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Effect of a Row of Trees Behind Noise Barriers in Wind

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Summary
The effect of a row of trees (in leaf) behind a noise barrier in wind is investigated. An experiment was set up along a highway. Measurements at a location with and without a row of trees behind a noise barrier were compared. This continuously monitoring lasted from the middle of the summer till the middle of fall. It is shown that for downwind sound propagation for an orthogonal incident wind, the efficiency of the noise barrier with trees becomes increasingly better compared to the noise barrier without trees, with increasing wind speed. The improvement by the trees is only slightly affected if the wind direction is not perfectly orthogonal to the barrier. Upwind sound propagation is affected only to a small degree by placing trees. Diffraction on the canopy of trees does not result in an increased total A-weighted sound pressure level due to the typical low-frequency spectrum of traffic noise. The contribution of wind-induced vegetation noise to the recorded noise levels can be neglected for highways with common dense traffic.

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1. Introduction

Meteorological conditions have important consequences for outdoor sound propagation. The effect of the presence of gradients in both temperature and wind speed and the occurrence of atmospheric turbulence needs to be taking into account when performing accurate analysis or prediction. The air flowing over the earth surface slows down due to friction in the atmospheric boundary layer. This results in a typical logarithmical wind speed profile above an unobstructed surface. The wind speed gradients will refract sound towards earth for downwind sound propagation. The presence of obstacles, such as noise barriers, will severely disturb the ambient meteorological situation. The altered wind profile in the vicinity of a barrier will results in a worse performance, since wind speed gradients become larger near the barrier. This results in an increased refraction of sound for downwind sound propagation, which will cause the shadow region behind a barrier to become smaller. The focus in this paper is on the effect of wind on noise barriers, since the effect of temperature is in most practical situations secondary to the effect of wind speed gradients [1].

Besides this additional refraction caused by the screen, turbulent inhomogeneities will also result in increased noise levels behind the barrier [2, 3]. However, the scattering by turbulence will mainly be observed in the deep shadow zone, where sound pressure levels are low. At large distances on the other hand, the superposition of scattered waves on diffracted waves will result in fluctuations of phase and amplitude [2], smoothing out interference patterns. For thin rectangular barriers and broadband traffic noise, these turbulence effects will be small in comparison with the screen-induced refraction, at limited distances behind the noise barrier [4].

To cope with the problem of screen-induced refraction by wind, the use of windscreens (or windbreaks) behind noise barriers is proposed. Since placing windscreens does not modify the construction of the noise barrier itself, it is easy to apply to the many kilometres of noise barriers already build along roads.

Trees as windbreaks have been used for hundreds of years as a method of improving crop productivity. Significant yield increases have been attributed to shelter effects (e.g. improved soil moisture, higher pollination, higher $C0_2$-levels and less mechanical damage to the plants). A population of trees can be selected to provide a good overall reduction of leeward mean wind velocity.

Naturally constructed barriers may lead to a decreased annoyance since their acceptance is usually higher [5]. So it is expected that placing a row of trees behind a noise barrier may also have some positive psychological effects. Placing trees behind a barrier on the receiver side results in a better integration of a noise barrier in the landscape.

So trees may be useful for wind speed reduction purposes and from a psychological point of view. However, when placing trees behind a noise barrier, one needs to account for the full effect of vegetation on sound propagating through it. Effects may arise from an increased scattering on the trees tops and from wind-induced vegetation noise.

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Schuller *et al.* measured the effect of a row of trees (in absence of wind) behind a small barn, and noticed a reduced attenuation at high frequencies (> 1–2 kHz) due to scattering, while the midfrequencies were more attenuated [6, 7]. When the trees lost their leafs, the positive effect in the midfrequency range remained unchanged. Trees in wind will also generate noise. For deciduous species, the rustling of leaves finds its origin in vibrations induced by the unsteady contacts between leaves and neighbouring leaves or branches. Noise from coniferous species is generated aeroacoustically: the Von Karman vortex shedding behind the needles will force the needles to vibrate [8]. Both in-situ experiments at the edge of different forests and experiments in an anechoic chamber are performed by Fegeant [8, 9]. Boersma characterised the natural ambient sound environment of a deciduous forest with increasing wind speed [10]. Both authors indicate that wind-induced vegetation noise (sound pressure levels, in decibels) increases linearly with the logarithm of wind speed. The shape of the emission spectra does not change with increasing wind speed. Emission peaks can be found around 4–5 kHz. It is also stated that some species generate more noise than others do, and the difference may be in the order of 10 dB [9].

Many descriptions of experiments can be found in literature on sound propagation through multiple rows of trees (forests). For frequencies lower than 1 kHz, ground attenuation is considered to be the prominent factor in absorption of sound due to the formation of a highly porous humus layer [11]. For higher frequencies (above 1 kHz) the attenuation is caused by vegetation. Trunks and branches will mainly reduce sound by scattering. Leafs on the other hand will scatter and also absorb sound, due to viscous dissipation and energy losses caused by heat conduction through the boundary layer of leaves [11]. Martens *et al.* investigated the absorption of sound energy by single leaves and stated that a very small amount of energy is effectively absorbed. Since the number of leafs in the canopy of trees is very large, this is an important factor [12]. With increasing frequencies the absorption will become the most important factor [13].

Several rough approximations for high frequency attenuation of sound propagating through trees can be found in literature. A square-root law for frequency dependence of sound attenuation by vegetation is proposed i.e. 3 dB increase in attenuation per doubling of frequency. Other models predict 6 dB attenuation per doubling of frequency. Of course these estimations are strongly dependent on vegetation type, vegetation density, distribution of trunk diametres, etc. [11, 14, 15]. Martens also performed an experiment with a model forest in an anechoic chamber. In the midfrequency range, dependent of the type of vegetation, there is often a small amplification of sound at the canopy height, relative to the situation without trees. Higher frequencies will be largely reduced when propagating through the vegetation. Foliage can be considered in this way as a low-pass filter [16].

