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Title

Measured light vehicle noise reduction by hedges

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Abstract
The acoustical effects of hedges result from a combination of physical noise reduction and their influences on perception. This study investigates the physical noise reduction so as to enable estimation of its relative importance. Different in-situ methods have been used to measure noise shielding by hedges. These include a statistical pass-by experiment where the real insertion loss of a hedge could be measured, three controlled pass-by experiments using a reference microphone at close distance, and transmission loss measurements using a point source. Thick dense hedges are found to provide only a small total A-weighted light vehicle noise reduction at low speeds. Measured insertion losses range from 1.1 dBA to 3.6 dBA. The higher noise reductions are found to be associated with an increased ground effect.

keywords : road traffic noise; vegetation; outdoor sound propagation

1. Introduction

A hedge (or hedgerow) is a row of closely planted shrubs or low-growing trees. Hedges are most often used as a way of defining land property boundaries or as windbreaks. Hedges may consist of single species or a mixture of species. A wide variety of shrubs and trees, both coniferous and deciduous species, can be used to form hedges, adding to their wide applicability.

When looking at the acoustical effects of hedges, two aspects can be distinguished.

On the one hand, leafs, twigs, branches and trunks can provide physical noise shielding. Noise reduction is obtained primarily by multiple scattering processes, causing sound energy to diverge away from a straight propagation path between source and receiver. Damped leaf [1][2] and branch [3] vibrations, and general visco-thermal absorption effects at leaf surfaces, may contribute to the acoustic shielding as well. In addition, ground effects can be enhanced [4] due to the presence of a highly porous decomposing plant litter layer above the soil in which the hedge is planted. Although hedges are typically of finite depth, depending on the source-receiver distance and source and receiver heights, the specular soil reflection spot could be located in the zone below the hedge. Furthermore, hedges may have an important influence on the local wind profile. As a result, refraction of sound by wind in the direct vicinity of the hedge might be altered.

The widely used ISO 9613-2 model [5], for predicting outdoor sound propagation, includes a correction for shielding by vegetation. The only predictor in this ray-tracing based model is the distance travelled through the vegetation under worst case i.e. downward-refracting conditions. Only when the (slightly bent) sound ray interacts for at least 10 m with the vegetation, a noise attenuation of 1 dB is predicted for the 1 kHz octave band. When the interaction path length exceeds 20 m, 0.06 dB/m is proposed. However, no distinction is made between the type of vegetation (e.g. a strip of forest, a shrub zone, or hedges). This means that for a common hedge thickness of 1 m or 2 m, a zero effect is predicted, which is however doubtful. Other vegetation related parameters that have been shown to play a role like biomass density [6][7], leaf size [6][7][8], and leaf orientation [9] are not considered in this engineering model. The importance of these parameters in case of hedges remains, however, a question.

On the other hand, it is known that hedges have a strong impact on the visual setting. The audio-visual interaction, in general, could be important when assessing e.g. loudness or noise annoyance. Two main effects play a role relating to hedges, namely visibility of the source and the mere presence of green elements.

Aylor [10] concluded that as long as the source of sound can be seen, reduction in the visibility of the source is accompanied by a reduction in apparent loudness. However, when the source is completely obscured by a barrier, this effect reverses, i.e. the apparent loudness increases [10]. Similar conclusions were found by Watts et al. [11]. Vegetation, (fully) visually screening the road traffic, seemed to increase noisiness compared to transparent vegetation. The latter was explained by erroneous expectations by the test subjects [11]. Visual attractiveness of vegetation did not appear to be relevant in the study of Watts et al. [11]. Hedges that made passing vehicles invisible resulted in significantly less noise annoyance [12]. At higher noise levels this effect seemed to be even more pronounced [12].

In many other experiments, visible vegetation has been shown to have a positive influence on noise perception. Attractiveness of courtyards, strongly linked to the presence of vegetation, was shown to be an important modifier when benefiting from the quiet side effect related to road traffic noise [13]. Non-human sounds like road traffic noise were perceived as less unpleasant and less stressful when the visual setting was less urban or greener [14]. Visible greenery was shown to significantly reduce noise annoyance at home [15]. Natural features present in the visual field were shown to be relevant predictors when assessing tranquility [16]. In another study [17], ninety percent of the subjects believed that hedges strongly reduce noise levels, most likely by implicitly including perceptional aspects in their answers. In this same experiment, view on hedges and vegetation resulted in clearly different electroencephalograms (EEG) at the subjects when submersed in a road traffic noise dominated soundscape, compared to subjects with a (full) view on the traffic noise source. It was therefore concluded that landscape plants provide excess noise attenuation effects through the subjects‘ emotional processing [17].

The acoustical effect of hedges is therefore expected to be a combination of both physical and perceptional aspects. However, their relative importance is unknown. To contribute to this discussion, the physical noise shielding of hedges is assessed by measurements in this paper. To the authors' knowledge no systematic, scientific studies have been reported yet on this subject.

2. Measurement approaches

Measurements near hedges have been performed independently by different researchers, employing various measurement methodologies. As the focus is on road traffic noise, real-life road traffic noise cases were included in this study. The measurements were performed near rather dense hedges, with thicknesses ranging from 1.3 to 2.5 m, having heights from 1.6 m to 4 m. An overview of the measurement approaches and basic hedge information is given in Table 1.

Four measurement methodologies have been applied. In a statistical pass-by experiment, a sample of real traffic passing in front of the microphone(s) was taken. These measurements were performed at the same location before and after the removal of a hedge. Variability in source emission cannot be controlled as different cars (having their own sound radiation pattern) drive by in presence or absence of the hedge. However, a statistically sufficient number of vehicles was measured in each case, so that the effect of single cars loose their importance in the final result. Exact vehicle speed was measured. Clearly, such measurements give an overall picture of what can be expected in realistic traffic conditions.

In the controlled pass-by experiments, the same cars drove along both the microphone located behind the hedge, and the reference microphone. Only passages where the speed of the cars was constant, and the acoustic measurements were undisturbed by other noise sources, were retained. This approach should lead to limited variability in source emission characteristics.

