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Noise barriers as a road traffic noise intervention in an urban environment

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Abstract
Intending to tackle road traffic noise in urban environments, noise barriers have been proven to effectively reduce environmental noise levels, leading to positive effects on noise perception by the exposed population. This work assesses the impacts of replacing an obsolete noise barrier in a site near a highway. The effects of this change were monitored via a combination of field surveys, acoustic measurements and noise maps. The results have shown that even though the barrier replacement led to a 4.1 dB reduction in the $L_{A,eq,(15\ min.)}$, the annoyance levels of the respondents increased. Possibly, the expectations regarding the improvement of the noise barrier were not met, after a history of complaints. Additionally, existing exposure-response relationships were not successful in predicting the annoyance levels in this particular case. In this dataset, noise annoyance presented a weak link with reported health problems, while a strong correlation was found with the comfort level to perform activities outdoors. Questions regarding the COVID-19 pandemic showed that even though the respondents were spending more time at home, they were less annoyed due to road traffic noise in the period when circulation restrictions were in place.

Keywords: Noise intervention, social survey, acoustic simulation, health effects.

1 Introduction

Evidence has emerged in the last decades on the existence of links between long-term exposure to road traffic noise and non-auditory health outcomes such as cardiovascular diseases, cognitive dysfunction, sleep disorder, among others [1]. Responding to the increasing concern regarding the negative impacts entailed by road traffic noise exposure, the World Health Organization (WHO) updated in 2018 their environmental noise guidelines, strongly recommending public policies to limit road traffic noise levels to stricter values [2].

Instead of using actual noise levels, the effects of road traffic noise on exposed populations are also assessed by the "annoyance" indicator. Noise annoyance is considerably quicker perceived than the build-up of somatic disease, thus it could be considered an early warning signal for other more severe health risks and impairments in quality of life [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 [4]. In this manner, large scale studies have previously established links between objective noise levels and subjective annoyance via so-called exposure-response relationships (ERR) or functions (ERF), as [5]. On the other hand, the implementation of noise interventions is still focused mainly on reducing objective noise levels; the decrease of annoyance is mostly disregarded or calculated only through predefined dose-effect relations, as the qualitative nature of annoyance is more complex to assess [6].

Noise barriers are a path-to-receiver solution to high environmental noise levels that has become ubiquitous along many road corridors in Europe. The main function of noise barriers is to shield receivers from excessive noise resulting from road traffic. Noise interventions such as noise barriers lead to lower noise levels which, in turn, result in reductions in noise annoyance [7].

This study investigates the impacts of noise barriers to mitigate road traffic noise in an urban environment. The changes enabled by replacing an obsolete noise barrier are assessed via acoustical measurements, noise maps, and surveys, as the result of a collaboration between the University of Antwerp and the Flemish Road Agency (*Agentschap Wegen en Verkeer* – AWV). The policy on dealing with the annoyance and noise levels caused by road traffic with noise barriers is analysed via a two-fold research question: firstly, what is the objectively measured noise reduction obtained with the replacement, including its effect on L_{den} and L_{day}? Secondly, is this expected limited noise reduction sufficient to significantly reduce noise annoyance and influence self-reported health issues or sleep quality?

2 Methodology

The study cases, processes and respective data collected in each step of this work are introduced in Figure 1 and further described in the following subsections.

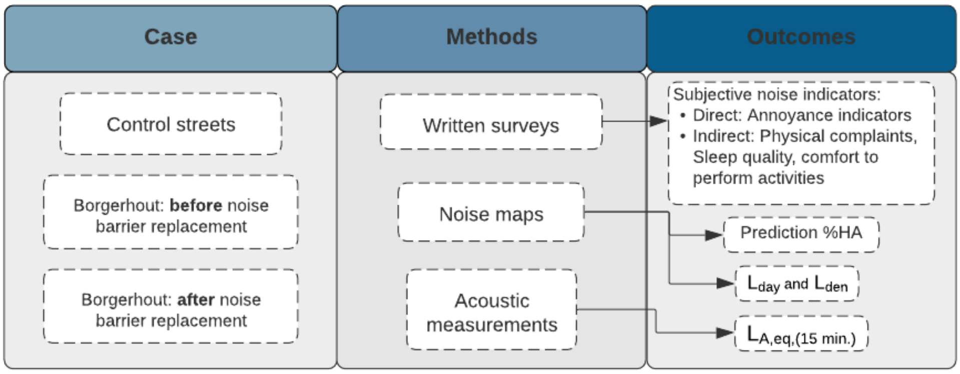

Figure 1 – Flowchart of the data collection process and respective outcomes.