The use of synthetic windscreens behind noise barriers to improve their performance was investigated with success in a wind tunnel experiment [17]. In this study, a traffic noise situation at scale was set up. Different configurations of single noise barriers and barriers on either side of a line source were tested, in combination with windscreens. The windscreens used in the experiment represent the wind reduction capacity of the canopy of trees. Measurements were performed at distances up to 10 times the barrier height behind the noise barrier in downwind direction, for a perpendicular incident wind. The wind velocities in the experiment were 6.4 m/s and 11 m/s, measured above the boundary layer in the wind tunnel. A full report on these experiments can be found in [17].

This paper reports on a full-scale in-situ experiment along a highway set up to resolve some uncertainties caused by the approximations made in the wind tunnel experiment. A site is found along a highway, where at some places behind a noise barrier a row of trees is present. A continuous measuring campaign was set up. Acoustical data and meteo data were collected simultaneously. The wind speeds used in the wind tunnel experiment were relatively high due to practical limitations of wind tunnels. In this full-scale experiment, all naturally occurring wind speeds will be present in the data set. The effect of wind directions, other than normal incidence in downwind direction, can be investigated. Since this field experiment uses real trees, the full influence of trees on sound propagation (not only the modification of wind profiles) will be observed.

However, the in-situ experiment also has some disadvantages. Only one configuration i.e. the present one is tested. The monitoring is performed at one fixed place behind the noise barrier. Since only two microphones are used (a first one behind the barrier without trees and a second one behind the noise barrier with trees), only the net effect of the trees can be investigated. In the full-scale experiment, disturbance by sources other than traffic may occur. However, since the traffic noise source is dominant, these disturbances will have a negligible influence on the average measured sound levels. The height of the top of the atmospheric boundary layer and the degree of turbulence in the vicinity of the barrier in the field experiment is not known, and will be quite variable. In the wind tunnel study on the other hand, every wind situation is reproducible and controllable. The height of the top of the boundary layer can be measured and adapted. These two types of experiment are complementary, and will reduce uncertainties inherent in both types of experiment.

This paper is organised as follows. First, the site were the field experiment is conducted is described in detail, as is the experimental set-up and the instrumentation used. Next, the experimental results obtained during the survey are presented. A statistical analysis of the data is performed. In a following chapter, the effect of the trees on the barrier performance in absence of wind is investigated. Finally, some conclusions are drawn.

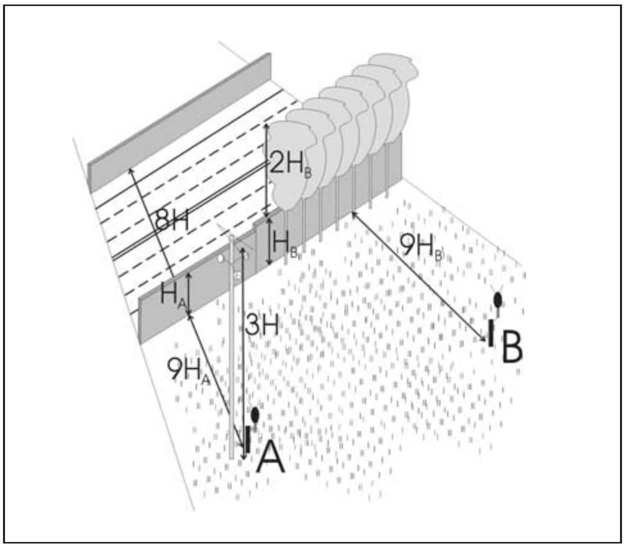

Figure 1. A sketch of the geometrical configuration of the in-situ experiment. The relevant distances and heights are shown, relative to the noise barrier height(s). H_A and H_B are the noise barrier heights near microphone positions A and B respectively, H is the average height of the noise barriers of part of the highway under investigation.

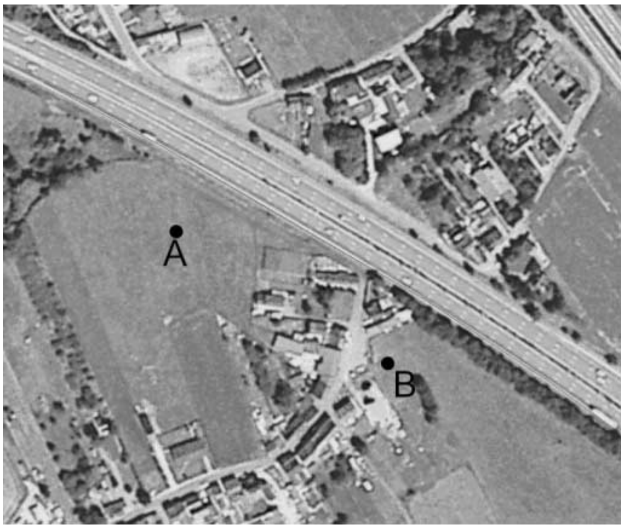

Figure 2. Ortho-photo indicating the positions of the two microphones.