In case of transmission loss measurements, there is full control over the noise source. Although a point source is a well-defined concept, realistic road traffic noise emission patterns are more complex [18].

The statistical pass-by experiment at Wolfratshausen is a true insertion loss (IL) measurement. Microphone positioning was exactly the same in presence and absence of the hedge. In between these measurements, the hedge was removed. The controlled pass-by experiments in Grenoble and Milton-Keynes involved a reference microphone, positioned at the same distance relative to the road as the microphone positioned behind the hedge. Both microphones were positioned at close distance to ensure the same noise emission characteristics of the passing vehicle.

In these measurements, the ground-reflected sound path will interfere with the direct sound path transmitted through the hedge. Such interference effects are strongly dependent on the exact source-receiver geometry. For the measurements at Wolfratshausen, the ground effect should cancel out due to the same microphone positioning in absence and presence of the hedge. A low wall being present in both situations would further limit the importance of soil reflections. For the transmission loss measurements in Derbyshire, the microphones at the source side and opposite side, relative to the hedge, were placed at the same distance relative to the point source, and at the same height. When subtracting these sound level spectra, the ground effect should cancel out, as long as the soil is uniform. In the controlled pass-by experiments at Grenoble and Milton-Keynes, different ground surfaces (and impedance discontinuities) were present near the reference and hedge microphone. The reference measurement at Ilkley was performed over asphalt ground yielding a different ground effect.

Table 1. Some basic properties of the different hedge measurements performed.

type of experiment	**noise source**	**ground effect included in measurements?**	**spectral data?**	**hedge species**	**hedge thickness (m)**	**hedge height (m)**	**Location**	**month of measurement**
statistical pass-by	road traffic noise	partly cancelled	no	Spruce (*Picea sp.*)	2	4	Wolfratshausen, Germany	October and November
controlled pass-by	road traffic noise	yes	yes	Laurustinus (*Viburnum tinus)*	1.8	2.6	Grenoble, France	February
				Hawthorn (*Crataegus monogyna*)	1.9	1.6	Milton-Keynes, UK 1	October
				Horn been (*Carpinus betulus*)	2	1.9	Milton-Keynes, UK 2	October
transmission loss	point source	yes	yes	Yew (*Taxus baccata*)	1.6	2.2	Derbyshire, UK 1	September
				Beech (*Fagus sylvatica*) 1	2.2	3.9	Derbyshire, UK 2	September
				Beech (*Fagus sylvatica*) 2	1.7	2.6	Ilkley, UK 1	August
				Laurel (*Prunus laurocerasus*)	2.5	2.7	Ilkley, UK 2	August

3. Cases and data processing

Plan views of the microphone positioning and sources at all measurement sites are schematically depicted in Fig. 1, including relevant distances and dimensions.

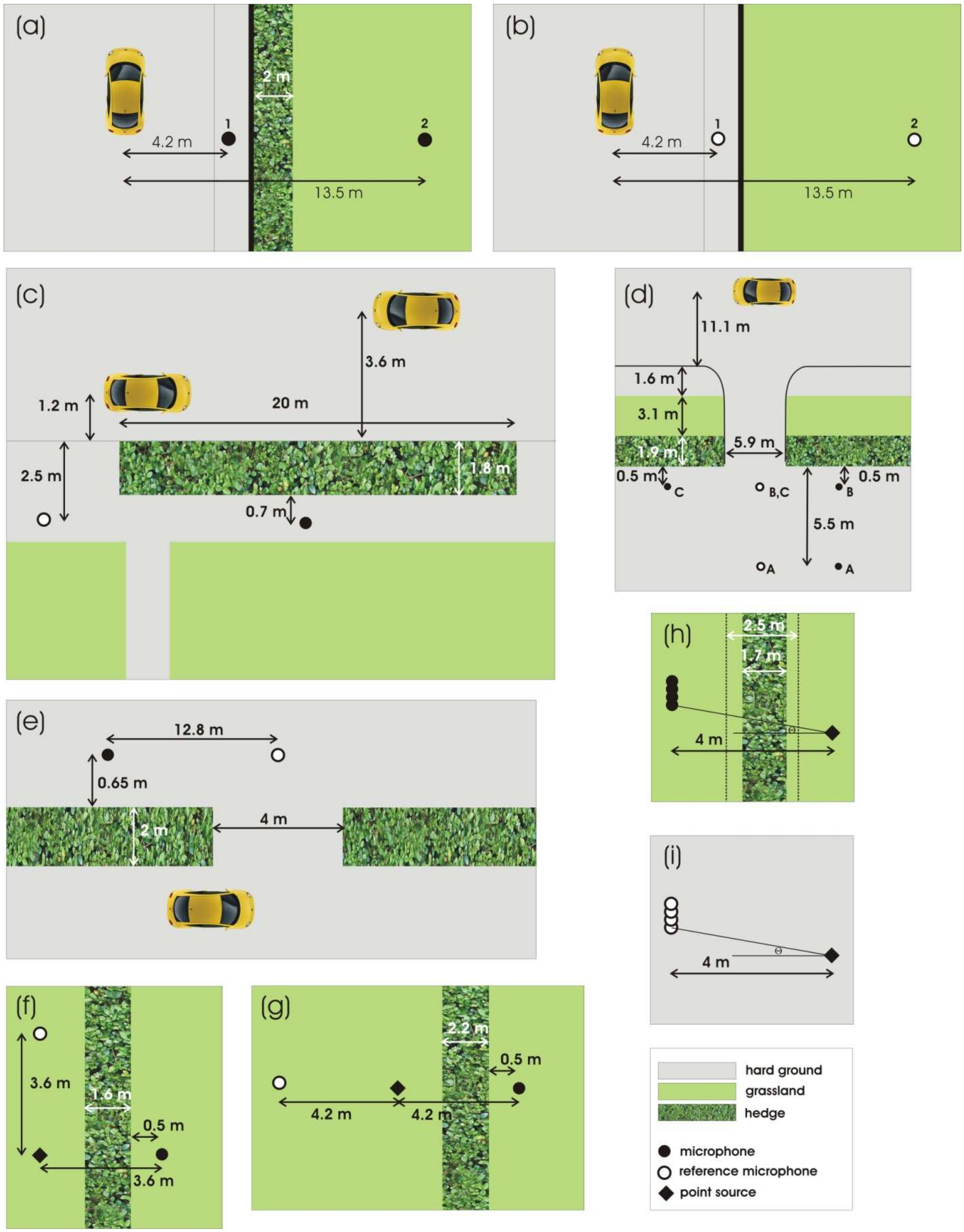

Fig. 1. Schematic plan views of the microphone positioning and source(s), relative to the hedge location, at all measurement sites, including relevant distances. (a) is the hedge measurement at Wolfratshausen, Germany, while (b) is its reference case. (c) is the measurement site in Grenoble, France. (d) and (e) are the two hedges measured at Milton Keynes, UK. (f) and (g) illustrate the point source measurements

