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PAPER

Evolution of building façade road traffic noise levels in Flanders

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The evolution of daytime façade noise levels by road traffic at 250 dwellings in Flanders is assessed. Three identical man-operated measurement campaigns have been conducted in the years 1996, 2001 and 2009, during fall. A practical methodology has been developed, based on short time noise measurements and context observations at these locations. The uncertainty introduced by short-term sampling has been quantified as a function of the noise level. Furthermore, a correction is proposed for measuring at a random moment during daytime. Analysis of the data showed that road traffic noise levels hardly changed globally over this period of 13 years. The distribution of changes in noise level at corresponding measurement locations is nevertheless rather wide—all improvements are equally compensated by increases in noise levels at other locations. The percentage of the dwelling façades exposed to daytime noise levels above 65 dBA has increased slightly between 1996 and 2001, but seems to stagnate in 2009. In spite of the increased interest and actions of policy makers during the past decades, noise exposure caused by road traffic at dwelling façades is a persistent problem.

Introduction

In the WHO (World Health Organization) report "Burden of disease by environmental noise",[1] it was concluded that at least one million healthy life years are lost every year from exposure to traffic related noise in the western part of Europe. Epidemiological estimates in terms of DALYs ("disability-adjusted life-years") list sleep disturbance, annoyance, ischaemic heart diseases, cognitive impairment of children and tinnitus as major health effects. In another study,[2] it was estimated that outside their homes, nearly 44% of the European population (in the year 2000) was exposed to road traffic noise levels above the WHO's threshold for the onset of negative health effects. Furthermore, noise pollution is among the most frequent sources of complaints regarding environmental issues in Europe,[1] especially in densely populated urban areas and residential areas near highways, railways and airports.

The increasingly growing scientific evidence of negative health-related effects by exposure to environmental noise has led to increased awareness of policy makers. To give an example, the European Environmental Noise Directive[3] obliges each member state to make noise maps of, amongst others, their major highways and highly populated agglomerations. A noise map gives an estimation of long-term averaged noise levels on a fine spatial resolution. Based on such maps, priority areas for noise abatement can be identified.

Although noise maps are valuable tools, they should be used with care. The areas covered by such maps are usually large and, as a result, simplifications of models are needed to reduce the computational cost. Especially, the complex sound propagation problem in urban areas[4,5] is usually not well-captured by noise mapping models. Furthermore, a good estimation of the relevant noise sources and their spatial and temporal distribution is needed given the fact that the acoustic environment is strongly source-driven. Most often, noise maps highly rely on the output

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Environmental impact

The negative health-related effects of continued exposure to road traffic noise have been quantified in recent years, stressing the importance of the environmental noise problem. Repeated measurements at the same locations allow a good estimate of the façade noise level evolution over time. Such an assessment, on the other hand, is often difficult with modeling approaches since local details/changes are often lacking. In spite of the increased interest and actions of policy makers during the past decades, noise exposure caused by road traffic at dwelling façades is a persistent problem in a highly motorized and densely built European region as studied here. Continued and well-thought actions are needed to prevent the fact that improvements at some locations are compensated by level increases at other locations.

of traffic models, inducing additional uncertainties. Furthermore, the focus in such models is mainly on predicting rush hour traffic intensity on major roads.

Another problem is that when comparing the evolution of the noise climate based on maps, only the effect of large infrastructural works will become visible. Due to lack of sufficient geographical detail, local measures aiming at road traffic noise reduction can stay invisible on a noise map. Examples are local changes in road surface cover, reduction of the number of lanes, placing speed bumps, *etc.* Most often, such measures could be rather important[6] in relation to the exposure to noise, since these are typically made close to dwellings. Furthermore, trends in the emission of individual cars are not captured, given the fact that bringing emission curves up-to-date is very costly. Also, the noise emission in realistic driving conditions[7,8] is not accounted for, which might differ from idealistic emission numbers as found *e.g.* in ref. 9.

Since noise maps are becoming an increasingly important policy tool, validation should be advised, certainly in the viewpoint of some well-identified problems as discussed in the previous paragraph. Extensive validations of noise maps with measurements have not been reported yet.

In this study, the evolution of the noise climate in Flanders is assessed by means of 3 repeated measurement campaigns in the years 1996, 2001 and 2009. In contrast to noise maps produced on behalf of the Environmental Noise Directive, all road traffic sounds are included in the measurement campaign. One could therefore expect more accurate exposure data to be extracted mainly for the smaller roads that are usually not accurately included in the traffic models. In order to limit the cost of such an operated monitoring campaign, a dedicated sampling strategy was developed. The uncertainty related to the followed methodology was carefully assessed. It was chosen to include measurements at a larger number of locations. As a consequence, the measurement duration at each point will therefore be limited. Research described, *e.g.* in ref. 10 and 11, indicated that short-term sampling can give reasonably accurate estimates of longer-term integrated equivalent noise levels.

Validation of the measurements with existing noise maps is beyond the scope of this study, but the measurement methodology presented here could be used for that purpose.

The use of fixed, low-cost microphones can be mentioned as a possible, affordable alternative for such man-operated measurement campaigns. The mass production of microphones for consumer electronics has led to very low prices. In ref. 12, it was shown that such microphones are reasonably accurate and highly cost-efficient. It was concluded that they are well-suited for environmental noise monitoring.

A similar repeated measurement campaign[13] was performed in the UK in the years 1990 and 2000. Measurements were performed outside 1000 dwellings, excluding weekends and school holiday periods. In contrast to the current study, 24 hour measurements were used. Two-thirds of the measurement locations in 2000 were the same as in 1990 to allow paired comparisons. The measurement locations were clustered in some selected local authority districts.

This paper is organized as follows. Firstly, the measurement methodology is described in detail, including the selection of measurement locations, the selection of sampling time and duration, and the instrumentation. In the next section, an overview is made of potential uncertainties related to this measurement methodology, and quantified where possible. In the Results section, the evolution of environmental noise in general, and road traffic noise in particular, is assessed at the measurement locations over the 3 repeated campaigns. Finally, some conclusions are drawn.