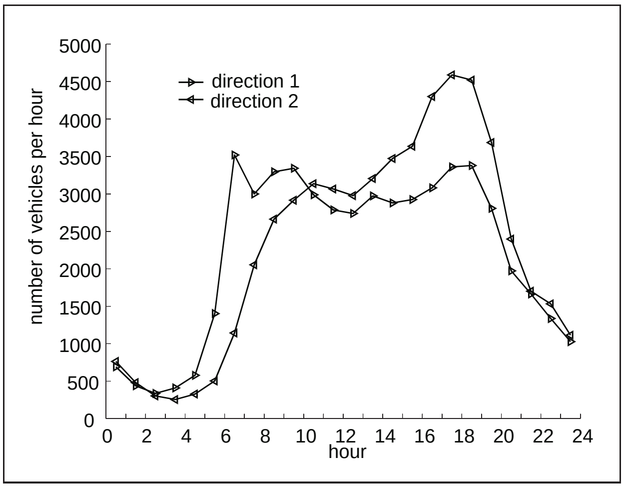

Figure 3. Number of vehicles per hour, averaged over all days of the week. The microphones are placed behind the noise barrier closest to the traffic lanes in direction 1.

2. Site description

The in-situ experiment is performed along a major highway (E40), near the city of Aalst, in Belgium. A sketch of the geometrical configuration of the in-situ experiment is given in Figure 1, together with the relevant distances relative to the noise barrier height. An ortho-photo of the part of the highway under investigation is shown in Figure 2. On both sides of the highway, a long concrete noise barrier is situated with an average height of 4 metres. The highway consisted of 3 traffic lanes and an emergency lane in both directions. A somewhat raised verge is situated in the middle of the highway. The distance between the noise barriers on either side of the road is about 32 metres. Measurepoint A is placed behind a part of the noise barrier where no trees are present. A single row of trees (and bushes) of about two times the barrier height is situated at measurepoint B. The distance between points A and B is about 100 metres. Simultaneous measurements are performed, together with meteo observations near point A. The noise barrier height at place A (3.75 m) is somewhat lower than at place B (4.25 m). The measurements will be performed at the same distances and heights relative to the noise barrier height at both places. The ground near point A is a sandy (grass)land. Measurepoint B is situated in a pasture with a uniform grass-covered soil.

Hourly countings of the number of vehicles (averaged over all the days of the week) near the noise barrier under investigation, measured by the Flemish government, are given in Figure 3. The traffic density on the part of the highway under investigation is sufficiently high to make traffic noise a continuous dominant contribution to the noise climate.

A wide variety of trees are present behind the barrier at site B. The monitoring is performed continuously and lasted from the middle of the summer (end of July 2001) till the middle of fall (end of October 2001). The trees were in (full) leaf during the experiment. A quick determination revealed that the population consisted in first place of ashes (Fraxini) and rowan trees (Sorbus aucuparia L.). Also some oaks (Querci) were present, together with small bushes.

The porosity of the canopy of trees at measurepoint B can only be estimated roughly. The porosity of the canopy of the trees must be seen as the unobstructed area for wind travelling through the canopy. A possible way to get an estimate of the porosity is using a digital photograph. With standard image processing software, a multicoloured detailed picture of the trees is reduced to a 1-bit per pixel image. The (white) air stays white, the green (leafs) and brown (branches and twigs) colours become black. The number of pixels in each category can be counted and in this way the porosity can easily be calculated. Using this procedure, the porosity of the canopy is estimated in the range from 13% till 15%. The porosity during windy conditions can however be higher due to the movement of branches and twigs and results in a larger unobstructed area. A second estimate of the porosity has been made at the end of October, and yielded 24%.

3. Experimental set-up and instrumentation

At point A and B 1/2-inch microphones (SIP95, 01dB) are used, together with the B&K outdoor set UA1404 (windscreen, shelter from rain and birdspikes). Calibration has been done with a pistonphone 4220 B&K. The microphones at both measure points are placed at 80% of the top of the barrier and at 9 times the barrier height behind it.

A-weighted total equivalent sound pressure levels over periods of one minute are recorded. Detailed spectra are measured with a frequency analyzer (2144 B&K, microphone 4188 B&K) at a few occasions during the experiment.

Since measurements of sound pressure levels will be performed in (high) wind speeds, special attention is paid to the estimation of noise levels generated by wind in the microphones. In an anechoic chamber, the noise in a microphone equipped with the outdoor set, generated by a steady, non-turbulent wind is measured. The microphone is placed on a rotating arm instead of creating a moving air stream. A similar experiment is described in [18]. In this way the additional creation of sound by e.g. a fan is avoided. With increasing angular velocity or wind speed, the noise (in dBA) increases approximately linearly with the logarithm of the wind speed (in m/s). The noise caused by turbulence in the incident wind itself may also contribute to increased sound pressure levels in the microphones [19]. No further attention is paid to this kind of wind-induced noise, since it can be considered being part of the natural ambient sound environment [20].

At a height of 12 metres, an anemometer and a windvane are placed. Statistical parameters concerning wind speed and wind direction are recorded over sample periods of 1 minute. The acquisition rate is 0.2 Hz. A pluviometer indicates the rainfall intensity. With decreasing wind speed, the wind direction becomes in general more variable. To exclude sample periods with a variable wind direction, some limits are set. The wind direction is measured with a resolution of 1 degree. To retain enough data, some deviation δ from the average wind directions $\overline{\theta}$ in a sample period relative to the wind direction under investigation θ_0 is tolerated, and defined as:

$$\left|\overline{\theta} - \theta_0\right| < \delta. \tag{1}$$

To exclude sample periods in which the wind direction is too variable, the sector in which 68% of the acquisitions fall (S) is also limited. This sector S is usually taken as two times the value of δ. If not stated differently, $\delta = 30$ and $S = 60$.