conducted at Derbyshire, UK. (h) represents the two hedge measurement at Ilkley; (i) is its reference measurement setup. The angle of incidence relative to the microphone array Θ is defined in (h) and (i). [Color online]

3.1. Wolfratshausen, Germany

The hedge under study was located in front of a dwelling along an urban main road. Close-by, a road crossing with traffic lights was present. Initially, a low 1.2-m high brick wall was present in combination with a 4-m high hedge (see Fig. 2). In the second part of this experiment, the hedge was removed allowing direct insertion loss measurements. The brick wall was still present.

Statistical pass-by (SPB) measurements according to ISO 11 819-1 [18] were performed. The maximum pass-by levels $L_{AF,max}$ of single cars were measured with 4 microphones. Microphone position 1 (see Fig. 1 (a) and (b)), in front of the hedge (at a height of 0.6 m above the road surface, and at 4.2 m from the middle of the near lane), was used to correct for the different air temperatures during both parts of the experiment, affecting the noise generated by the interaction between tires and road surface (stone mastic asphalt, with a maximum aggregate size of 11 mm, SMA 11 S). A temperature correction coefficient of 0.04 dB/°C was found to be appropriate based on these measurements. The air temperature during the measurements in presence of the hedge was 4 °C, in absence of the hedge 6 °C.

The other 3 microphones (microphone position 2, see Fig. 1 (a) and (b)) were mounted on top of each other at heights of 0.8 m, 1.2 m and 5 m, at a lateral distance of 13.5 m from the middle of the near lane. The microphone heights of 1.2 m and 5.0 m were chosen according to the specifications given in ISO 11 819-1 [18]. The velocity of each passing car was recorded using a radar system.

Only the pass-by noise of single passenger cars on the near lane was retained. Measurements were considered valid when the sound pressure level before and after pass-by was at least 6 dB below $L_{AF,max}$ [18] and in absence of traffic on the opposite lane. The average pass-by velocities ranged from 30 to 55 km/h, with an average near 45 km/h.

Fig. 2. Photograph showing the hedge under study for the statistical pass-by measurements at Wolfratshausen, Germany (see Fig. 1 (a) and (b)). [Color online]

3.2. Grenoble, France

The hedge under study was located along a street in the city centre which could be categorized as quiet. The hedge was 2.60 m high, 1.80 m thick and 20 m long (see Fig. 1 (c)). Measurements were carried out while the outdoor temperature was -5°C. A first microphone was positioned behind the hedge, at a height of 1.5 m, at about 0.7 m from the border of the hedge, and at 2.5 m from the street edge (see Fig. 1 (c) and Fig. 3). The second microphone was located directly beside the hedge, at the same distance relative to the edge of the road. Measurements were logged as 1-s integrated equivalent sound pressure levels. Light vehicles, as present in the street, were used.

The controlled pass-by measurements were supervised to ensure the absence of other sounds except for the passing car, to guarantee single pass-by's of light vehicles and to select only cars driving at constant speed to have approximately the same noise emission near both microphones. In total, 10 individual passages were retained, including vehicles driving in both directions. Estimated vehicle speeds ranged from 20 km/h to 40 km/h, with an average near 30 km/h.

Fig. 3. Photographs showing microphone positioning and hedge details for the controlled pass-by experiment at Grenoble, France (see Fig. 1 (c)). [Color online]

3.3. Milton-Keynes, UK

Two controlled pass-by experiments were performed, during each of which the reference microphones were positioned opposite a gap in a long straight hedge parallel to a road.

The times at which cars were passing the hedges, or the gaps in the hedges, were determined using time-domain audio signals from the sound peaks caused by vehicles crossing cables laid on the ground. The times between successive front and back wheel crossings of the cables were used to measure the speeds of the cars. The time domain signals were windowed accordingly before taking a Fast Fourier Transform of these sections of time domain signals, and were further processed to 1/3-octave band levels. The resulting spectra thus represent energy averages over the passage times which were typically less than a second.

In a first experiment (see Fig. 1 (d) and Fig. 4), two distances behind the 1.9-m thick hedge were considered (position A, at 5.5 m behind the hedge; and position B, at 0.5 m behind the hedge). In addition, the measurement at close distance behind the hedge was repeated, but now on the other side of the gap in the hedge (position C, also at 0.5 m behind the hedge). The reference microphones were placed each time at the same distance normal to the road and above an acoustically-hard surface. The microphones were positioned at a height of 1 m above the ground surface. A hard asphalt ground was present both behind and in front of the hedge. There was a 3.1-m deep piece of grassland at the road side near the part bordered by the hedge, together with a 1.6-m deep foot path. The same car was used for 6 pass-bys.

In a similar, second experiment (see Fig. 1 (e) and Fig. 5), different cars passed another 2-m thick hedge. The microphones were positioned at 0.65 m behind the hedge. Asphalt ground was present at all locations now, except for the zone below the hedge. The microphone heights were 1 m as well.

In these experiments, vehicle speeds ranged from 22 km/h to 49 km/h. The average vehicle speed was 34 km/h.

