervention existed. The selection of these streets was conducted based on local traffic with a speed restriction of 50 km/h, asphalt as pavement surface, similar type of buildings, proximity to motorways, industry, airports, railways, etc.

2.2 Objective acoustic measurements and noise simulation maps

AWV conducted objective acoustic point measurements in August 2013 and after installing the noise barrier in October 2020. A class I sound level meter class was used to register the A-weighted 15 minute equivalent noise level in dBA ($L_{A,eq(15\ min)}$) for ten measurement points at different heights and distances from the noise barriers. Additionally, traffic intensity per hour during the measurements was counted in both directions on the E313. In this count, vehicles are categorized into light and heavy vehicles.

The traffic count was also necessary as input to perform noise modelling in the software IMMI. Simulations in IMMI aid in estimating the new noise barrier effect on the sound pressure levels as point measurements that provide L_{day} and L_{den} as output. L_{den} is generally reported by authorities and is widely used for exposure assessment in health effect studies. The simulations used the calculation scheme from SRM-II (Standard Calculation Method – 2). The traffic volume counted by AWV in 2013 was used to determine the L_{day} before and after the new barrier installation and compare it to the objective measurements. Simulations were also performed to achieve L_{den}, but with the traffic volume obtained from the open database of the Flemish Government in June 2020, when the surveys were distributed.

2.3 Self-administrated surveys

Self-administrated surveys were used to evaluate the respondents' socio-demographics and quantify subjective noise-exposure indicators: directly, noise annoyance, and indirectly, quality of life.

2.3.1 Description

The paper version survey (6 pages recto-verso) with a pre-paid return envelope and a link/QR-code to the online survey were placed in the residents' mailbox. The written standardized questionnaire contained 26 questions, of which the first ten were related to the socio-demographics (Table 1). The Ethics Committee for the Social Sciences and Humanities from the University of Antwerp approved the methodology and survey used in this study and all respondents remained anonymous. For Borgerhout, the survey was distributed to 164 residences in June 2020, before replacing the existing noise barrier. 56 responses were received in total, reaching a response rate of 34.1%. The surveys in the control streets were distributed in June 2016 for 695 residences; 25.0% of these were filled in (174 responses).

Table 1: Socio-demographic data of respondents

Site	Declared gender		Age in years (%)			Education level*		
	Female	Male	18 to <40	40-60	>60	Low	Middle	High
Control streets	50.6	44.3	33.9	41.6	8.7	11.1	25.7	57.3
Borgerhout	70.9	28.6	20.4	42.6	37.0	19.6	35.7	42.9

*Low: no schooling completed, primary school and general/technical/vocational lower secondary school; middle: general/technical/vocational upper secondary school and bachelor's degree - one cycle of 3 academic years; high: master's degree at a university college - two cycles: 4 or 5 academic years - or university.

The remaining questions were formulated based mainly on the SLO (Schriftelijk Leefomgeving-sOnderzoek - Written Living Environment Study) [5], including questions related to other sources of annoyance besides noise (light, smell) and supplemented with additional in-depth questions. The following direct subjective noise indicators were identified from the survey (answers scale in brackets):

1. Annoyance: the extent of the noise annoyance in and around the house over the last twelve months (1. Not at all, 2. Slightly, 3. Moderately, 4. Very or 5. Extremely);
2. Road traffic noise annoyance (RTA): the extent to which road traffic noise causes annoyance (1. Not annoyed at all, 2. Slightly annoyed, 3. Moderately annoyed, 4. Severely annoyed, 5. Extremely annoyed).

Quality of life is an indirect subjective noise indicator that was assessed via questions equally divided into three domains:

- Domain 1: questions on how often they suffered from six different physical complaints related to health problems. Response categories were: 1. Never, 2. A few times per year, 3. A few times per month, 4. A few times per week and 5. Daily;
- Domain 2: questions assessing sleep quality;
- Domain 3: question on the comfort level to perform certain indoors and outdoors activities. Response categories were: 1. Easy, 2. Rather easy, 3. Rather difficult, 4. Difficult.