One has to take into account differences in soil coverage between points A and B when calculating the effect of the trees on the barrier performance with increasing wind speed. This can be done by comparing the differences in equivalent sound pressure levels between A and B in wind ($L_{Aeq,1\min}(i|A,u)$ and $L_{Aeq,1\min}(i|B,u)$) to the average difference in equivalent sound pressure level between both places in absence of wind ($L_{Aeq,1\min}(A,0)$ and $L_{Aeq,1\min}(B,0)$). So the net effect on noise barrier performance by the trees ($\mathrm{d}Lp(i|u)$) in wind for wind speed u at datapoint i is calculated as follows:

$$\mathrm{d}Lp(i|u) = \left[L_{Aeq,1\min}(i|A,u) - L_{Aeq,1\min}(i|B,u)\right] - \overline{L_{Aeq,1\min}(A,0) - L_{Aeq,1\min}(B,0)}. \tag{2}$$

At the height were the meteo data is measured, there will be some wind most of the time. As a consequence, a windless period is considered to be a period where the average wind speed is lower than 1 m/s. So $u = 0$ m/s must be read as $u < 1$ m/s.

4. Results and discussion

4.1. A row of trees behind a noise barrier in wind

4.1.1. Statistical parameters

The sample estimate of the population standard deviation for wind speed (class) u is defined as:

$$\sigma_{dLp}(u) = \sqrt{\sum_i^n \frac{\left(\mathrm{d}Lp(i|u) - \overline{\mathrm{d}Lp(u)}\right)^2}{n-1}}, \tag{3}$$

where n is the number of samples and $\overline{\mathrm{d}Lp(u)}$ is an estimate of the mean improvement by the trees based on the sample, for the wind speed (class) considered.

The standard error of the mean takes into account both population variance and sample size:

$$\sigma_{\overline{dLp}}(u) = \sqrt{\frac{\sigma^2_{dLp(u)}}{n}}. \tag{4}$$

Depending on the type of analysis, both quantities are used in this paper.

4.1.2. Results

About 112000 useful datapoints (combined acoustical data and meteo data) were collected during this measurement campaign. From this dataset, about 87000 datapoints were retained after removing rainy periods and disturbance by noise from other sources than traffic noise. The latter is based on the assumption that a large discrepancy in sound pressure levels ($>$ 7 dBA) between both measurement sites indicates the presence of a disturbing noise source. This threshold is (intuitively) set, taking into account that the improvement of the barrier performance in presence of the trees is well below that value. On the other hand, this threshold is large enough to allow some deviation in the sound levels as occurs in practice. During daytime, A-weighted total equivalent sound pressure levels were quite constant and were higher than 60 dBA most of the time. The minimum measured equivalent sound pressure level over periods of 1 minute at night was about 50 dBA.

Wind speed data is grouped in classes with a width of 1 m/s, for which the centre value of the classes is given for identification in the next plots.

The effect of the presence of trees behind a noise barrier in wind for wind directions orthogonal to the noise screen ($\delta = 30$, $S = 60$) is first analyzed, for both upwind and downwind sound propagation. The average net effect per wind speed class is shown in Figure 4. Even for low wind speeds, trees cause a net positive effect for downwind sound propagation. An almost linear relationship between wind speed and improvement of the barrier behaviour by trees is observed. The best-fitted curve based on the average improvement by a single row of trees (in leaf) with increasing wind speed can be described by the following equation (with $R^2 = 0.94$):

$$\mathrm{d}Lp = 0.40 + 0.27u, \tag{5}$$

with $\mathrm{d}Lp$ in dBA and u in m/s, measured at a height of 12 metres. For wind speeds higher than 10 m/s, an improvement of more than 3 dBA is obtained.

In a wind tunnel study at scale 1/20 [17], the net effect of the windscreens followed the same trend and was in the same order of magnitude. A direct comparison is however not possible due to differences in geometrical test set-up.

Upwind sound propagation is only slightly affected by the trees. For small wind speeds (< 4 m/s), there is a net negative effect since the upward refraction of sound by the wind is counteracted by the wind speed reduction by the trees. Higher wind speeds will not be reduced sufficiently to prevent upward refraction of sound. The best-fitted curve based on the average improvement by trees with increasing wind speed can be described by (with $R^2 = 0.96$):

$$\mathrm{d}Lp = -0.25 + 0.05u, \tag{6}$$

with $\mathrm{d}Lp$ in dBA and u in m/s, measured at a height of 12 metres.

The errorbars for upwind sound propagation are smaller since this wind direction occurred more often during the measurement campaign. It should be emphasised that for high wind speeds the results need to be interpreted with care due to the relatively small amount of data. A statistical analysis is performed to check whether the net improvement with increasing wind speed is significant (see section 4.1.3 statistical significance of the observations).

To be of practical use, the above mentioned effects should not be too sensitive on wind direction. Therefore it is investigated to what extent the wind direction may deviate from exact orthogonal direction to still observe the above mentioned effects. With increasing δ (and S) from orthogonal wind direction and for downwind sound propagation, the net effect of the trees decreases slightly (see Figure 5). For values of δ up to 45°, this decrease is only 0.5 dBA. For upwind sound propagation and for a wind direction orthogonal to the noise barrier, the negative net effect by trees is slightly more pronounced when δ is small (see Figure 6). For higher wind speeds, no significant differences can be observed, taking into account the limited amount of data when values of δ are small. So the net effect of trees behind noise barriers is not sensitive to deviations in wind direction.