Methodology

Selection of measurement locations

The region under study is Flanders (see Fig. 1), which is the northern part of Belgium. Flanders is a region with an area of 13 522 km^2 and a rather high population density (in 1996: 435 inhabitants per km^2; in 2009: 459 inhabitants per km^2).[14] About one-quarter (24.7% in 2001) is built-up area, of which 42.2% is taken up by dwellings.[14] Flanders, located in the centre of Europe, is an important transit region given its close distance to many major sea harbors and large cities like Brussels, Amsterdam and Paris. Flanders has a dense network of roads (about 70 000 km of roads in 2001).[14] The distance travelled on these roads is estimated to be about 44 × 10^9 km for passenger traffic and nearly 30 × 10^9 ton kilometres for freight transport (in 2001).[14] As a result, many dwellings are located very closely to rather busy roads.

Noise measurements were performed at 250 locations, distributed over the region of Flanders. The number of locations was determined taking into account both the extent of the region of interest and the cost of the measurement campaign. A period of 3 months was assigned to perform the measurements to avoid strong seasonal variations in traffic. In this time frame, a single investigator could visit about 250 locations and perform measurements of limited duration. One drawback—in addition to costs—of extending the campaign would require more investigators, making subjective evaluation of the context less comparable.

The measurement locations were determined using a household driven sampling methodology. A rather crude methodology based on (non-commercial) telephone guides in the year 1996 was used. In such guides, the first sorting criterion is the city name and secondly the last name of the telephone owner with corresponding address. In 1996, almost every family in Flanders owned a fixed telephone. With fixed intervals, pages were selected, and the first address appearing in the upper corner was retained.

Since Flanders has a very dense road network, road traffic noise is very widespread. As a result, random sampling will mainly select locations with road traffic noise as the major contribution to the soundscape. An important fraction of the selected dwellings are near local roads (near 90%). This can be seen as an advantage since such locations are usually not sufficiently resolved in noise maps. The spatial distribution of the locations is shown on the map in Fig. 1.

In the repeated measurement campaigns in 2001 and 2009, the same 250 locations were taken. No stratification has been performed based on *e.g.* traffic intensity, speed limit or road top surface. Such data were not present in sufficient detail when setting up the experiment in 1996. In recent years, access to such

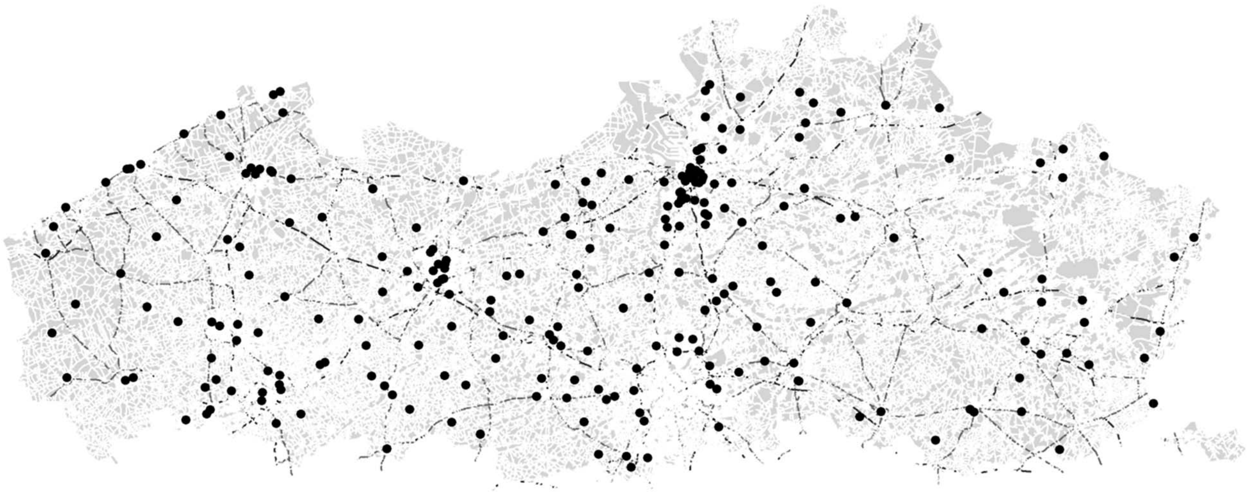

Fig. 1 Map showing the spatial distribution of the measurement locations over the region of Flanders.

detailed traffic related information has increased. However, the same locations were retained in the repeated campaigns, limiting the variations caused by changes in measurement locations. Such relative measures will allow a better estimate of road traffic noise evolution over time and can be considered as the main strength of this study. Since this study aims at assessing the general evolution of building façade road traffic noise levels, a case-wise comparison of the effect of local measures is beyond the scope of this study.

The focus of this study is on (road) traffic noise evolution. Because the same sample was taken over the years, changes in local population density are not accounted for. The results can only be interpreted as (changes in) population exposure as far as the hypothesis holds that local population density changes are limited over the 13 year duration of the study.

Sampling time and duration

The measurement campaigns were each time performed in the period October–November–December. Measurements were not performed during weekends and school holiday periods (at maximum of 3 weeks within this period), since traffic during these days is not representative of typical workdays.

Measurements were performed during daytime (between 7:00 h and 19:00 h) for practical reasons and given the fact that road traffic noise exposure at local roads is most prominent during that period. It can further be expected that during nighttime, other sources might become important like (continuous) noise from industry and road traffic noise from highways at larger distance because of downward refraction by *e.g.* the presence of temperature inversion.

Ideally, data should be obtained for a 24 hour period or longer, however, leading to a long-lasting and very costly campaign (using the offline technology of 1996). As the target was to repeat the campaign regularly, this was unacceptable. Advantages of man-operated measurements are that the microphone and logger are easily safeguarded, and an investigator on site can make useful observations (see further). On the other hand, a measurement period that is too short will be influenced by short-term fluctuations to a large degree, leading to non-representative samples. Given the time frame of 3 months and the choice for a single investigator, only a single visit per site is possible. A single 20 minute observation was expected to yield stable observations at locations where the noise level—and hence traffic intensity—is of practical interest. Extending the duration to, *e.g.*, 1 hour was considered to be inefficient, given the fact that within this time frame, traffic intensity does not change very much during daytime. This was recently confirmed with urban long-term measurements.[11] The uncertainty produced by this choice is evaluated in detail further in this paper.