Two surveys, one prior and one after the new noise barrier installation, would have been ideal for investigating the noise barrier effect on residents' perceived noise annoyance and quality of life. However, due to the COVID-19 pandemic and consequent measures to restrain circulation implemented in Flandres from October 2020 until the current date, the post-intervention survey results could have been biased. Firstly, mandatory teleworking tends to increase the residents' time at home during the day, possibly changing their perception of noise and quality of life compared to regular times. Additionally, lower traffic volume was reported since March 2020. Figure 2 shows the daily average traffic volume per month in E313 (road segment: Antwerp-East to Wommelgem towards Liège) between February 2019-2020 and 2020-2021 (retrieved from the open database of the Flemish Government[1]). The impacts of the two lockdowns on traffic volume are distinguishable (March to May 2020 and October – current date). Between lockdowns, the traffic volume increased to an amount closer to the reference in 2019, but differences of more than 5000 vehicles/day were still observed.

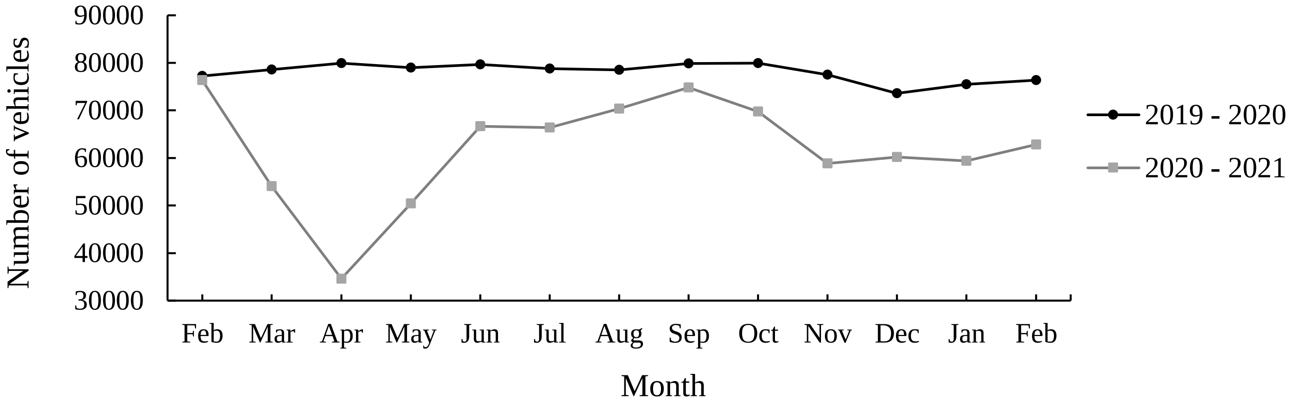

Figure 2: Average traffic volume per month on E313 during February 2019-2021.

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[1] http://indicatoren.verkeerscentrum.be/

2.3.2 Survey data analysis

The arithmetic average and variability of annoyance and quality of life indicators were calculated once the verbal scale used in the questions was translated into an ordinal measurement scale. Firstly, the statistical differences in the average of Annoyance and RTA between the two independent groups (Borgerhout and control streets) were checked by t-tests.

Secondly, a link was created between noise annoyance and the quality of life indicators in the three domains previously described. Kendall's τ_b correlation was performed to check the existence and strength of those associations. The τ_b correlation coefficient is a non-parametric measure of strength and direction of associations between two ordinal variables with an assumed monotonic relationship. Correlation coefficients range from -1 to +1. A value of ± 1 indicates a perfect degree of association between the two variables, while values close to 0 determine weak relationships.

2.4 %HA and exposure-response relationships

Previous studies have established exposure-response relationships by utilizing large datasets resulting from different studies, with different demographics, from different countries, both in cities and small towns. Among those, the ERRs defined by Guski et al. [2] (Eqs. 2 and 3) are commonly used. The ERRs from [2] are based on the same dataset, but Eq. 3 excludes studies conducted in the Alpes and Asia.