With increasing wind speed, the standard error of the mean increases due to a decreasing amount of data, as shown in Figure 7 for downwind sound propagation and in

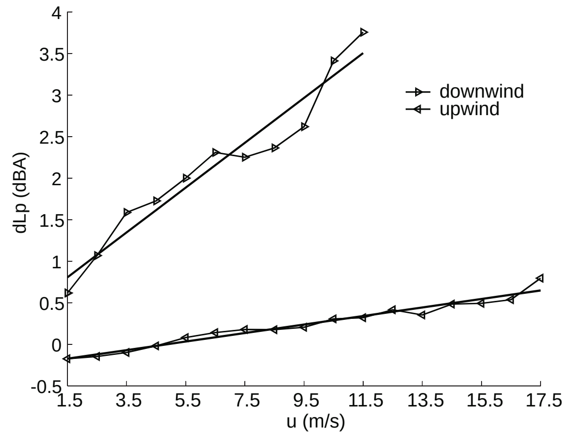

Figure 4. Average net efficiency of placing a row of trees behind a noise barrier with increasing wind speed. The effect of wind directions orthogonal to the noise barrier is shown, for both downwind and upwind sound propagation. The best-fitted linear curves on these data are given. Errorbars (standard error of mean) for each wind speed class are drawn.

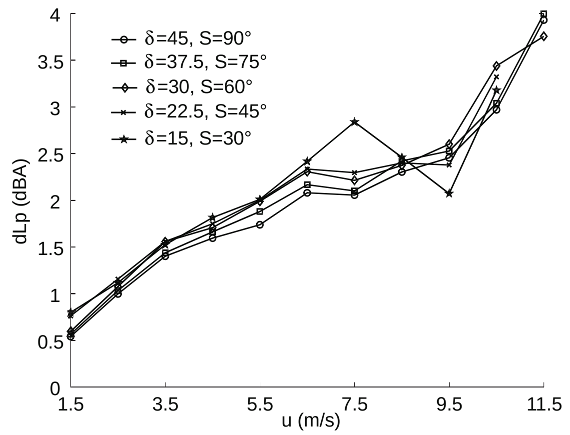

Figure 5. Average net efficiency of placing a row of trees behind a noise barrier with increasing wind speed, for a normal incident wind direction and downwind sound propagation. Deviations to the normal direction range from 15° to 45°.

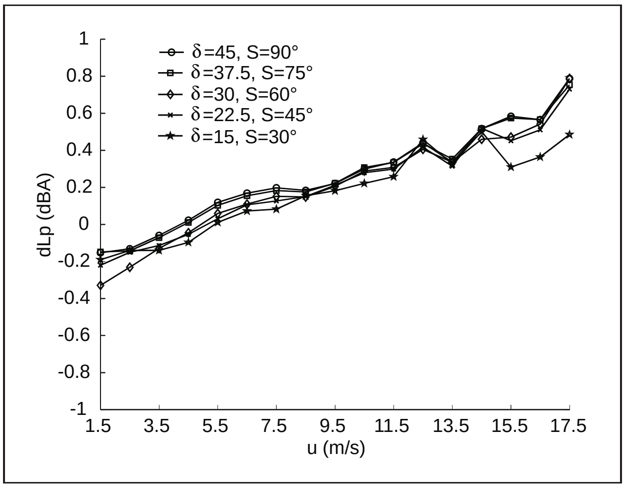

Figure 6. Average net efficiency of placing a row of trees behind a noise barrier with increasing wind speed, for a normal incident wind direction and upwind sound propagation. Deviations to the normal direction range from 15° to 45°.

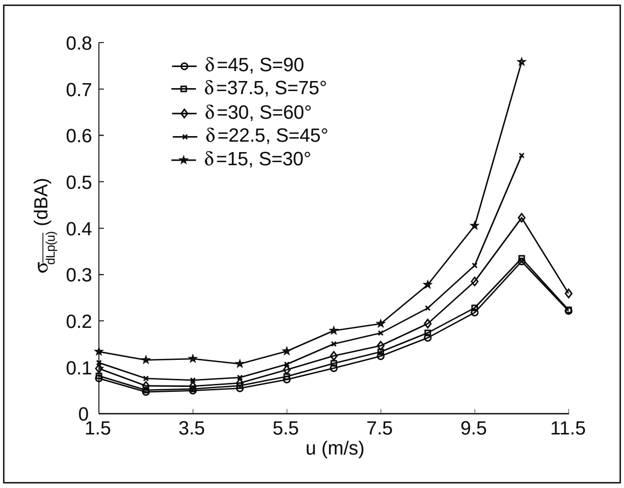

Figure 7. Standard error of mean on the efficiency of placing a row of trees behind a noise barrier with increasing wind speed, for a normal incident wind direction and downwind sound propagation. Deviations to the normal direction range from 15° to 45°.

Figure 8 for upwind sound propagation. This trend is not observed for very low wind speeds since wind direction in these classes is often too variable. As a result, many datapoints are excluded from the dataset for low wind speeds. When values of δ and S decrease, the standard error of the mean becomes larger. However, these values are still small, and give confidence in the results obtained.

Possible disturbing factors affecting the measurements in the presence of wind are noise generation in microphones and wind-induced vegetation noise. The remainder of this chapter is devoted to excluding these effects.

An estimation of the wind-induced microphone noise is obtained from the experiment with the rotating arm as described in section 3. The relationship between sound pressure levels generated by wind and wind velocity was investigated for the combination of microphone and outdoor equipment used in the monitoring campaign. The best-fitted linear regression line in the logarithm of the wind speed yields

$$L_{\text{wind}} = 56.2 \log u - 10.6, \tag{7}$$

with L_{wind} in dBA and u in m/s.

Wind speeds in the field experiment are measured at a height of 12 metres. The heights where the microphones are positioned are at most 3.4 metres. So wind speeds will be well below 10 m/s at the microphone positions. Since the measured $L_{Aeq,1\text{min}}$ values behind the screens are in all cases higher than 50 dBA, wind-induced noise in the microphone will not influence the measurements.