Nowadays, there is a trend towards the use of unassisted distributed microphone systems as discussed in the Introduction; for consistency with the first measurement campaign in 1996, a man-operated procedure was continued in the successive campaigns.

Instrumentation and measurement methodology

The noise level measurements were performed with a $^1/_2$ʺ electret microphone (type Bruel & Kjaer 4189) connected to a pre-amplifier (type Bruel & Kjaer 2669C). The logging of the measurements was done with a 01dB SIP95 handheld device in the year 1996, and a Svantek 959 handheld device in 2001 and 2009. The measurement chain was calibrated daily with a Bruel & Kjaer 124.06 dB pistonphone, producing a pure tone of 251.2 Hz. The Bruel & Kjaer 4189 microphone capsule has a flat frequency response in the audible frequency range. A 90 mm diameter windscreen (type Bruel & Kjaer UA 0237) was used to limit wind-induced microphone noise. The microphone and logger were attached to a tripod, with the microphone membrane positioned parallel to the length axis of the road.

The microphone membrane was positioned at a height of 1.5 m, and at a distance of 1 m in front of the building façade facing the street. In case this was not possible, measurements were performed as close as possible to the building façade. The microphone height of 1.5 m is chosen to allow an easy and fast setup of the measurement equipment. This is also the typical ear height of a person. In case the selected address was not at ground level (*e.g.* in an apartment building), measurements were performed near the entrance of the building. In other cases, a similar location along the same road was chosen as close as possible to the selected address or GPS coordinates. Deviations from the desired measurement position were noted by the investigator.

The acoustical parameters of main interest are the total A-weighted equivalent noise levels, and the 5th and 95th percentile values, representative of the loudest events and background noise levels, respectively. These parameters are indicated by L_{Aeq}, L_{A5} and L_{A95}, respectively. The basic logging was performed as 1-s equivalent A-weighted levels. Next, the equivalent levels over 2 successive 10-minute periods, together with statistical levels, were calculated.

Each location was visited once during each measurement campaign. In the case of clearly identifiable noise other than road traffic noise, measurements were performed anyway, but the presence of a non-road traffic noise source was noted by the operator to exclude or include such measurements, depending on the analysis made. The advantage of this approach is that the sample is representative of any noise present during daytime. The disadvantage is that a number of locations will have to be rejected when strictly looking at road traffic noise. The sequence of locations visited during the different campaigns was not fixed, and the different locations were not visited at the same day of the week or at the same hour for practical reasons.

During the 20-minute measurements, the investigator made a number of additional observations. Mainly, the subjectively important noise sources audible at the microphone position were identified (the road of the measurement address, a larger road in the neighborhood, train and plane passages, and all other non-road traffic related sounds were noted). A rough estimate of the weather conditions (sunny, cloudy, wet road surface) and wind speed (no wind, weak, moderate, strong) were made. During intense rainfall or snowfall, measurements were not performed. Periods with snow present on the road are not representative of the climate in Flanders, and given their large influence on vehicle speed and traffic intensity, such periods were excluded. No constraints on wind speed were imposed (see further).

Analysis of uncertainty

The measurement methodology followed in this study induces some uncertainties, which are assessed in more detail in this section. The effect of measuring at a random day in the week and the influence of weather conditions on averaged noise levels is evaluated. The uncertainty induced by short-term sampling is assessed in detail, and a correction for measuring at a random hour during daytime is proposed.

Overview of dataset

In Table 1, an overview of the number of observations during the 3 campaigns is given. The number of identifiable corresponding locations is shown by means of a comparison between 1996 and 2001, and between 2001 and 2009. Given the fact that the locations were visited in each campaign by different investigators, and because of changes in *e.g.* house numbering or road reorganization, not all locations could be linked.

The total number of locations with dominant road traffic noise is further shown. The measurement locations with clearly identifiable other noise sources do not necessarily have to be the same in the different campaigns. This leads to a lower number of comparable road-traffic dominated measurement locations. The distinction is further made between addresses on local roads and addresses on major roads (under the jurisdiction of the Flemish government rather than the local authority). Another category is made for locations with clearly identifiable noise from major roads at a measurement address on local roads. The latter category will not be considered when strictly looking at local roads in further analysis.

Table 1 Overview of the number of measurements, and their distribution over different categories. The number of corresponding valid measurements between successive campaigns is indicated as well

	1996	2001	2009
All locations	250	250	250
Corresponding locations	*247*	*234*	
Locations with dominant road traffic noise	164	203	157
Corresponding locations	*140*	*134*	
Locations near major roads	26	26	26
Locations near local roads with important contributions from major roads	11	13	24
Locations with dominant local road traffic noise	127	164	107
Corresponding locations	*99*	*94*	

Influence of week number, day of the week, and meteorological conditions

The distribution of the observations in the 3 campaigns over the different weeks of the year is shown in Fig. 2. In 2001, measurements started two weeks earlier than in 1996. In 2009, the campaign started one week later. Because of the larger number of days with high rainfall in 2009, a number of measurements were needed in the second week of January to complete the campaign, so beyond the earlier defined time frame. Weeks with a lower number of observations most likely contain many days with continuous rainfall. At weeks with a high number of observations, regions with many observation points at

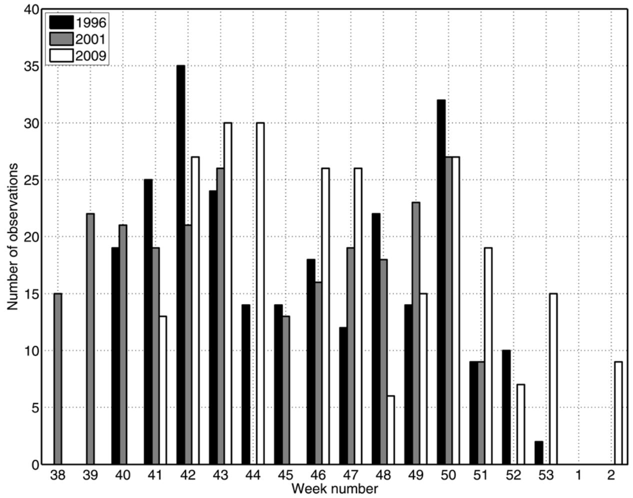

Fig. 2 Distribution of the number of observations (all corresponding measurement locations) over the different weeks of the year.

close distance were visited, near more densely populated parts in Flanders. Analysis of traffic intensity data shows that week-by-week variations are unlikely, especially since holiday periods were excluded.