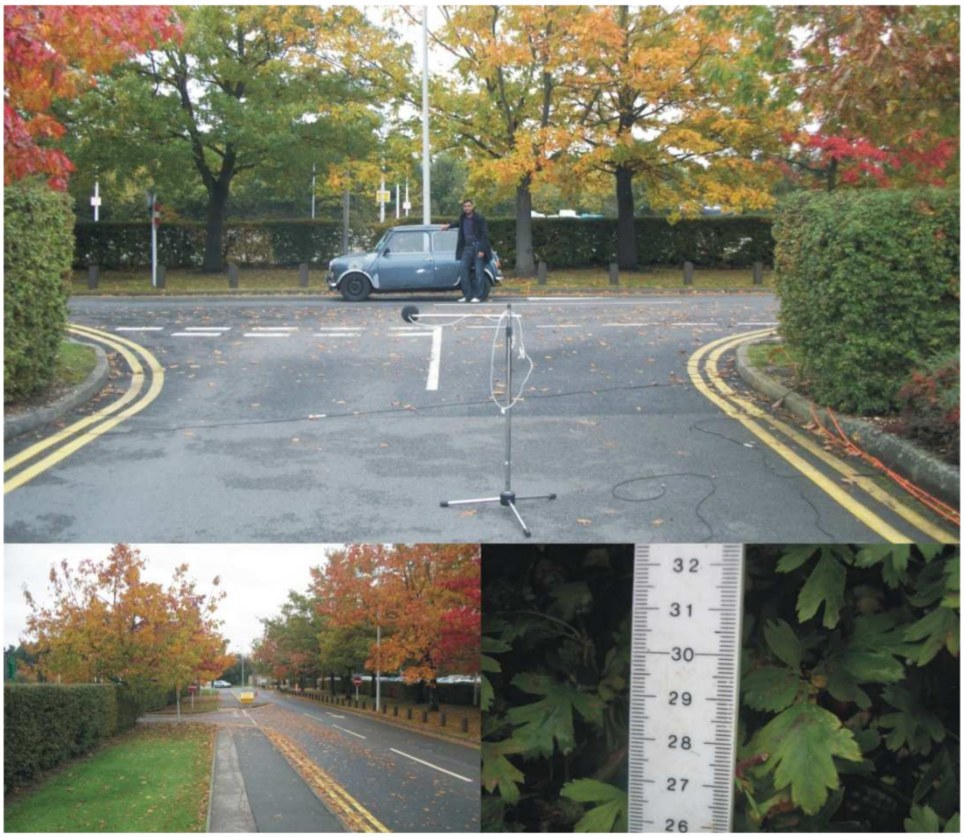

Fig. 4. Photographs of the measurement location near hedge 1 (see Fig. 1 (d)) at Milton-Keynes, UK. [Color online]

Fig. 5. Photograph of the measurement location near hedge 2 (see Fig. 1 (e)) at Milton-Keynes, UK. [Color online]

3.4. Derbyshire, UK

Two hedges were considered for the transmission loss measurements using a point source. An omni-directional dodecahedron loudspeaker was used as noise source, and the level differences at various locations near the hedges were measured in 1/3-octave bands. The loudspeaker produced white noise at a high signal-to-noise ratio and measurements were repeated 3 times, at different emission levels. The source was located at a distance of 1.5 m from the hedges. The source and the microphone at the opposite side of the hedge were located in a plane, orthogonal to the length axis of the hedge (see Figs. 1 (f) and (g)). The reference microphones were located at the source side of the hedge, at the same distance from the source as the microphone at the other side of the hedge. The source and all receivers were positioned at a height of 1.5 m above the ground. As long as the soil is uniform the ground effects should cancel out when subtracting sound level spectra. Grass-covered ground was present at both sides of the hedges. The distance between the microphone at the non-directly exposed side and the hedge was 0.5 m.

3.5. Ilkley, UK

Transmission losses due to a laurel and beech hedge in Ilkley were measured (see Fig. 1 (h)). The reference measurements were performed over asphalt ground with the same-source receiver setup, in absence of reflecting objects (not in the vicinity of the hedge), as illustrated in Fig. 1 (i).

The in-situ experimental setup consisted of an array of four microphones and a speaker. The four microphones used in the array were mounted horizontally 100 mm apart from each other on a steel bar with a diameter of 15 mm, and at a height of 1.5 m above the ground. The centre of the sound source was positioned at 1.5 m above the ground as well.

In these experiments, a sinusoidal sweep was emitted containing the sound frequencies in between the lower limit of the 100-Hz 1/3-octave band and upper limit of the 10000-Hz 1/3-octave band, with a duration of 10 seconds. Each measurement was repeated eight times. The recorded signals were deconvolved to obtain the sound pressure impulse response. The impulse responses recorded on each of the four microphones were filtered in 1/3-octave bands and averaged to determine the root mean square pressure which was then used to calculate the sound pressure level. The use of impulse responses and averaging was needed to ensure a very high signal-to-noise-ratio in the presence of various unrelated sources of background noise. Measurements were performed at azimuthal angles between 0 and 22 degrees by moving the microphone array. The same methodology was used in case of the reference measurements in absence of the hedge in order to calculate the hedge insertion loss.

4. Results

4.1. Wolfratshausen, Germany

Results from the measurements in Wolfratshausen, Germany, are depicted in Fig. 6 and Table 2. The scatter plot of measured vehicle speed as a function of measured maximum levels during pass-by of single vehicles, using FAST time-weighting ($L_{AF,max}$), is shown. The sound pressure levels are corrected to a reference air temperature of 20 °C. In contrast to the other methodologies applied in this study, there is no control over the noise source, and therefore statistical inference is needed to quantify the shielding provided by the hedge. Linear regression, expressing level as a function of the logarithm of the vehicle speed, is commonly used in statistical pass-by measurements. The other receiver heights (not shown) give similar curves. These regression curves are used to calculate the insertion loss of the hedges at 3 vehicles speeds, and this data is summarized in Table 2. The hedge yields modest insertion losses, and there is a slightly larger insertion loss at higher receiver positions. This is plausible as there is a larger part of the propagation path interacting with the hedge at higher receivers. The measured losses are statistically significantly different from zero at all receiver heights and vehicle speeds. The hedge seems to perform slightly better at low vehicle speeds, although this finding is not statistically significant.