The effect of wind-induced vegetation noise is estimated to be small. In an experiment by Fegeant [9], emission peak levels very close to the edge of deciduous forests (oaks, aspens and birches) are measured. During the cited experiment it was found that sound pressure levels (in dB) are proportional to 30 times the logarithm of the wind speed (in m/s), for the wind speed interval between 0 and 10 m/s. This relationship will be used here to estimate

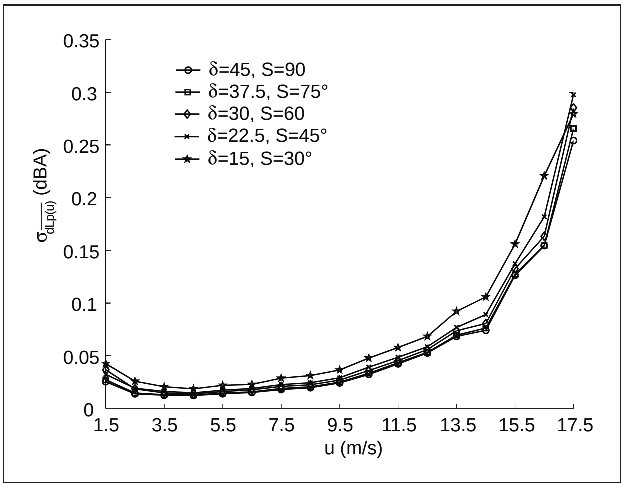

Figure 8. Standard error of mean on the efficiency of placing a row of trees behind a noise barrier with increasing wind speed, for a normal incident wind direction and upwind sound propagation. Deviations to the normal direction range from 15° to 45°.

the wind-induced vegetation noise as a function of wind speed. This relationship will however also be used outside the measurement interval of reference [9] making it only a rough, first estimation.

The 95th percentile value of our measurements is chosen to evaluate vegetation noise since it samples the periods where instantaneous traffic density is low and therefore noise from the trees is more likely to be observed, especially for high wind speeds.

In Figure 9, the measured 95th percentile (total) sound pressure levels (measured at place B) with increasing wind speed are shown. For high wind speeds, the wind-induced vegetation noise is expected to be completely responsible for the background noise. So the 95th percentile values will be the upper limit for the wind-induced vegetation noise. The trend line of Fegeant allows to estimate

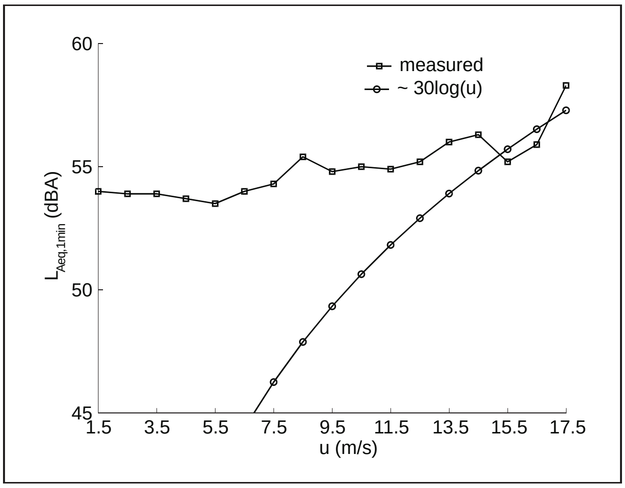

Figure 9. Estimation of wind-induced vegetation noise (dB) and measured "background noise" (dBA) with increasing wind speed.

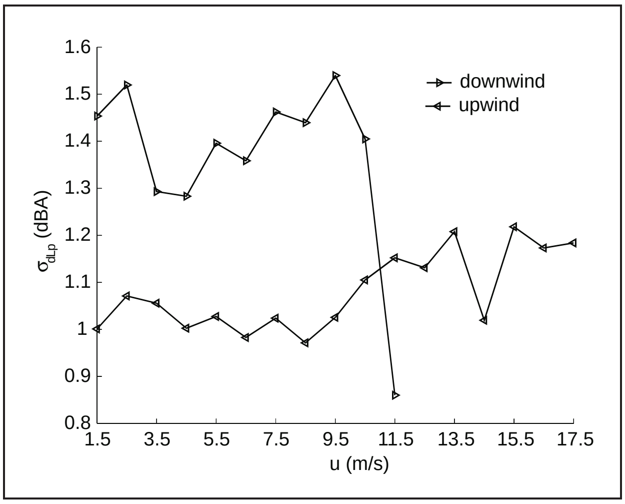

Figure 10. The standard deviation on the effect of trees per wind speed class for the wind directions under investigation.

sound pressure levels generated by trees in wind at lower wind speeds. These 95th percentile values in our experiment are expressed in dBA. Since wind-induced vegetation noise resulting from deciduous species has an emission peak near 4–5 kHz [9], one has to take into account differences up to 1 dB when comparing A-weighted with unweighted sound pressure levels as obtained in [9].

4.1.3. Statistical significance of observations

A statistical analysis is necessary since the improvement of the barrier performance by the trees ($\mathrm{d}Lp$) relative to the variation on these data is low. A second reason to perform a statistical analysis is the large difference in the amount of data per wind speed class.

An overview of the standard deviation on the net effect of trees per wind speed class is given in Figure 10. With increasing wind speed, measurements become more variable. The fluctuations in wind speed are expected to decrease as wind speed reduces, resulting in smaller fluctuations on measured sound pressure levels. This trend is not clearly observed since the number of observations in some classes is low. For downwind sound propagation the standard deviation is somewhat higher than for upwind sound propagation.

Table I. Probability that the net effect by trees for each combination of wind speed classes is equal for a normal incident wind direction and downwind sound propagation. In the headers of the columns and rows, the centre values (in m/s) of the wind speed classes (with a width of 1 m/s) are shown. An example: the chance that the average net effect of the trees for wind speeds between 3 m/s and 4 m/s is equal to the net effect of wind speeds between 4 and 5 m/s is 12%.