2.1 Cases

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)

Two streets in the vicinity of the E313 highway, located in the district of Borgerhout (specifically, in the 'Garden District' – *Tuinwijk*), were the object of this study. The road surfacing at the stretch of the highway

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

beside the site has 2x5 lanes constructed in SMA-C, with a double New Jersey in the central reservation. The speed limit 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. This barrier was designed considering the allowed exposure to environmental noise levels at the construction time and traffic intensity of 4000-4500 vehicles/day. After regular complaints of inhabitants of Tuinwijk, acoustical measurements performed in August 2013 by AWV indicated that the noise barrier in place 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 noise barrier along the E313 section close to *Tuinwijk* was replaced by a 6m high aluminium noise barrier. The design of the new noise barrier aimed to decrease the A-weighted long-term average sound level over day-time (L_{day}) to less than 65 dB(A) for all the residences from the two streets, and at least a few points with noise levels below 60 dB(A).

2.1.2 Control streets

A single group comprising five streets located in different districts of Antwerp were selected for comparison purposes. No noise intervention existed in these streets and they were relatively quiet compared to the noise barrier site. 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 Acoustic measurements and noise maps

Objective acoustic point measurements were performed at two moments: 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 in the two streets. Additionally, the traffic intensity per hour during the measurements was counted in both directions on the E313 highway. In this count, vehicles were categorised into light and heavy vehicles.
The traffic count was also necessary as input to perform noise modelling. The noise maps were produced with the software IMMI, using the calculation scheme from SRM-II (Standard Calculation Method – 2) to obtain L_{day} and L_{den} as ten punctual values. The traffic volume counted in 2013 was used to determine the L_{day} before and after the new barrier installation and compare it to the objective measurements. L_{den} is generally reported by authorities and is widely used for exposure assessment in health effect studies. The simulations performed to obtain L_{den} used the traffic volume retrieved from the open database of the Flemish Government in June 2020, when the pre-surveys were distributed.

2.3 Field surveys

2.3.1 Questionnaire design

The paper version survey (6 pages recto-verso) with a pre-paid return envelope and a link/QR-code to the online version of the survey were placed in the residents' mailbox. 695 surveys were distributed in the control streets during June 2016; 25.0% of these were filled in (174 responses). For Borgerhout, two surveys campaigns took place, before and after the barrier replacement, in June 2020 and 2021, respectively. From the 164 potential respondents, 56 answers were received from the pre-survey; from the 161 post-surveys delivered, 58 were answered, leading to response rates of 34.1% and 36.0%, respectively.

The Ethics Committee for the Social Sciences and Humanities from the University of Antwerp approved the methodology and survey used in this study; all respondents remained anonymous. The questionnaire contained 27 questions, of which the first ten were related to socio-demographics. These questions were followed by five general questions taken from the SLO (Schriftelijk Leefomgevings Onderzoek – Survey on the Living Environment) [8] regarding the quality of life and annoyance. These annoyance-related questions assessed the overall annoyance level caused by different sources (noise, light, smell, and others) and noise annoyance caused by the different noise sources (air, rail and road traffic, priority vehicles, schools, etc). Additional in-depth questions assessed health problems, sleep quality, and the comfort level of specific activities (indoors and outdoors).

The following direct subjective noise indicators, referred to as "noise annoyance indicators", were identified from the survey. The verbal scale of the answers was formulated using a 5-point scale, as recommended by [9].

1. *Annoyance*: the extent of the noise annoyance (caused by all noise sources) in and around the house perceived over the previous year. Response categories: Not at all (1), Slightly (2), Moderately (3), Very (4), and Extremely annoyed (5);
2. Change in annoyance (*ΔAnnoyance*): the reported change in annoyance (all noise sources) over the previous two years. Response categories: Greatly reduced (-2), Slightly reduced (-1), Remained the same (0), Slightly increased (+1), and Greatly increased (+2);
3. Road traffic noise annoyance (*RTA*): the extent of the annoyance explicitly caused by road traffic noise. Response categories: Not at all (1), Slightly (2), Moderately (3), Very (4), and Extremely annoyed (5);
4. Change in road traffic noise annoyance (*ΔRTA*): the reported change in RTA perceived over the previous year. Response categories: Greatly reduced (-2), Slightly reduced (-1), Remained the same (0), Slightly increased (+1), and Greatly increased (+2).