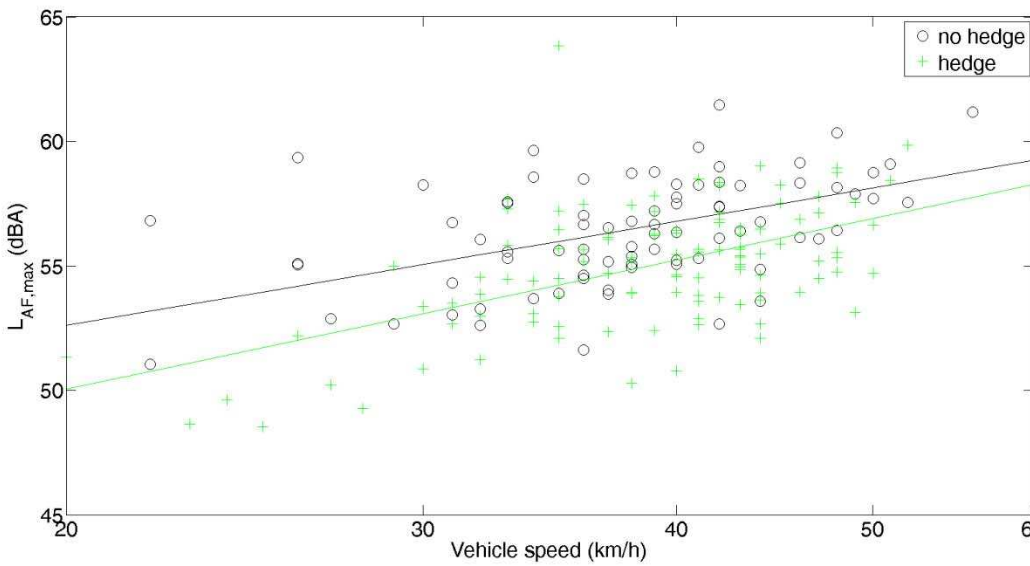

Fig. 6. Scatter plots of measured vehicle speed for single passing vehicles vs measured $L_{AF,max}$ (microphone position 2, at a height of 1.2 m) in presence (83 passages) and absence of the hedge (111 passages). The best fitted straight lines are shown. Case : Wolfratshausen, Germany. [Color online]

Table 2. Predicted hedge insertion losses at 3 vehicle speeds, based on the regression model for $L_{AF,max}$, derived from the statistical pass-by experiments. The values in between brackets are the 95% confidence intervals, assuming normal distribution of the absolute sound pressure levels, and assuming a t-distribution for the difference in levels. Case : Wolfratshausen, Germany.

	30 km/h			40 km/h			50 km/h		
microphone position	no hedge (dBA)	hedge (dBA)	IL (dBA)	no hedge (dBA)	hedge (dBA)	IL (dBA)	no hedge (dBA)	hedge (dBA)	IL (dBA)
2 (h=0.8 m)	53.0 (52.6-53.4)	51.4 (51.1-51.8)	1.6(1.1-2.1)	54.7 (54.5-55.0)	53.3 (53.1-53.5)	1.4(1.1-1.7)	55.9 (55.5-56.3)	54.8 (54.5-55.2)	1.1 (0.6-1.6)
2 (h=1.2 m)	55.1 (54.8-55.5)	53.1 (52.8-53.5)	2.0(1.6-2.4)	56.8 (56.6-57.0)	55.2 (55.0-55.4)	1.6(1.4-1.8)	58.1 (57.7-58.5)	56.9 (56.6-57.3)	1.2 (0.7-1.7)
2 (h=5.0 m)	59.4 (59.0-59.8)	57.2 (56.9-57.6)	2.2(1.7-2.7)	61.0 (60.8-61.3)	59.3 (59.1-59.5)	1.7(1.4-2.0)	62.3 (61.9-62.7)	60.9 (60.6-61.3)	1.4 (0.9-1.9)

4.2. Grenoble, France

The spectral insertion loss over the 10 passages is shown by means of the box plots in Fig. 7. In addition, the distribution of the total A-weighted road traffic noise reduction based on these individual passages is shown as well. The maximum measured insertion loss is 2.4 dBA, while the minimum insertion loss is negative (-0.9 dBA). The median on the data is 1.2 dBA. The signal-to-noise ratio at all 1/3-octave bands considered exceeds 10 dB. In this analysis, the maximum 1-s equivalent sound pressure levels during the pass-bys were used.

The spectral insertion losses show a large variation at low frequencies and a consistent positive ground effect near 200 Hz-500 Hz, due to the difference between a soft soil below the hedge and a hard ground near the reference microphone position. Possibly, the soft soil effect could have been reduced due to the presence of temperatures below 0° C at the moment of the measurements. An important influence here is the soil moisture content, for which data is lacking.

The large variation at low frequencies is caused by shifts in the zone where sound interacts with the ground caused by the presence of cars in both the far or close lane. In addition, the typical engine noise radiation patterns and directivity of individual cars adds to this variation. Above 2 kHz, foliage scattering effects become dominant, and a rather consistent behavior is observed. At 4 kHz, the median IL is near 4 dB.