%HA can be calculated by the ERRs or retrieved from the surveys, corresponding to answers at a high position on the annoyance response scale. [2] considers the cut-off point between "highly annoyed" and "not highly annoyed" at 75% on a 0–100 scale. To measure %HA in this work from the verbal 5-point response scale, we considered both cases where the cut-off point is at 60% and 80% of the response scale.

$$\text{Estimated \%HA} = 78.9270 - 3.1162 \times L_{den} + 0.0342 \times L_{den}^2 \tag{1}$$

$$\text{Estimated \%HA} = 116.4304 - 4.7342 \times L_{den} + 0.0497 \times L_{den}^2 \tag{2}$$

3. Results

3.1 Objective acoustic measurements and simulations

$L_{A,eq,(15\ min.)}$ data obtained from the pre and post-objective noise measurements and the L_{day} calculated from the acoustic simulation in IMMI are depicted in Figure 3, as boxplots. The control streets presented an average $L_{A,eq,(15\ min.)}$ of 58.7 ± 6.1 dB. The grouping of several different streets, with different traffic intensity during the measurements has caused this significant standard deviation.

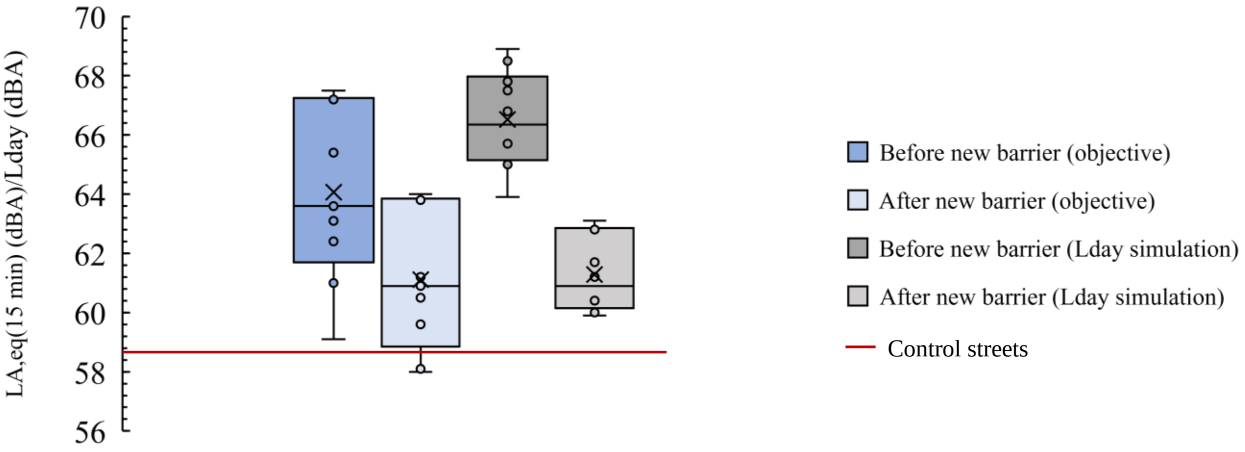

Figure 3: Results of objective acoustic measurements and IMMI point simulations.

The average of the different measurement points taken in August 2013 in Borgerhout resulted in an $L_{A,eq,(15\ min.)}$ of 64.3 ± 2.8 dB(A). The 65.0 dB(A) threshold was only exceeded at five out of 10 measurement locations. For one measurement point, the noise level was already below the 60.0 dB(A) threshold. For the new noise barriers, the average noise level dropped by 4.1 dB(A). The inhabitants are now exposed to an $L_{A,eq,(15\ min.)}$ 60.2 dB(A) ± 2.7 dB(A), which is 1.5 dB(A) higher than in the control streets. No measuring point has a value above 65.0 dB(A), but only two points are below 60 dB(A).

The average L_{day} for before and after the barrier replacement are, respectively, 2.2 and 1.1 dB(A) higher than the average $L_{A,eq,(15\ min.)}$. Also, the drop between the two conditions was expected to be 5.2 dB(A). Possibly, the SRM II method underestimates the noise-reducing effect of the old noise barrier.