	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5
1.5		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.5			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.5				0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.5					0.01	0.00	0.00	0.00	0.00	0.00	0.00
5.5						0.04	0.11	0.07	0.02	0.00	0.00
6.5							0.74	0.80	0.26	0.01	0.00
7.5								0.61	0.19	0.00	0.00
8.5									0.41	0.01	0.00
9.5										0.09	0.02
10.5											0.55
11.5											

A variance analysis (see any textbook on statistics) has been performed with the statistical software package SPSS to see if the improvement of the performance of the noise barrier in wind by the trees is significant when comparing different wind speed classes. The data of most wind classes have equal variance. The condition requiring a normal distribution of the data is also fulfilled, and if not, the large amount of data in most wind speed classes will compensate. The least-significant-difference test has been used to check whether the averages of two data sets are equal. The null hypothesis states that the average improvement by the trees for two wind speed classes is equal. When this hypothesis can be rejected with a certainty of 95%, the data will be considered different. The probability that 2 wind speed classes have an equal mean is given in Table I for downwind sound propagation, in Table II for upwind sound propagation and in Table III for a wind direction parallel to the noise barrier. Combinations that can be considered equal (with an error of 5%) are placed in the grey-filled boxes.

For wind flowing parallel to the noise barrier, there is a high probability that the results for $\mathrm{d}Lp$ from different wind speed classes are equal. Only a small number of wind speed classes can be considered different. These results indicate that using relative measurements is justified in the experiment. For downwind and upwind sound propagation, the effects of the low wind speed classes are significantly different from each other, except for some neighbouring classes. For wind speeds higher than 10 m/s for upwind sound propagation, no distinction (with a certainty of 95%) between different wind speed classes can be made.

Table II. Probability that the net effect by trees for each combination of wind speed classes is equal for a normal incident wind direction and upwind sound propagation. In the headers of the columns and rows, the centre values (in m/s) of the wind speed classes (with a width of 1 m/s) are shown.

	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5
1.5		0.43	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.5			0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.5				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.5					0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.5						0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6.5							0.18	0.24	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
7.5								0.96	0.43	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.01
8.5									0.42	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.01
9.5										0.02	0.02	0.00	0.03	0.00	0.01	0.02	0.02
10.5											0.79	0.06	0.51	0.04	0.11	0.11	0.05
11.5												0.13	0.66	0.06	0.14	0.14	0.06
12.5													0.42	0.47	0.53	0.42	0.14
13.5														0.19	0.27	0.23	0.09
14.5															0.95	0.74	0.24
15.5																0.80	0.27
16.5																	0.37
17.5																	

Table III. Probability that the net effect by trees for each combination of wind speed classes is equal for a wind direction parallel to the noise barrier. In the headers of the columns and rows, the centre values (in m/s) of the wind speed classes (with a width of 1 m/s) are shown.

	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5
1.5		0.08	0.00	0.00	0.00	0.00	0.03	0.04	0.52	0.76	0.56
2.5			0.09	0.00	0.04	0.02	0.39	0.39	0.54	0.20	0.97
3.5				0.04	0.59	0.35	0.69	0.89	0.15	0.06	0.77
4.5					0.18	0.46	0.06	0.18	0.02	0.01	0.48
5.5						0.67	0.44	0.65	0.10	0.04	0.68
6.5							0.28	0.46	0.06	0.03	0.61
7.5								0.88	0.28	0.11	0.85
8.5									0.27	0.11	0.81
9.5										0.47	0.78
10.5											0.48
11.5											

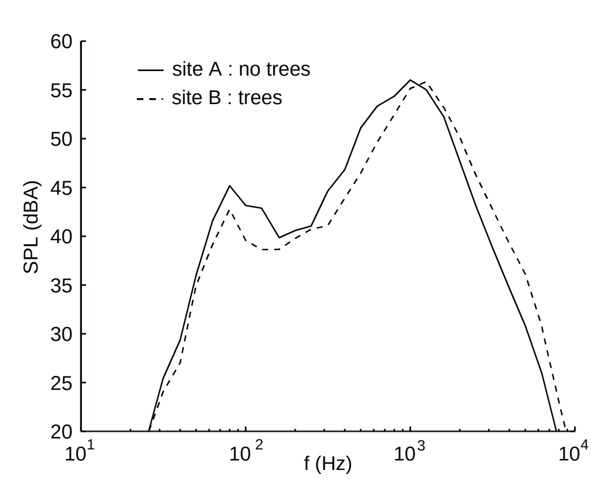

Figure 11. Spectra measured at A and B in a windless period.

4.2. The effect of a row of trees behind a noise barrier in absence of wind

Spectra at both sites are measured. The sound pressure levels in 1/3 octave bands, averaged out over a period of 1 minute in a windless period are given in Figure 11.

The acoustic source at location A and B is the same, since the microphones are only 100 metres apart along the direction of the highway. The section of the highway under investigation has the same road surface. Since both microphones are positioned at the same distance and height relative to the noise barrier height, differences in spectra between both places may only result from differences in ground coverage and from the presence of trees.

To separate out the effect of the trees (combined with the effect of the noise barrier), the ground effect is estimated. As a simple model for the diffraction of traffic noise over the noise barrier, a line source is placed on top of the barrier. The sound pressure as a result from the interaction between the direct and reflected waves can be calculated with the following formula:

$$p = \frac{\mathrm{e}^{\mathrm{i}kr_1}}{\sqrt{r_1}} + R\frac{\mathrm{e}^{\mathrm{i}kr_2}}{\sqrt{r_2}}, \tag{8}$$

where R is the plane wave reflection coefficient, k is the wavenumber, r_1 and r_2 are the direct and ground-reflected ray path lengths.