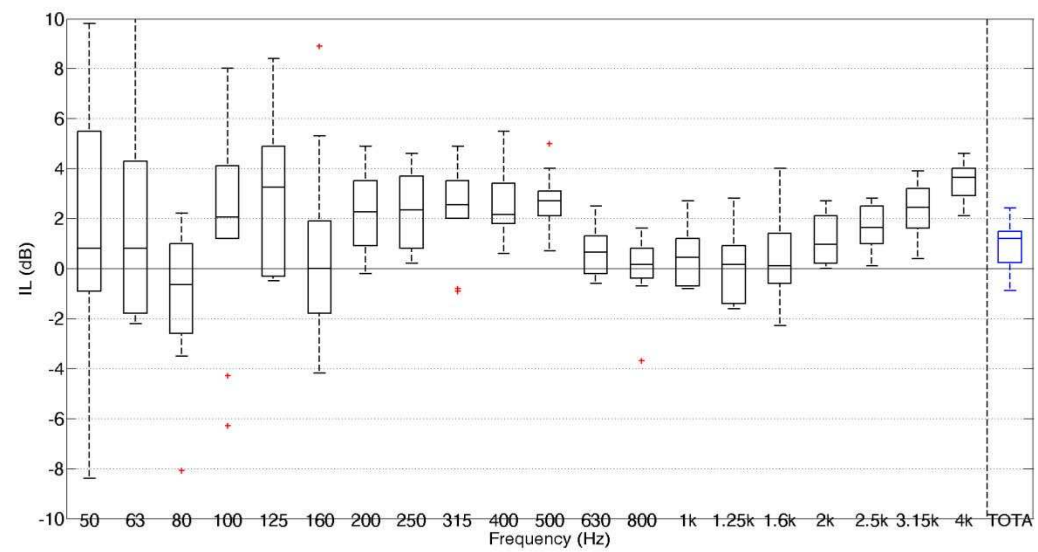

Fig. 7. Boxplots showing the insertion losses per 1/3-octave band, together with the total A-weighted insertion loss of single passing cars. The (middle) horizontal line in the box indicates the median of the data. The box is closed by the first and third quartile. The whiskers extend to 1.5 times the interquartile distance above the maximum value inside the box, and to 1.5 times the interquartile distance below the minimum value inside the box. Data points that fall outside these limits are indicated with the plus-signs. Case : Grenoble, France. [Color online]

4.3. Milton-Keynes, UK

4.3.1. Measurement results

The spectral insertion losses at the 3 microphone positions near the first hedge, and those measured near the second hedge, are depicted in Fig. 8. At position A (see Fig. 1 (d)), 5 m further from the hedge than position B, a larger (positive) ground effect was measured. At the highest frequencies considered, the close positioning behind the hedge gave larger insertion losses. The presence of a few meters of grassland (see Fig. 1 (d)) could be responsible for the increased soil effect when comparing to the measurements near hedge 2. The latter, however, seems more effective in reducing high frequency sound. Above 4 kHz, 5 dB insertion loss was measured. Near position C (hedge 1), smaller insertion losses at high frequencies are observed. A plausible reason for this finding is a smaller biomass density at this specific location in the hedge.

The medians of the total A-weighted insertion losses provided by the first hedge are 2.8 dBA at position A, 2.5 dBA at position B, and 1.9 dBA at position C. Near the second hedge, 2.0 dBA was measured. The minimum and maximum insertion losses at both hedges and all receiver positions considered were 1.5 dBA and 3.6 dBA.

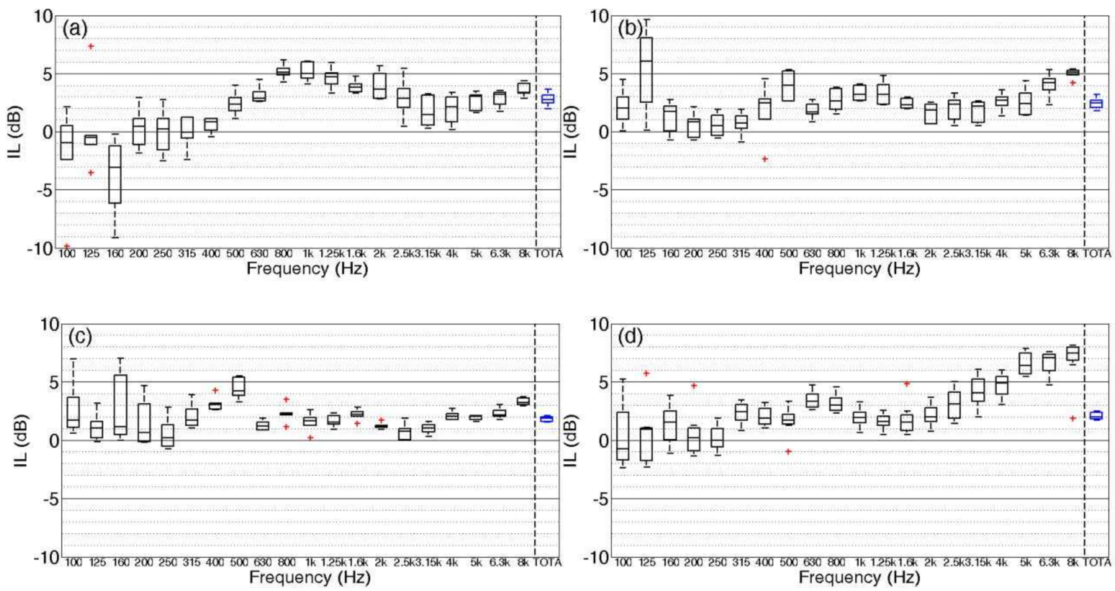

Fig. 8. Boxplots showing the insertion losses per 1/3-octave band, together with the total A-weighted insertion losses of single passing cars. Near hedge 1 (a-c, corresponding to measurement positions A, B, and C, respectively), there were 3 times 6 pass-by's by the same car. Near hedge 2 (d), there were 8 pass-bys by different cars. Case : Milton-Keynes, UK. [Color online]

4.3.2. Numerical modelling

The acoustical, physical effect of the hedges is a combination of both the local ground effect and the interaction with above-ground biomass. For the second Milton-Keynes hedge (see Fig. 1 (e)), the measured insertion loss between the hedge microphone and reference microphone is predicted by calculating the difference in ground effect in both cases, and by using an empirical relationship between sound reduction by foliage and leaf-area density (LAD), leaf size and propagation length, originally proposed by Aylor [7]. As suggested by other research [6][20][21], the ground and the foliage effects can be treated independently as they do not seem to interact, basically since different parts of the sound frequency spectrum are affected.

For sound propagating towards the microphone opposite the gap in the hedge, a rigid ground surface was assumed. To the microphone behind the hedge sound propagates first over a rigid road surface, then across an 11-cm high kerb at the road edge, then soft soil below the hedge, and then again a rigid surface. A 2D-BEM code [22] was used to calculate the difference in ground effect at these microphone positions. In these calculations, a source height of 1 cm was assumed which is appropriate for the noise generation at the tyre/road interface. The impedance of the soft ground is modelled using a slit-pore model [23] with a flow resistivity of 50 kPas/m^2 and porosity of 0.5. Best fits for use in Aylor's foliage attenuation model were a leaf area density (LAD) of 4.5/m, a propagation path length interacting with the vegetation of 2.2 m, and a mean leaf width of 0.03 m. No detailed assessments of the hedge or soil properties were made. However, the best fitted values can be considered as realistic. The values for LAD are rather high; a possible reason is that part of the woody biomass is included. Aylor's foliage attenuation formula predicts attenuation only at high frequencies. The measured and predicted attenuation at lower frequencies (400 Hz to 1 kHz) is due to differences between the soils at the reference and hedge location.