The indirect subjective noise indicators were further investigated in three domains:

1. Domain 1 (Physical complaints): the frequency respondents reported experiencing symptoms related to different health problems (headaches, fatigue, dizziness, insomnia, heart palpitations, and gastrointestinal complaints);
2. Domain 2 (Sleep quality): Sleep duration and time needed to fall asleep, the frequency of feeling well-rested, waking up too early or having difficulty waking up;
3. Domain 3 (Comfort level to perform activities): comfort level to conduct activities indoors and outdoors, as concentrating during working or studying, reading or watching television, speech intelligibility during a phone call or conversation, and relaxing or unwinding.

Considering that the respondents were asked to take into account mainly the 1-year period before the survey distribution when choosing their answers, the COVID-19 pandemic and consequent measures to restrain circulation implemented in Flanders could have played a role in their perception, especially in the post-survey. Firstly, mandatory teleworking tends to increase the residents' time at home during the day. Additionally, lower traffic volume was observed from data retrieved from the open database of the Flemish Government[1]. From November 2020 to April 2021, when a national lockdown was in place, the traffic volume presented, on average, approximately 14500 fewer vehicles/day than the respective period in 2019-2020, before the pandemic. From August to October 2020 and May to June 2021, the traffic volume increased to an amount closer to the reference in 2019, but differences of more than 6300 vehicles/day were still observed.

In an attempt to assess the pandemic's unknown effect on this research, the post-survey was further supplemented with three questions. The respondents were asked how much their time spent at home and the annoyance level caused by (road traffic) noise had changed due to the mobility restrictions and lockdowns compared to the normal situation.

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

2.3.2 Data processing

The arithmetic average and variability of the direct and indirect subjective noise indicators were calculated once the verbal scale used in the questions was translated into an ordinal measurement scale. The statistical differences in the average of continuous and binary variables across the independent groups (Borgerhout in the pre and post-surveys, and control streets) were checked by t-tests and chi-square tests. The sociodemographic composition was also investigated within the study cases.

In addition to demonstrating the impacts of the noise barrier replacement on the subjective noise indicators, the correlations between the noise annoyance and the indirect subjective noise indicators were also investigated in the three domains. For that, nonparametric Kendall τ_b correlations were used. T_b gives insights on the strength and direction of associations between two ordinal variables: a value of ± 1 indicates a perfect association between the two variables, whereas values close to 0 indicate weak or nonexistent relationships.

2.4 Percentage of highly annoyed people (%HA) and ERRs

Previous studies have established exposure-response relationships by using large datasets from different studies, with different demographics, from different countries, both in cities and small towns. The ERRs defined by Guski et al. [5] (Eqs. 1 and 2) are commonly used in the context of annoyance prediction. Eq. 1 was constructed based on a complete dataset, while Eq. 2 excludes from this dataset the 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. [5] 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% higher part of the response scale.

$$\%HA = 78.9270 - 3.1162 \times L_{den} + 0.0342 \times L_{den}^2. \quad (1)$$

$$\%HA = 116.4304 - 4.7342 \times L_{den} + 0.0497 \times L_{den}^2. \quad (2)$$

3 Results and discussion

3.1 Acoustic measurements and noise maps

Figure 2 displays, as boxplots, the average and standard deviations from the point measurements as $L_{A,eq.(15min.)}$, obtained from acoustic measurements, and the L_{day}, calculated from the acoustic simulation in IMMI. The average $L_{A,eq.(15\ min.)}$ obtained from the control streets is also presented in Figure 2, this being 58.7 ± 6.1 dB. For the control streets, the standard deviation may have been high as different streets, with different traffic intensities, were pooled together to form this average.

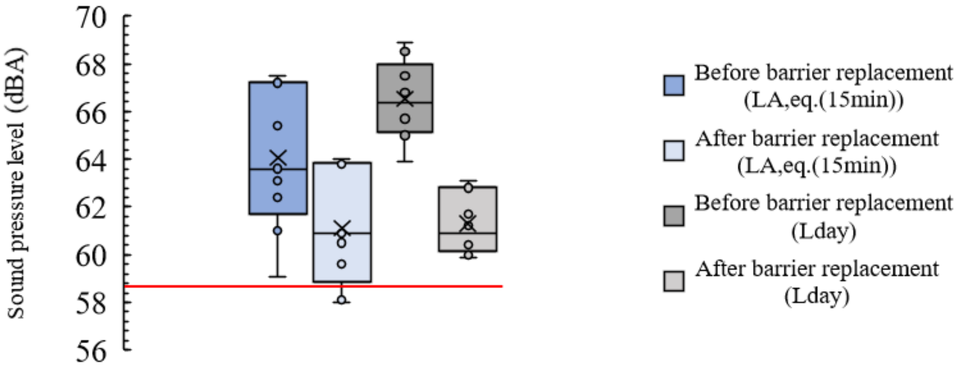

Figure 2 – Results of objective acoustic measurements and noise simulations.