The distribution of the measurements over the days of the week is shown in Fig. 3. In 1996, more measurements were performed on Wednesdays and Thursdays. In 2001, more observations in the dataset are present for Tuesdays. In 2009, Mondays are more prominent. Traffic counts in Flanders on major roads[15] (no highways) show that the traffic intensity on Mondays is typically smaller, while an increase is observed on Fridays, compared to the weekly averages (only considering workdays). When expressed in dB ($=10\log_{10}(I_t)$, with I_t being the traffic intensity), values of −0.18 dB for Monday and +0.13 dB for Friday are obtained, respectively. As a result, it could be concluded that the effect of measuring at the same locations at different days of the week over the three campaigns was considered to be rather limited. As a result, no corrections were applied.

The influence of the qualitative meteorological observations by the operator on averaged noise levels over all corresponding locations is shown in Fig. 4 and 5. The lengths of the error bars are equal to the 95% confidence intervals on the averages in each category, assuming a normal distribution of the data. It is shown that the equivalent sound pressure level does not increase systematically by wind-induced microphone noise. In 1996 there seems to be a decreasing trend, while in 2009 an increase is observed which is closer to the expectations. During the campaign in 2001, no clear trend is observed. A possible reason for the rather limited effect of wind on the measured noise levels is the low microphone height and its presence very close to building façades, giving some shelter. In addition, measured noise levels are sufficiently high to mask wind induced microphone noise under normal weather conditions. When going from sunny over cloudy to rainy weather, a limited decreasing trend is observed in 1996 and 2001. An increase in average noise level is found in 2009 in case of rainy weather. Given the fact that no clear trends are observed that are consistent over the 3 measurement campaigns, no data are excluded based on weather conditions.

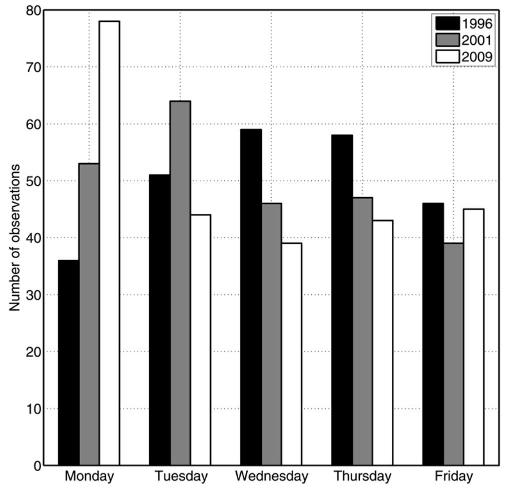

Fig. 3 Distribution of the number of observations (all corresponding measurement locations) over the different days of the week.

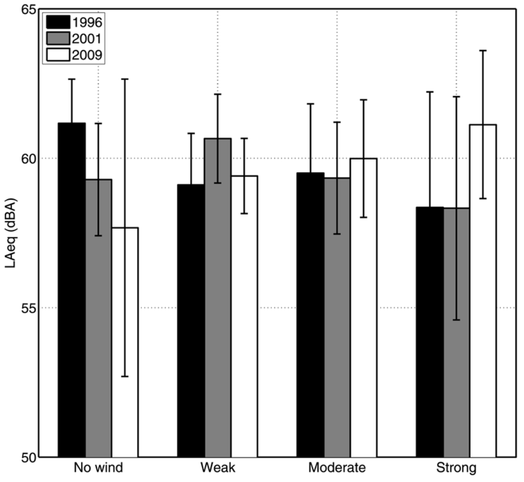

Fig. 4 Averaged noise levels (all corresponding locations) as a function of qualitative wind speed observations. The error bars indicate the 95% confidence intervals on the averages in each category.

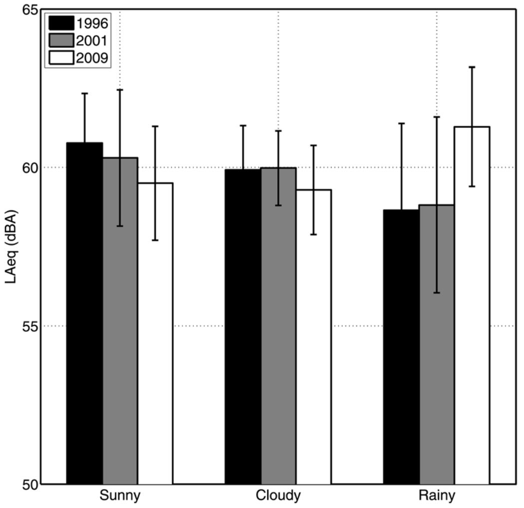

Fig. 5 Averaged noise levels (all corresponding locations) as a function of sunny, cloudy or rainy weather. The error bars indicate the 95% confidence intervals on the averages in each category.

Influence of short-time sampling

The feasibility to acquire a reasonably accurate estimate of longer-term noise levels based on short-term sampling is confirmed by other researchers. In ref. 10, many studies were analyzed leading to the conclusion that a measurement duration between 10 minutes and 1 hour is standard practice. Estimates of day-equivalent levels (L_{day}) based on a single 15 minute sample lead to level deviations within ±2 dBA and ±3 dBA in 90% of the locations considered, at main and local streets respectively.[10] In ref. 11, taking 3 times 15 minute samples is advised in a dense urban setup, yielding location-dependent level deviations in the range within ±1.5 dBA and ±3.4 dBA, in 90% of the cases of random sampling during daytime. These errors hold for extrapolating to day–evening–night equivalent levels L_{den}[3] in the area considered in ref. 11. Note that in the current study, the aim is not to extrapolate to longer-term levels, but to look at the evolution in road traffic noise exposure over time by using a limited measurement duration. The results obtained in the cited references show that even short-term sampling is representative of the noise climate at a given location.