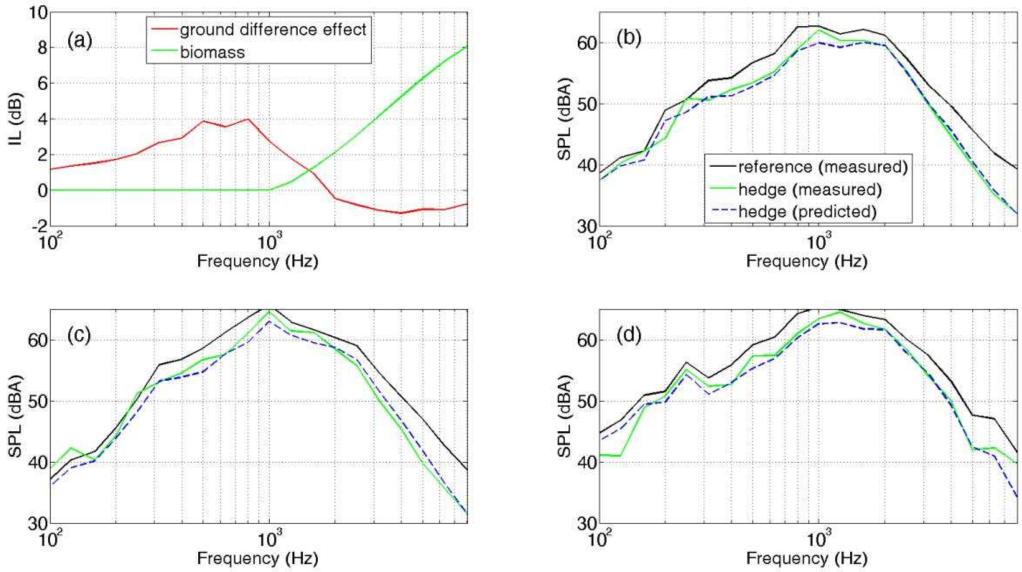

Fig. 9. Insertion loss predictions (a) for the difference in ground effect near the reference microphone position and the microphone behind the second hedge (see Fig. 1 (e); BEM calculations were used), and the foliage/twig scattering and absorption (indicated as biomass effect, using an empirical formula based on Ref. [7]). In (b), (c) and (d), these insertion losses are applied to a number of pass-by measurements at the reference position, and compared to the measured sound pressure level spectrum behind the hedge. Case : Milton-Keynes, UK. [Color online]

Figure 9 compares different vehicle pass-by measurements including predictions in the presence of the hedge. The noise spectrum measured at the reference microphone location is therefore used as basis. When accounting for the difference in soil effect and foliage/biomass attenuation, the pass-by spectrum at the microphone behind the hedge can be predicted with good accuracy.

The share in the total noise reduction by above-ground biomass, making use of the previous predictions, is 0.7 dBA, 0.5 dBA, and 0.7 dBA for the cases selected in Fig. 9. The share in noise reduction by the differences in ground effect is then 1.6 dBA, 1.9 dBA, and 1.5 dBA. These results show that although shielding provided by above-ground biomass might be limited for light vehicles at low speeds, hedges provide the opportunity to benefit from soft ground effects.

4.4. Derbyshire, UK

The results of the insertion loss measurements using a point source near two hedges are presented in Fig. 10. These graphs show a rather peaky behavior. Although attempts were made to minimize differences in soil effect between the reference microphone position and the microphone at the other side of the hedge (see Fig. 1 (f) and (g)), some clear differences were found below 1 kHz. Most likely, the impedance discontinuity in soil caused by the succession of grass, soil below the hedge, and again grass on the propagation path between the source and receiver behind the hedge is strongly different from the uniform grass-covered soil between source and reference position. In this frequency range, ground effects are in general positive.

At frequencies above 1 kHz, foliage effects are expected. A more complex behavior is found than for the pass-by experiments with cars. In the latter, averaging of different sound paths intersecting with the hedge is inherently included as the cars were moving. Here, a specific part of the hedge is insonified in this fixed source-receiver configuration. Both hedges give rather similar maximum insertion losses in this frequency range. Reflections from the hedge towards the reference microphone (which was located at the source side of the hedge) could be responsible for interferences observed in the high frequency range.

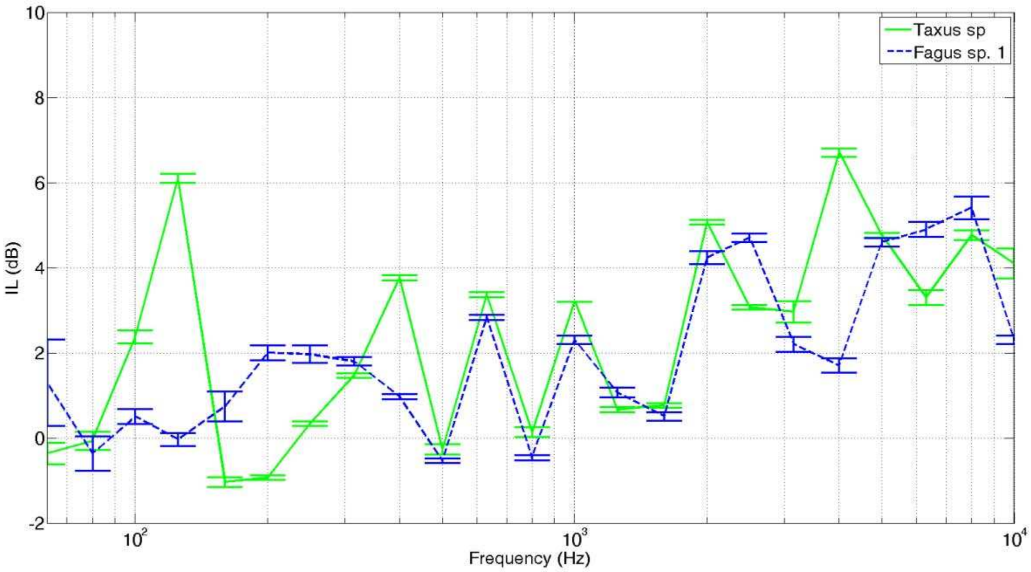

Fig. 10. Insertion loss measurements by two hedges using an omni-directional loudspeaker. The total length of the errorbars are two times the standard deviations as a result of 3 repetitions at different amplification levels of the source, without changing microphone and source position. Case : Derbyshire, UK. [Color online]