The acoustic measurements performed before the noise barrier replacement resulted in an average of 64.3 ± 2.8 dB(A). The 65.0 dB(A) threshold was exceeded in five of the 10 measuring points, while the 60.0 dB(A) threshold was only achieved in one point. After the barrier replacement, the average noise levels dropped to 60.2 dB(A) ± 2.7 dB(A): a 4.1 dB(A) drop, on average, from the initial situation. No measuring point had a value above 65.0 dB(A) in the new condition, but only two points were below 60 dB(A). Also, the inhabitants are now exposed to an average $L_{A,eq.(15\ min.)}$ 1.5 dB(A) higher than in the control streets.
A comparison between the acoustic measurements and the simulated L_{day} shows that the second is 2.2 and 1.1 dB(A) higher before and after the barrier replacement, respectively. Also, the drop in L_{day} resulting from the barrier replacement was expected to be 5.2 dB(A). Possibly, the SRM II method underestimates the noise-reducing effect of the old noise barrier.
Noise simulations were also performed to calculate L_{den}. This parameter could not be compared with the objective acoustic measurements as the traffic volume obtained from the Flemish Government in June 2020 was used instead of the traffic count performed in 2013 by AWV. L_{den} before the noise barrier replacement was estimated as 62.4 dB(A) ± 3.0 dB(A). After the replacement, this value was expected to drop by 5.2 dB(A), reaching an L_{den} of 57.2 dB(A) ± 2.1 dB(A). L_{den} below 53 decibels, as recommended by [2], could not be achieved for any simulated point.

3.2 Questionnaire results

3.2.1 Sociodemographics

Firstly, the sociodemographic profile of the respondents was drawn. Double respondents found in the before and after survey were removed from this part of the analysis. As the respondents were anonymous due to ethical constraints, those who participated in both pre and post-surveys in Borgerhout were identified based on six variables: street, gender, age, type of home, level of education, and the number of family members.

Table 1 shows the most relevant part of the sociodemographic data of these unique respondents.

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

Table 1 – Sociodemographic data of respondents.

Case	Gender		Level of education			Age	Inactive×	Living with children
	Male	Female	Low	Middle	High			
Control	53.3%	46.7%	11.8%	51.6%	36.6%	39.2 (16.2)	39.7%	33.3%
Borgerhout	37.3%	62.7%	20%	56.2%	19.1%	51.3 (20.8)	32.6%	38.5%

* Level of education was registered in eleven categories, but grouped into three for this analysis: 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), and high (master's degree at a university college - two cycles: 4 or 5 academic years - or university).
× Percentage of retired and unemployed people (whether or not looking for a job). All others (including students) are categorised as active.

T-tests and chi-square tests were conducted to confirm whether the differences in the sociodemographic profile shown in Table 1 were significant between Borgerhout and the control streets. Respondents in the reference streets were significantly younger ($p < 0.000$) than the respondents from Borgerhout. More respondents in the control streets seem to have obtained a master's degree, which could be explained by the tendency of younger people to pursue higher diplomas. Also, Borgerhout's respondents consist of considerably more females than in the control streets ($p=0.01$). The percentage of respondents active in the labour market ($p=0.65$) and those living with children ($p=0.42$) did not differ significantly between the two cases.

3.2.2 Annoyance indicators (Direct subjective perceived noise)

From the post-surveys in Borgerhout, residents who reported starting living at the address one year or less before the survey distribution were removed, as they would not be capable of assessing the changes caused by the noise barrier replacement. The means of the annoyance indicators are presented in Table 2.

Table 2 – Average noise annoyance indicators (standard deviation).

Indicator	Case		
	Control	Borgerhout	
		Pre	Post
*Annoyance**	2.23 (.99)	3.66 (1.20)	4.00 (1.06)
ΔAnnoyance×	0.46 (.85)	1.21 (.82)	1.16 (.92)
*RTA**	2.29 (1.08)	3.77 (1.29)	4.21 (1.06)
ΔRTA×	0.48 (1.06)	1.23 (.99)	1.16 (.99)

*Response scale: Not annoyed at all = 1; Slightly annoyed = 2; Moderately annoyed = 3; Very annoyed = 4; Extremely annoyed = 5.
× Response scale: Greatly reduced = -2; Slightly reduced =-1; Remained the same = 0; Slightly increased =1; Greatly increased = 2.