Short-term sampling introduces two forms of uncertainty: (1) uncertainty related to the representativeness of the sample of road vehicles and (2) uncertainty with regard to the representativeness of the sampling instant during daytime. The first type of uncertainty is assessed in the next section, but is hard to correct for. For the second type, a correction is proposed.

Representativeness of the sample of road vehicles

This type of uncertainty is checked in more detail by splitting the 20-minute measurement duration into two 10-minute samples. In Table 2, the root-mean-square value of the difference between the 2 successive 10-minute intervals, averaged over the whole measurement campaign, is shown. This root-mean-square value is equal to the standard deviation of the sample.

The averaged differences are consistent over the different campaigns. Based on the notations of the investigator concerning dominant noise sources at the locations, three selections were made. First, all noise samples are considered. The presence of non-traffic related noise events leads to larger differences between successive 10-minute levels. For locations with both local road traffic noise and noise from larger roads near the observation point, differences become somewhat smaller. In case a selection is made of locations with local road traffic noise only, these averaged differences increase again. This can be explained by the smaller sample of road vehicles taken over 10 minutes on low density local roads, in contrast to the more continuous contributions from high intensity larger roads.

In Fig. 6, the differences between successive 10 minute periods per location are averaged per 5-dBA intervals. These results confirm previous remarks. At higher noise levels, deviations are smaller. In general, there is a decreasing trend with increasing noise levels. At very quiet locations, no conclusions are possible because of the large influence of accidental noise events on equivalent levels.

When evaluating uncertainty on the noise evolution over time, this level-dependent standard deviation caused by short-term sampling (σ_{st}) is simplified to a linearly decreasing value between 2 dB in the 5-dBA intervals 40–45 dBA, and 0.5 dBA in the 75–80 dBA interval.

Correcting for hourly-dependent traffic intensity

The second type of uncertainty caused by taking short measurement intervals is now considered. Measurements at the corresponding locations during the three campaigns were not performed at the same hour during daytime since such an additional constraint would largely extend the duration of the full campaign. The distribution of the hours at which measurements started during the different campaigns is shown in Fig. 7. Given the fact that traffic intensity can vary significantly during the daytime period, a correction is proposed. This correction is based on traffic counts[15] at 20 stations distributed over the whole of Flanders, leading to the hourly-dependent corrections as shown in Fig. 8. The smallest averaged traffic intensities are observed between 11:00 h and 12:00 h, the highest intensities between 17:00 h and 18:00 h. As a reference, the average fraction of the traffic intensity during the daytime hours is used.

Table 2 Standard deviation of the samples based on successive 10 minute measurements, averaged over some categories and per campaign

	1996	2001	2009
All corresponding locations/dBA	1.37	1.24	1.34
Dominant road traffic noise/dBA	0.96	1.13	1.14
Dominant local road traffic noise/dBA	1.13	1.27	1.27

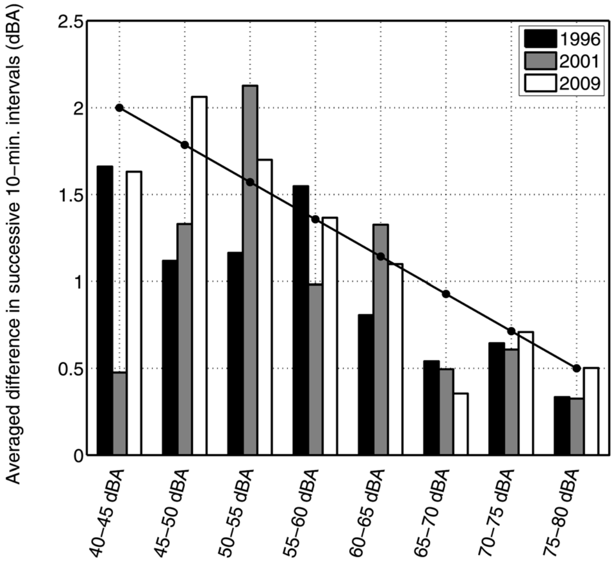

Fig. 6 Sample standard deviation based on 2 successive 10-minute measurement intervals as a function of noise level (all corresponding locations). The straight line shows the level-dependent correction which will be used to assess uncertainty during analysis.

The proposed corrections for the averaged traffic intensity are directly expressed in dB values in Fig. 8. The error bars have a length of two times the standard deviation based on the hourly counts at the 20 stations. When expressed on a dB scale, the upper and lower extents of the error bars are not symmetric. Especially during the morning from 7:00 h to 8:00 h, the correction is very small, but with a large standard deviation. By considering typical averages and standard deviations, the uncertainty related to measuring at a random hour during daytime (σ_{int}) is approximated by an hourly independent value of 1 dB.

Results

In Table 3, an overview is given of the average differences at corresponding locations from 1996 to 2001, and from 2001 to 2009. The 95% confidence intervals are shown as well, assuming a normal distribution of the differences when considering all relevant measurements. The standard deviation on which the confidence intervals are based is the root-sum-square value of the average level difference between corresponding measurement locations, and twice the simplified level-dependent standard deviation caused by short-term sampling σ_{st}, as previously

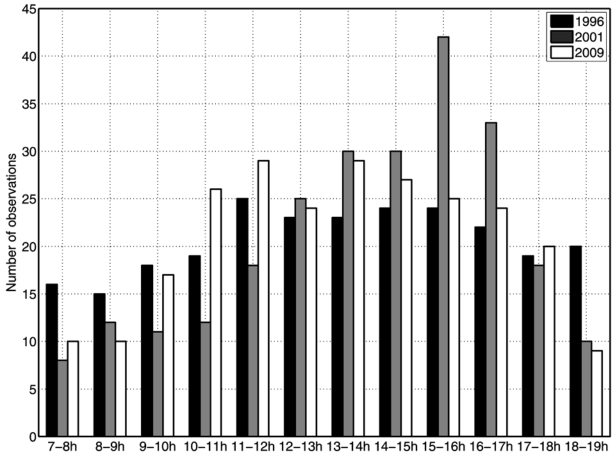

Fig. 7 Distribution of the number of measurements (all corresponding locations) over the daytime hours.