For the IMMI models, L_{den} before the noise barrier replacement is 62.4 dB(A) ± 3.0 dB(A), while after replacing the noise barriers, this value is expected to drop on average by 5.2 dB(A), reaching a L_{den} of 57.2 dB(A) ± 2.1 dB(A). The L_{den} below 53 decibels could not be achieved for any simulated point.

3.2 Surveys

Table 2 provides a summary of sample size, central tendency, and variability measures for the subjective noise indicators retrieved from the ordinal scale adapted to the surveys' answers.

Table 2: Descriptive statistics and t-test results for the annoyance indicators in both test sites

Variable	Site	Responses	Mean	Standard deviation	95% Confidence interval		p-value
					Lower Bound	Upper Bound	
Annoyance	Control streets	170	2.23	0.99	2.08	2.38	<0.000
	Borgerhout	56	3.66	1.19	3.34	3.98	
RTA	Control streets	161	2.29	1.08	2.12	2.45	<0.000
	Borgerhout	56	3.77	1.29	3.42	4.11	

The average noise annoyance level observed for the control streets is considered 'sightly annoying', while in Borgerhout's site, this parameter is, on average, 'very annoying'. The same categories of annoyance are reported for both sites concerning road traffic as the noise source. The similar values found between the two annoyance indicators possibly indicate that either the respondents did not differ the noise sources causing annoyance or road traffic noise is clearly identified as the main source of annoyance in general, which can be confirmed by the long history of road traffic noise related complaints.

As normality and equal variance (by Levene's test) were confirmed across the variables, independent t-tests were carried out, with a 5% significance level. The last column of Table 2 shows the p-values obtained from these tests. As $p < 0.000$, there is strong evidence that, compared to residents from the control streets, respondents from Borgerhout are significantly more annoyed both by noise in general and road traffic noise specifically. Therefore, the higher noise annoyance levels justify the implementation of a noise intervention. It is important to remark the susceptibility of this subjective noise indicator to changes in objective noise levels for different sites, namely 5.6 dB(A) difference in average $L_{A,eq,(15\ min.)}$ between Borgerhout and the control streets.

Table 4 presents Kendall's τ_b correlation coefficient between the subjective parameters and quality of life indicators.

Table 4: Kendall's correlation coefficient (τ_b) between subjective parameters and quality of life indicators

Domain	Indicator		Site			
			Control streets		Borgerhout	
			Annoyance	RTA	Annoyance	RTA
Health problems (1)	Headaches		0.11	0.04	0.07	0.24*
	Fatigue		0.14*	0.16*	0.40**	0.37**
	Dizziness		0.18	0.17*	0.08	0.12
	Insomnia		0.20**	0.12	0.26*	0.23*
	Heart palpitations		0.06	0.12	0.11	0.24*
	Gastrointestinal complaints		0.10	0.15*	0.06	0.16
Sleep quality (2)	Sleep duration (night)		0.02	-0.08	0.08	0.09
	Sleep duration (day)		-0.11	-0.05	0.13	0.12
	Time to fall asleep		0.12	0.08	0.13	0.08
	Early awakenings		0.12	0.16*	0.05	-0.02
	Difficulty waking up		0.01	0.07	0.05	0.07
	Feeling well-rested		-0.14**	-0.10	-0.10	-0.07
Comfort level for activities indoors and outdoors (3)	Concentration during reading	In	0.14*	0.17*	0.27*	0.26*
		Out	0.31**	0.19**	0.47**	0.42**
	Concentration during working or studying	In	0.16*	0.08	0.24	0.28*
		Out	0.38**	0.19*	0.39**	0.39**
	Concentration watching TV	In	0.08	0.08	0.14	0.17
	Speech intelligibility during a conversation	In	0.07	0.04	0.26*	0.22
		Out	0.26**	0.20**	0.54**	0.46**
	Speech intelligibility on the telephone	In	0.06	0.02	0.24	0.21
		Out	0.21**	0.16*	0.42**	0.41**
	Relaxing or unwinding	In	0.19**	0.11	0.30**	0.34**
		Out	0.33**	0.22**	0.50**	0.48**

*Correlation is significant at the 0.05 level (2-tailed)

**Correlation is significant at the 0.01 level (2-tailed)

Among the health problems comprising Domain 1, the self-reported fatigue and insomnia presented the most significant correlations with the annoyance indicators for both sites. τ_b positive values prove that increases in perceived annoyance follow increments in the reported physical complaints. For Borgerhout, those correlations are even stronger, as expected, due to community dissatisfaction with the noise levels in that area.