ANOVA with Tukey posthoc tests carried out among the three cases revealed that, for a significance level of 5%, the four annoyance indicators did not differ statistically between the pre and post-survey, but differed from the control group.

In the control streets, the residents were, on average, 'slightly annoyed' by noise. Both before and after the noise barrier replacement, the means were closer to the 'very annoyed' condition. In the same manner, the annoyance caused by road traffic noise (*RTA*) is considerably higher than the control case, with even higher averages than *Annoyance*. These values may represent that the objective reduction of 4.1 dB(A) presented in Section 3.1 could not enhance the respondent's perception of noise, and road traffic is clearly identified as the main cause of annoyance by noise. Even though a reduction was achieved, the residents may have been expecting a greater decrease in (road traffic) noise as a result of the barrier improvement. The dissatisfaction towards the noise barrier is translated into the higher annoyance levels and confirm the subjective character of these indicators. The *ΔAnnoyance* and *ΔRTA* values also demonstrate that the residents did not perceive the objective reductions caused by the improvement in the noise barrier.

3.2.3 Sleep quality, physical complaints, and comfort level to perform activities (indirect subjective perceived noise)

The respondents indicated to what extent they were suffering from some physical symptoms (Domain 1), their sleeping behaviour (Domain 2) and difficulties performing activities indoors and outdoors (Domain 3). [4] stated that the assessment of potential health effects triggered by noise exposure needs to be mediated by annoyance indicators or some other appraisal measure. In this manner, Table 3 shows the correlations between *Annoyance* and *RTA* and the reported indicators across the three domains, expressed as the Kendall τ_b correlations. Only the statistically significant relations are presented, at significance levels of 1% and 5%.

Table 3 – Kendall's correlation coefficient (τ_b) between *Annoyance* and RTA with quality of life indicators.

Domain	Indicator		*Annoyance*			*RTA*		
			Control	Pre	Post	Control	Pre	Post
Physical complaints (1)	Headaches						.24*	.24*
	Fatigue		.14*	.40**	.35**	.16*	.37**	.32**
	Dizziness					.17*		
	Insomnia		.20**	.26*	.28*		.23*	.26*
	Heart palpitations						.24*	
	Gastrointestinal complaints					.15*		
Sleep quality (2)	Sleep duration (night)							
	Sleep duration (day)							
	Time to fall asleep							
	Waking up too early					.16*		
	Difficulty waking up							
	Feeling well-rested		-.14*		-.27*			
Comfort level to perform activities (3)	Concentration during reading	In	.17*	.27*		.18*	.26*	
		Out	.24**	.39**	.55**	.17*	.34**	.50**
	Concentration during working or studying	In	.17*					
		Out	.23**					
	Concentration while watching TV	In						
	Speech intelligibility during a conversation	In		.29*	.35**		.24*	.32*
		Out	.24**	.45**	.49**	.20**	.37**	.41**
	Speech intelligibility on the telephone	In		.27*				
		Out	.22**	.43**	.50**	.14*	.40**	.45**
	Relaxing or unwinding	In	.21**	.30**			.34**	
		Out	.37**	.42**	.42**	.21**	.39**	.37**

*Correlation is significant at the 0.05 level (2-tailed)
**Correlation is significant at the 0.01 level (2-tailed)

Fatigue and insomnia presented the most significant correlations with the annoyance indicators in the three cases among the health problems comprising Domain 1. T_b positive values prove that increases in perceived annoyance follow increments in the reported physical complaints. For Borgerhout, those correlations are stronger, as expected, due to community dissatisfaction with the noise levels in that area.
Regarding Domain 2, almost no significant correlations were found with the annoyance indicators. This behaviour could be attributed to significant decreases in L_{night} compared to L_{day}, resulting in lower perceived

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

noise during the regular sleeping time of residents. Additionally, less loud noise events happen during the night, which are less disturbing than the relatively constant, neutral sounds as from road traffic [10].
The strongest and most significant correlations in Table 3 were found for Domain 3. Without exception, it is more difficult to perform these activities outdoors when feeling annoyed by noise in general and by road traffic noise. [11] also observed a similar trend of discomfort in performing activities such as watching television, resting and talking for a sample in which 48.4% of the respondents reported experiencing noise-related annoyance.