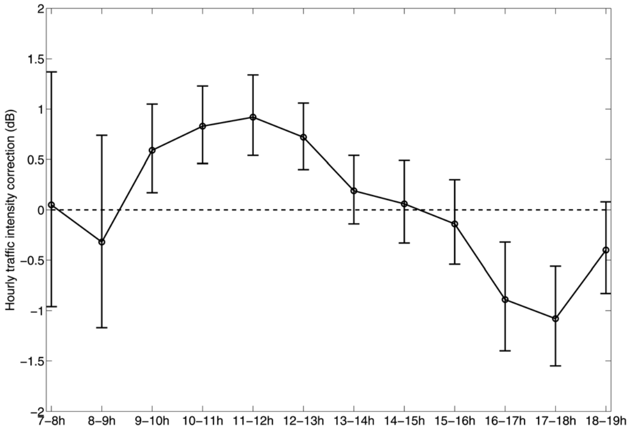

Fig. 8 Hourly dependent correction in dB for traffic intensity at daytime hours. The error bars have a length of two times the standard deviation based on the hourly counts at the 20 stations considered.

discussed. In addition, the uncertainty related to measuring at different hours in the successive campaigns is accounted for.

Given the fact that a global confidence interval is aimed at in Table 3, the level-dependent standard deviations were weighted by their occurrence in the dataset, leading to a single global standard deviation σ_{st} of 1.18 dBA. The latter was shown to be very consistent (±0.01 dBA) over the three measurement campaigns. The distinction is further made between neglecting and taking into account the hourly correction for traffic intensity as presented in Fig. 8. In the first case, the simplified hourly independent correction of 1 dB is added twice to the standard deviation. Note that the part of the variation related to the measurement methodology uncertainty involves some approximations, however, they are small compared to the average level difference between corresponding measurement locations over the different years.

The main finding is that this study revealed nearly no significant evolution for both general environmental noise and road traffic noise. The confidence intervals on the difference in levels all contain zero, and as a result, only some trends can be identified. Taking into account the hourly correction as for traffic intensity as presented in Fig. 8 has only a slight influence on the averaged level differences.

There is a slight tendency for an increase in the background noise level (L_{A95}) from 1996 to 2001, and from 2001 to 2009. From 1996 to 2001, there was a decrease in the sampled equivalent level for local roads, which seemed to stagnate from 2001 on. Total road traffic noise at corresponding points is very stable between 1996 and 2001, and increases slightly between 2001 and 2009. The decrease in noise levels at local roads observed in 2001 is stopped in 2009. Note that these findings are only slight tendencies, which are far from being statistically significant.

The distribution of the measured noise levels at locations with (dominant) road traffic noise is shown in Fig. 9. The hourly correction for traffic intensity as presented in Fig. 8 is accounted for. The lengths of the error bars equal twice the global standard deviation (σ_{i}) on the averages in each class. This global standard deviation is based on the level-dependent standard deviation caused by short-term sampling ($\sigma_{\mathrm{st,i}}$) and by taking into account the sampling error ($\sigma_{\mathrm{ns,i}}$) since only a limited number of samples are present in the different level categories. The latter can be expressed as

$$\sigma_{\mathrm{ns,i}} = \sqrt{\frac{P_{\mathrm{i}}(1-P_{\mathrm{i}})}{N_{\mathrm{i}}}}, \tag{1}$$

with N_{i} the number of samples in a given class, and P_{i} the fraction of the data falling in this category.

The uncertainty by short-term sampling, expressed as a fraction, is approached as

$$\sigma_{\mathrm{st,i,fraction}} = \frac{\sigma_{\mathrm{st,i}}}{\Delta_{\mathrm{dB}}}\frac{|P_{\mathrm{i+1}} - P_{\mathrm{i-1}}|}{2}, \tag{2}$$

with Δ_{dB} the width of the dB class, which equals 5 in Fig. 9.

Table 3 Globally averaged level differences between corresponding locations and successive campaigns, for different subsets of the data. The 95% confidence intervals (CIs) on the averaged differences are given

	Difference between 2001 and 1996		Difference between 2009 and 2001	
	Mean/dBA	95% CI	Mean/dBA	95% CI
L_{Aeq}, all corresponding locations	−0.10	[−0.76, 0.57]	−0.12	[−0.79, 0.54]
L_{A5}, all corresponding locations	−0.12	[−0.81, 0.57]	−0.02	[−0.71, 0.66]
L_{A95}, all corresponding locations	0.20	[−0.56, 0.96]	0.21	[−0.66, 1.08]
L_{Aeq}, dominant road traffic noise	0.04	[−0.68, 0.76]	0.12	[−0.67, 0.91]
L_{Aeq}, dominant road traffic noise, correction for hour of day	−0.03	[−0.72, 0.66]	0.24	[−0.48, 0.97]
L_{Aeq}, dominant local road traffic noise	−0.32	[−1.22, 0.57]	0.04	[−0.94, 1.03]

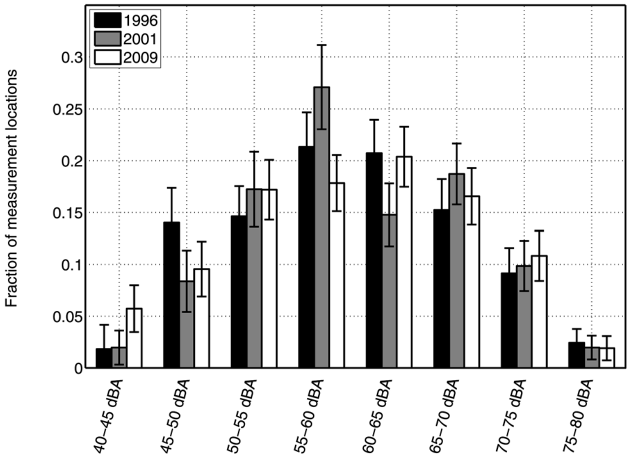

Fig. 9 Distribution of the measurement locations with dominant road traffic noise over 5-dBA classes for L_{Aeq} at the building façade during daytime. Measurements were corrected for hourly-dependent traffic intensity as depicted in Fig. 8. The error bars have a length of two times the global standard deviation σ_i, as calculated with eqn (1)–(3).