Overall, self-reported sleep quality (Domain 2) did not present correlations with annoyance levels. Possibly significant decreases in L_{night} compared to L_{day} results in lower perceived noise during the regular sleeping time of residents. Fyhri and Klæboe's survey [3] measured sleep quality in their surveys by a single and general question. The correlation obtained between this parameter and annoyance by road traffic noise was fairly weak; the authors affirm that the general character of the assessment caused this result. The present study supports that, even though sleep quality is thoroughly evaluated in several questions, the correlation with annoyance indicators does not exist or is also relatively weak.

The respondents' report on difficulties experienced to perform some activities (Domain 3) shows that, without exception, outdoors activities are highly impacted by noise annoyance. For indoors activities, relevant links were found for concentration during reading, working or studying, and relaxing. Still, those are weaker compared to the correlations of annoyance with the respective outdoor activity. In all cases, correlations are also stronger for Borgerhout than the control streets.

Similar to the annoyance levels, the τ_b values found in the three domains are comparable for annoyance to general environmental noise and road traffic noise specifically.

3.3 Measured and calculated %HA

Table 5 presents the measured and calculated %HA using these ERRs and the simulated $L_{den.}$

Table 5: Measured and calculated %HA

Condition	Measured %HA		Calculated %HA	
	20%	40%	[2] full dataset	[2] limited dataset
Control streets	1.7	13.0	-	-
Old barrier Borgerhout	26.8	64.3	18.8	14.6
New barrier Borgerhout	-	-	13.6	8.3

Firstly, the measured %HA before the noise barrier replacement is considerably higher than %HA calculated from the equations established by Eqs. 1-2 [2]. This is in line with the limited sample size used in this research compared to those studies; the smaller the number of respondents, the more significant individual influences, e.g. time spent at home, noise sensitivity, and façade insulation, impact %HA. Additionally, the residents of Borgerhout had officially reported several complaints about the noise levels, which is expectedly translated into their answers.

Compared to the control condition streets, the %HA of residents before the noise barrier replacement reinforces the need for the replacement conducted in 2020. Also, the switch in the cut-off reveals that most respondents are, at least, highly annoyed by road traffic noise. Such figures correlate well with the fact that most inhabitants were exposed to L_{den} considerably above the recommendations from the WHO [1]. Even though the calculated %HA is low, the difference in values between the before and after condition leads to significant decreases in %HA, caused by the L_{den} drop of 5.2 dB(A). A comparison between the values calculated and the %HA from the post-survey to be conducted can give insights into L_{den} reductions effects in residents' perceived noise annoyance.

4. Conclusion

The noise barrier replacement in Borgerhout dropped $L_{A,eq,(15\ min.)}$ in 4.1 dB(A); this new situation differs from the control streets is 1.5dB(A). The estimation of this drop, in terms of $L_{day,}$ was expected to be 5.2 dB(A). Considering the complaints history from the exposed residents, translated as a high %HA reported in the pre-survey, and the high L_{den} experienced before the noise intervention, it is expected that this reduction in objective noise levels will improve the perception of noise in this area considerably.

Annoyance levels correlate differently with the quality of life indicators across the three domains. A weak link was observed with health problems, while a strong correlation is confirmed with the comfort level to perform activities outdoors. No link was obtained with spleep quality.

The difference in the measured %HA to those calculated from the ERRs shows that those models might not estimate %HA fairly for small samples or particular situations where high L_{den} is reported.

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