3.2.4 The effect of the COVID-19 pandemic

Figure 3a shows a breakdown of the answers on the changes in time spent at home due to the COVID-19 pandemic. Half of the respondents had their time at home during the day increased, while 37% stayed at home longer during the evenings. Additionally, the respondents answered to what extent the annoyance levels due to (road traffic) noise had changed exclusively due to the pandemic, as depicted in Figure 3b. A significant number of respondents (33%) did not report changes in the *Annoyance* levels caused by noise in general; the remaining answers were equally distributed between those who identify an increase or decrease in *Annoyance*. Regarding the annoyance caused by road traffic noise (*RTA*), 46% describe being less annoyed by this noise source. Even though the time at home spent by the respondents had increased, the traffic volume reduced substantially due to the circulation restrictions in that period. These data also sustain that the annoyance levels presented in Table 2 were not amplified by the changes in behaviour caused by the COVID-19 pandemic.

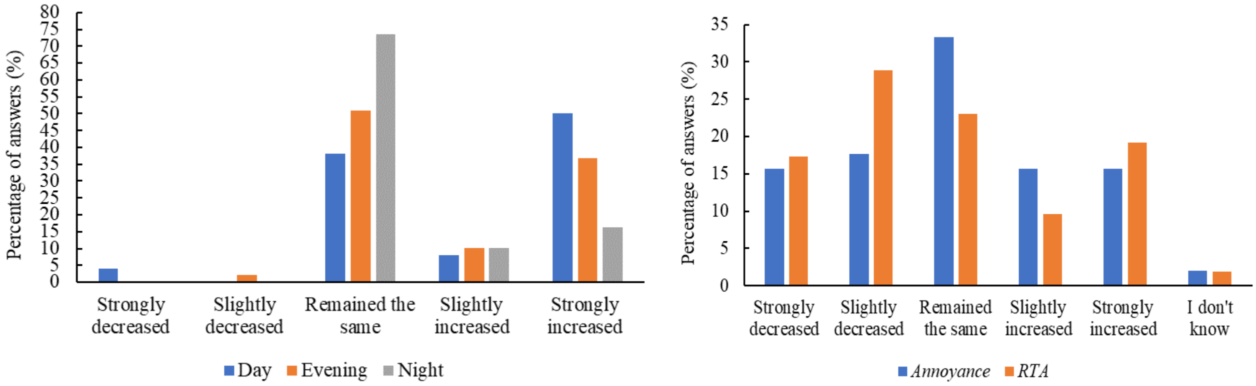

Figure 3 – Changes caused by the pandemic a) time spent at home; b) *Annoyance* and *RTA*.

3.2.5 %HA and ERRs

Table 4 presents the measured and calculated %HA using these ERRs and the simulated L_{den}.

Table 4 – Measured and calculated %HA.

Case	Measured %HA		Measured %HA (Road traffic noise)		Calculated %HA	
	20%	40%	20%	40%	[5] full dataset	[5] limited dataset
Control streets	1.8	12.4	2.5	15.5	-	-
Borgerhout pre	26.8	64.3	37.5	67.9	18.8	14.6
Borgerhout post	39.6	73.6	50.9	83.0	13.6	8.3

The %HA measured before the noise barrier replacement is considerably higher than %HA calculated from the equations established by [5]. As the noise barrier replacement decreased L_{den}, the Eq. 1 and 2 predict a reduction in the %HA, which is not observed in the measured result. The increase in %HA for the post-survey can be attributed to the expectations regarding the improvement of the noise barrier not being met. These results aligned with [6], who stated that social, psychological or economic factors play a more significant role in annoyance evaluations than acoustic or physical factors. Therefore, local annoyance models need to be created to estimate noise annoyance more accurately in those particular situations.

4 Conclusions

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 in 1.5dB(A). Even though the objective sound levels are closer to an 'ideal' situation, the residents of Tuinwijk in Borgerhout have a complaint history regarding the exposure to road traffic noise. Therefore, the reduction in the environmental noise promoted by the noise barrier replacement could not reduce the annoyance levels accordingly. 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 sleep quality. The difference in the measured %HA to those calculated from the ERRs shows that those models might not estimate %HA fairly or particular situations where high L_{den} is reported. Even though the residents had spent more time at home due to the circulation restrictions resulting from the COVID-19 pandemic, most respondents reported being less annoyed by road traffic noise, most likely due to the significant reductions in traffic volume observed during that period.

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