The global standard deviation in each class then equals

$$\sigma_i = \sqrt{\sigma^2_{st,i,fraction} + \sigma^2_{ns,i}}. \tag{3}$$

In many classes, significant changes in exposure from 1996 to 2001 are observed. The situation in 2009 is again closer to the one in 1996 for levels above 50 dBA.

The percentage of the dwelling façades exposed to noise levels above 65 dBA by road traffic noise is summarized in Table 4. From 1996 to 2001, there is an increase from 27% to 30%. In 2009, this percentage stagnates. When explicitly corrected for the different traffic intensities at the measurement hour, a small but non-significant decrease is noticed from 2001 to 2009.

A more detailed analysis of the change in noise level from road traffic is shown by means of the distribution of differences between corresponding measurement locations in Fig. 10. The hourly-corrected data were considered. The uncertainty in this difference-distribution is caused by short-term sampling, which might lead to shifts between adjacent classes. However, the latter is much more limited than the uncertainties presented in the previous figures, and cannot be clearly represented in this distribution plot. The distribution of the differences between 2001 and 1996, between 2009 and 2001, and between 2009 and 1996 is considered separately. Positive values indicate an increase in noise level relative to the previous campaign.

Although the median of the distribution of change is very close to zero, a rather broad distribution is found. At many corresponding locations, significant decreases in the sampled noise levels are observed. However, these are compensated to a similar degree with increases at other locations. The difference in fraction taken by locations with an increase or decrease in noise level, compared to the previous campaign, is less than 1%.

Table 4 Fraction of the corresponding measurement locations exposed to dominant road traffic noise above 65 dBA L_{Aeq} during daytime at the building façade. The values in between brackets are the standard deviations on these fractions as calculated with eqn (1)–(3)

	1996	2001	2009
Dominant road traffic noise > 65 dBA	0.27 (0.04)	0.30 (0.04)	0.31 (0.04)
Dominant road traffic noise > 65 dBA (correction for hour of day)	0.27 (0.04)	0.31 (0.03)	0.29 (0.04)

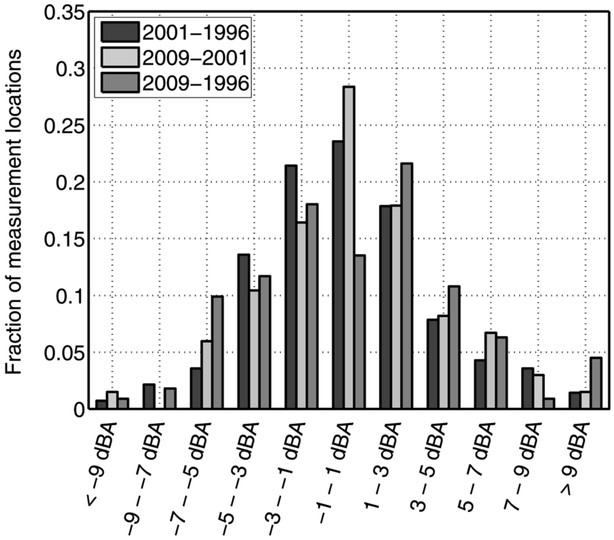

Fig. 10 Distribution of the difference in measurements (between the different campaigns) at corresponding locations with dominant road traffic noise over 2-dBA classes for L_{Aeq} at the building façade during daytime. Measurements were corrected for hourly-dependent traffic intensity as depicted in Fig. 8.

From 1996 to 2001, the classes with a small decrease in noise level are somewhat more prominent, however compensated with higher fractions in the classes with a high increase. The class with zero difference is somewhat more populated when comparing between 2009 and 2001. This difference-distribution is also more symmetric than the one between 2001 and 1996.

In Fig. 11 and 12, the level difference between two successive campaigns at each corresponding location is depicted as a function of the level of the oldest campaign. In Fig. 13, the level difference between the 1996 and 2009 measurements are shown. The level difference over time does not seem to depend on the noise level at a given location. Only above 70 dBA, the level difference tends to be smaller. Such locations are probably characterized by very busy, continuous traffic. Only very drastic changes in infrastructure or traffic management could change these major flows. Especially at the lower levels, part of the level difference is caused by uncertainty related to the current measurement methodology.

Conclusions and discussion

In this study, a man-operated measurement methodology was proposed to investigate the evolution of daytime building façade noise levels by road traffic in the region of Flanders, Belgium. One of the constraints was finishing the measurement campaign in a 3-month period by a single operator, excluding weekend days and holidays. Measuring at 250 locations and taking 20-minute samples were considered to be appropriate for an area with the size and population of Flanders. The first campaign was conducted in 1996, and repeated in the years 2001 and 2009.

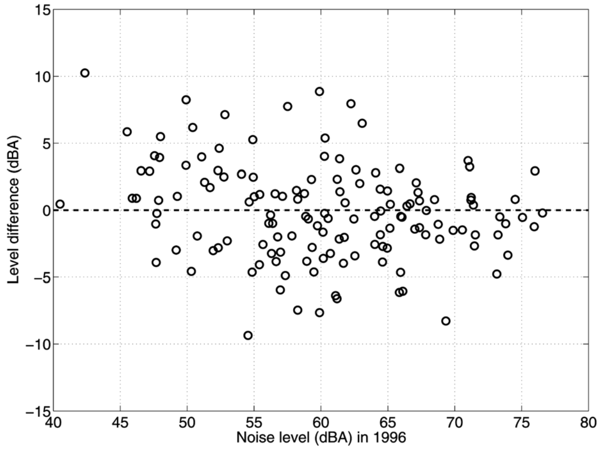

Fig. 11 Scatter plots between level difference at corresponding locations (with dominant road traffic noise) and the noise level in 1996 (L_{Aeq}), between the 2001 and 1996 campaigns. Measurements were corrected for hourly-dependent traffic intensity as depicted in Fig. 8.