No specific measurements were done to quantify the ground impedance at the site under investigation. Both the Delany and Bazley model [21] and the 2-parameter model of Attenborough [22] were used to estimate ground impedance. Appropriate values for the non-acoustic parameters for the soils were found in literature[23, 24]. An effective flow resistivity of 400 kPa s/m^2 is used for the sandy soil at site A. For the pasture at site B, a value of 200 kPa s/m^2 is chosen. The 2-parameter model also needs

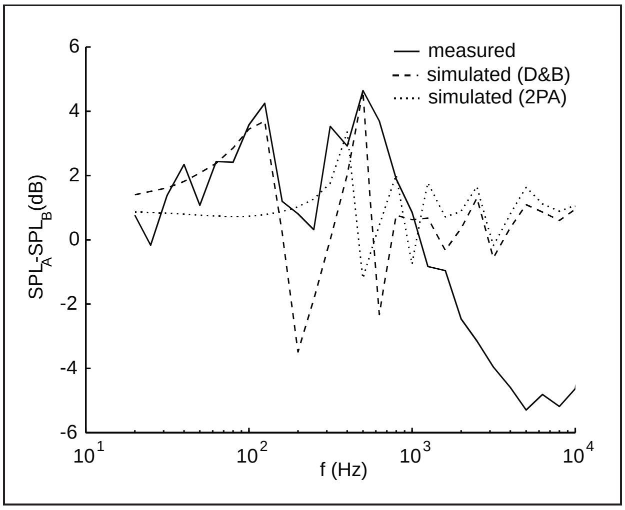

Figure 12. Measured difference in sound pressure levels between A and B for a windless situation, together with the simulated difference between both places accounting for the ground effect only. The ground impedance model of Delany and Bazley (D&B) and the 2-parameter model of Attenborough (2PA) are used.

an estimation of the effective layer thickness (0.02 m at site A, 0.025 m at site B).

The relative differences in sound pressure levels between place A and B as a function of frequency is given in Figure 12. By comparing the simulated ground effect with the measurements, the effect of the trees (combined with the noise barrier) can be estimated. For frequencies higher than 1–2 kHz, differences can not be explained anymore by the ground effect, and find their origin in scattering on the canopy of the trees. This is consistent with other experiments found in literature [6]. For frequencies near 10 kHz, an increased sound pressure level of about 6 dB is observed behind the noise barriers with trees [7, 11]. Both impedance models agree well for frequencies higher than 1 kHz. As to the Delany and Bazley model, trees have little influence for frequencies lower than 100 Hz. The 2-parameter model on the other hand already indicates some attenuation for these very low frequencies. Between 100 Hz and 1 kHz, the presence of trees results in an attenuation of sound independently of the impedance model used to eliminate differences in ground type. This typical increased attenuation in the midfrequency range and a decreased attenuation at higher frequencies, resulting from the placement of a row of trees behind a barrier, is consistent with the measurements of Schuller *et al.* [6, 7].

It is clear that trees can have a positive or negative effect depending on the spectrum of the source (in absence of wind). However, the contribution from the increased scattering of sound in the high frequency range to the total A-weighted sound pressure levels will be small for traffic noise. Martens stated that the total sound pressure levels resulting from traffic noise will not be changed when propagation through rows of trees: the frequency of the dominant peaks is too low to be amplified or weakened [16]. Therefore placing trees behind noise barriers along highways will not result in a significantly lower attenuation in a windless situation.

5. Conclusion

This paper reports on a field experiment set up to study the feasibility of increasing noise barrier performance in downwind conditions by modifying wind profiles with trees used as windbreaks. Already for low wind speeds a statistical significant (but small) decrease of the reduction of barrier insertion loss for downwind sound propagation is observed. With increasing wind velocity, this effect increases. For wind speeds between 6 m/s and 7 m/s, measured with an anemometer at a height of 12 m, an increase in insertion loss of more than 2 dBA is obtained. For wind speeds between 11 m/s and 12 m/s, the use of trees behind a barrier results in an improvement of almost 4 dBA. For wind direction up to 45° away from the downwind direction, the effect is only 0.5 dBA lower. So the net effect of trees behind barriers is not very sensitive to deviations in wind direction. For upwind sound propagation, the positive effect of the wind (upward refraction) is neutralised for low wind speeds. This results in a slightly worse situation (maximum -0.5 dBA). For higher wind speeds the use of trees has a small positive effect (< 1 dBA). An analysis of variance revealed that for downwind and upwind sound propagation for an orthogonal incident wind direction, only for high wind speeds and for some neighbouring wind speed classes, differences in net improvement were not significant with a certainty of 95%.

The presence of a row of trees behind a noise barrier results in increased sound pressure levels at high frequencies due to scattering on the canopy of the trees. Typical traffic noise however produces only a small amount of acoustic energy in the high frequency range relative to low frequency bands. So the contribution of this scattered sound to the total A-weighted sound pressure levels is small. For highways with dense traffic, wind-induced vegetation noise is also proven to be of minor importance.

The results obtained in this field trial follow the same trends as in the previously conducted wind tunnel experiment [17]. This increases confidence in critical approximations made in the wind tunnel experiment such as the representation of trees by woven polyester windbreaks. This field experiment confirms the positive effect of windbreaks (trees) on the performance of noise barriers in downwind situations and allows to conclude that a combination of noise barriers with trees and bushes should be considered in future applications. This work should therefore be regarded as a proof of concept and further research may be required to optimise some of the parameters (porosity of the windbreaks, heights, . . .) involved and to estimate their sensitivity.

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