4.5. Ilkley, UK

The averaged insertion loss over different angles of incidence relative to the microphone array are shown in Fig. 11 for two different hedges. Below 1 kHz, the difference in ground effects near the hedge and those over rigid ground in the reference case (see Fig. 1 (h) and (i)) leads to pronounced shifts in interferences in these spectral insertion loss plots. When comparing to the Derbyshire measurements, insertion losses above 1 kHz show a more smooth increase with frequency, since hedge reflections are not captured by the reference microphone and due to the fact that averaging is performed over different angles of incidence.

The Prunus hedge shows a higher insertion loss in the frequency interval between 2 kHz and 5 kHz than the Fagus hedge. The Prunus hedge is thicker (2.5 m vs 1.7 m) and has larger leaves (measured average area of single leaves of 0.0094 m^2 vs 0.004 m^2). Visual inspection revealed that leaves were present not only at the outer surfaces of the hedge, but also in its middle section at the Prunus hedge. The Fagus hedge, on the other hand, consisted of a large air gap and only branches in the middle region.

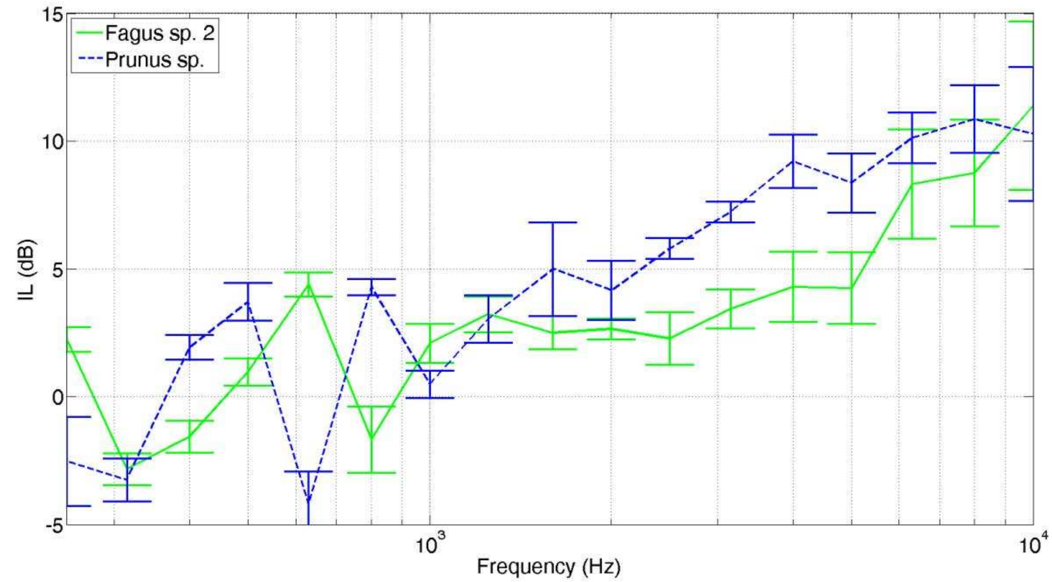

Fig. 11. Insertion loss measurements by two hedges using an omni-directional loudspeaker, averaged over different angles of incidence on the microphones (angles between 0 and 22 degrees). The total length of the errorbars are two times the standard deviations of the responses over the different angles. Case : Ilkley, UK. [Color online]

5. Conclusions and discussion

Relatively thick hedges provide only minor physical noise reduction in case of light vehicles at speeds below 50 km/h. Statistical pass-by experiments along a hedge yielded reductions in the range 1.1 dBA to 2.2 dBA, depending on vehicle speed and receiver height. In a first controlled pass-by experiment, insertion loss measurements were found in the range -0.9 dBA to 2.4 dBA, with a median at 1.2 dBA. Controlled pass-by experiments at two other hedges gave median values in between 1.5 dBA and 3.6 dBA.

Spectral analysis showed an improved ground effect due to the presence of a hedge in the frequency range between 250 Hz and 1 kHz. A small piece of grassland in front of the hedge was shown to strengthen this effect.

Above 1 kHz, foliage and twigs/branches are responsible for the noise reduction. With increasing sound frequency, biomass scattering (and absorption) becomes more prominent. At 5 kHz, noise reductions between 2 dB and 10 dB were measured due to the different hedges considered in this study. This suggests that hedges offer only limited A-weighted road traffic noise reductions.

Accurate predictions of the noise shielding by the above-ground biomass present in a hedge were possible with an empirical relationship originally proposed by Aylor. Such numerical predictions indicated that ground effects are dominant over above-ground biomass effects when considering pass-by noise of light vehicles at low speeds along hedges.

The microphones in the different case studies were located fairly close to the hedges. Under such conditions, diffraction at horizontal or vertical edges, or downward scattering by such edges, are expected to be small, leading to the largest possible noise reductions. Even under these conditions, the observed noise reduction by the hedges is rather limited. In addition, the position of source, hedge and receiver determines the location of the specular reflection point on the ground. Only when the latter is situated below the hedge, one can benefit from the "forest floor"-effect. At the other hand, the part of the sound field that is transmitted through the belt is expected not to be influenced by receiver distance.

The current study involved pass-bys of light vehicles only. It can be reasonably expected that in case of heavy vehicles, given the larger importance of low-frequency engine noise, the noise reduction provided by a hedge will be even lower.

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