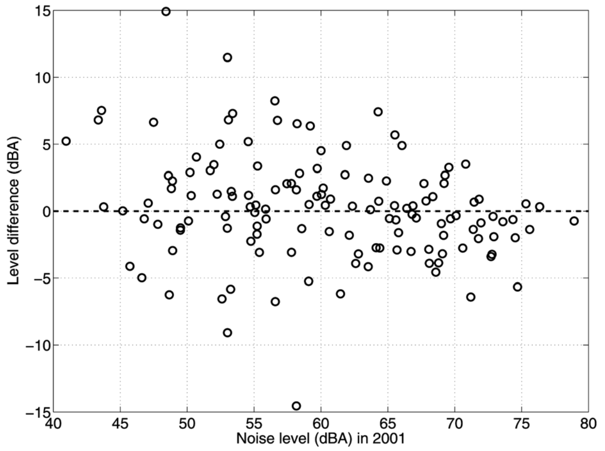

Fig. 12 See the caption of Fig. 11, but now between 2009 and 2001.

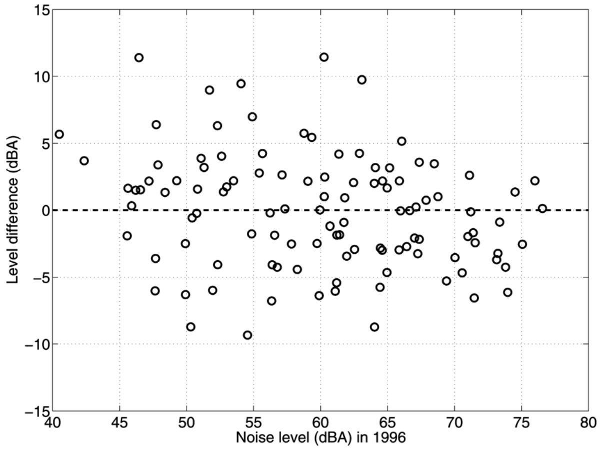

Fig. 13 See the caption of Fig. 11, but now between 2009 and 1996.

The uncertainty related to the short term sampling was assessed by splitting the 20-minute measurement duration into two 10-minute samples. With increasing equivalent sound pressure level, this uncertainty becomes smaller. This behavior was simplified to a standard deviation of 2 dBA in the 40–45 dBA class, linearly decreasing to a value of 0.5 dBA in the 75–80 dBA class.

Measurements at the corresponding locations during the three campaigns were not performed at the same hour during daytime since such an additional constraint would largely extend the duration of the full campaign. The effect of measuring at a random hour during daytime hours was assessed based on traffic counts at 20 major roads in the Flanders region, leading to hourly dependent corrections.

This study shows no general, significant evolution in environmental noise levels over the 13-year period considered. The confidence intervals on these differences in the level all contain zero and, as a result, only some slight trends could be identified. This holds for environmental noise in general (equivalent levels, background noise, and the 5% loudest levels), equivalent levels near local and major roads with dominant road traffic noise, and equivalent levels near local roads dominated by local road traffic noise. Given the uncertainty of the measurement method, this implies that a change, if any exists, would have to be less than about 1 dBA. Alternatively, it can be stated that the observed changes in noise exposure are so small that they are not statistically significant taking into account the used sample size.

The distribution of changes in noise level at corresponding locations with dominant road traffic noise is nevertheless rather wide. This means that all improvements are nearly equally compensated by increases in noise levels at other locations. From 2001 to 2009, there is a trend towards stagnation of noise levels. The fraction of measurement locations with changes between −1 dBA and +1 dBA has increased when comparing the difference distribution between 2009 and 2001 to the one between 2001 and 1996.

The general trends observed in this study are consistent with those from a similar study[13] performed in the UK. In the latter, it was concluded that changes in noise exposure between 1990 and 2000 are small in magnitude, and trends in these changes are subtle. A decreasing trend in equivalent noise levels during daytime was observed, which was on average equal to −0.53 dBA at corresponding locations[13] (during the same daytime hours as considered in the current study). In the current study (all locations), the values are −0.10 dBA (between 1996 and 2001) and −0.12 dBA (between 2001 and 2009). The 10% loudest levels (L_{A10}) during daytime showed a decrease of −0.59 dBA from 1990 to 2000.[13] In this study, L_{A5}-values showed an averaged decrease equal to −0.12 dBA from 1996 to 2001, and −0.02 dBA from 2001 to 2009. As for the background noise, the current study observed an average increase of 0.20 dBA (from 1996 to 2001) and 0.21 dBA (from 2001 to 2009). In the UK study,[13] L_{A90} remained more or less constant during the day, but increased slightly during the night. These observed trends, confirmed by the UK study,[13] are consistent with a model assuming that the noise of individual cars decreases, leading to lower maximum levels, while an increase in traffic raises background levels.[16]

The percentage of dwellings with dominant road traffic noise above 65 dBA during daytime in the current dataset (which is near 30%) is much higher than that in the aforementioned UK study[13] (near 10%). Despite these high percentages of highly exposed building façades, there has been an increase between

1996 and 2001, followed by a stagnation towards 2009. The aforementioned study[13] found that in 2000 10% of the UK population was exposed to noise levels during the day higher than 65 dBA, a number that had decreased from 12% in 1990.

The region of Flanders is representative of many highly motorized densely built European regions. Exposure to road traffic noise at dwelling façades appears to be a persistent problem, in spite of the increased interest and actions of policy makers during the past decades. It should be mentioned that the first round of noise action plans, associated with the Environmental Noise Directive,[3] was approved by the Flemish government after the measurement campaign in 2009 was finished.

The results presented in this study do not intend to show that additional measurement campaigns are of no use. The absence of changes in general in the period considered cannot be transferred to the future. Such large-scale measurements are also valuable in the viewpoint of validation of calculated noise maps, to obtain accurate noise exposure data at local roads and to assess the effect of (very) local noise reducing measures.

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