Integration of the efficiency of noise barrier caps in a 3D ray tracing method. Case of a T-shaped diffracting device

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Abstract

Road barrier diffracting caps have shown a renewed interest for several years since they give the opportunity of increasing the barrier efficiency without changing its overall height. First investigations on the efficiency of road barrier caps calculated with a boundary element method (BEM) have shown that the efficiency obtained with coherent line sources is underestimated compared to that with incoherent line sources, more representative of road traffic noise. The present work deals with the characterisation of the real performance of a T-shaped absorbing cap with road traffic noise conditions. Two different approaches are compared: on one hand calculations with the help of a BEM program able to achieve 2D and 2D½ simulations are made; on the other hand outdoor measurements on a test-wall using a maximum length sequence technique are carried out. The goal in the two approaches is to isolate the top edge diffracted sound field in order to determine an extrinsic value of octave band efficiency of the cap for many source–receiver pairs. These results integrated in a ray tracing prediction method enable the integration of air absorption along each ray path and give the real efficiency of such a device in the case of complex and realistic configurations for barriers of finite length.

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1. Introduction

Improvement of road barrier acoustic efficiency has been investigated for many years [1–15]. One of the most promising solutions is the adding of a cap (or crowning) at the top edge of a straight barrier which increases noticeably the barrier efficiency without changing its overall height. For an absorbing cap more or less 1 m wide, the estimated improvement of the protection in the barrier shadow zone is between 1 and 4 dB(A) depending on the positions of source and receiver, as well as shape of cap, material used and height of barrier. However, these results come from 2D BEM calculations. In previous papers [16,17,21], road barrier caps efficiency has been calculated with the help of a BEM software package (named MICADO [18]) for both coherent and incoherent line sources along the barrier. Results have shown that the efficiency obtained with coherent line sources is underestimated compared to that with incoherent line sources, more representative of a real traffic noise. Moreover, for a point source, cap efficiency appeared to be strongly dependent on the angle of diffraction. Thus the integration of the acoustical effect of such diffracting devices in a 3D ray tracing method requires the knowledge of cap efficiency for any source–receiver pair.

In the present paper, a T-shaped barrier is investigated. The cap (named T-shaped cap hereafter since it gives to the straight barrier the profile of a T) is made of 0.85 m wide and 0.25 m thick elements made of porous wood-cement. These elements are laying side by side all along the top edge of the test wall (Fig. 1).

Preliminary measurements of the absorption coefficients ($\alpha_{\text{sabine}}$) for a 3 m × 4 m 13 cm high with 5 cm deep grooves sample in a reverberant chamber give the values 0.15, 0.4, 0.95, 0.8, 0.85 and 0.85 for the octave bands 125, 250, 500, 1000, 2000 and 4000 Hz respectively.

2. MICADO calculations

In the present work, a boundary element method based on a variational approach [18] is used to obtain the 2D solution where barrier and cap are considered to be infinitely long in the $y$-axis direction (Fig. 2). The code has been adapted for imaginary computations necessary to obtain the 2D $\frac{1}{2}$ solution (slantwise propagation from a point source) as proposed by Duhamel [19,20]. The program, named MICADO, has been extensively presented elsewhere [18,21].

In order to isolate the only top edge diffraction, reflections on the ground have to be cancelled in the BEM calculations. This is done by setting the linear or point source as well as the receiver at zero height on a reflecting horizontal ground. It is assumed here that, for a given pair of source–receiver S1–R1 located above the ground, the single performance of the cap associated to the only simply diffracted field (no ground effect) is similar to that relative to the pair S–R located on the ground (Q–S1–S and Q–R1–R being aligned) with Q the top edge point of the diffracted path (Fig. 2).
For a point source–receiver pair, the efficiency \( \text{Eff} \) of the cap is given for each frequency band by:

\[
\text{Eff} = 10\log_{10} \left( \frac{\int_{\Delta f} |p_{\text{ref}}|^2 \, df}{\int_{\Delta f} |p_{\text{cap}}|^2 \, df} \right)
\]

where \( \int_{\Delta f} |p_{\text{ref}}|^2 \, df \) and \( \int_{\Delta f} |p_{\text{cap}}|^2 \, df \) are the integrals in a given frequency band \( \Delta f \) of the calculated squared pressures for the reference straight barrier and the T-shaped barrier, respectively. The efficiency is calculated in the same way for an incoherent line source. A positive value of the efficiency means a reduction of noise behind the barrier.

Fig. 1. Geometry of the T-shaped barrier. Cap element dimensions and arrangement (top) and view from below in site (back).

Fig. 2. Notations on a diffracted ray (perspective, side and top views).
Calculations have been carried out on a wide grid of sources and receivers located on the reflecting ground. Distance between barrier and point source (x-direction on Fig. 2) varies from 1 to 500 m (the same for receiver) when abscissa (y-direction on Fig. 2) between source and receiver extends from 0 to 3000 m.

Preliminary measurements have shown that the acoustic impedance of the tested cap could be well modelled as the one obtained with a 5 cm thick layer of glasswool laying on a hard surface. For a given frequency, the impedance is then determined from the two-parameter version of Delany and Bazley’s model [32] with an air flow resistivity of 30 kPa s m$^{-2}$ for glasswool.

3. MICADO results

3.1. Results with no air absorption

Air absorption cannot be taken into account easily when source is an incoherent line. Moreover, to be integrated in a ray tracing method, this effect has to be applied on each acoustic path. Thus, the line source is approximated as a series of point sources put along it (Fig. 3).

Fig. 4 shows a comparison of cap efficiency obtained for an incoherent line source (located 12 m behind the barrier) and for a summation of point sources every 10 and 20° (from $\theta_i = 0–80°$, plus 85 and 88°).

In the case of a sum of point sources, the global efficiency $\text{Eff}$ is written as:

$$\text{Eff} = 10 \log_{10} \left( \frac{\sum y_{Si} \int_y p_{\text{ref}, Si}^2 dy}{\sum y_{Si} \int_y p_{\text{cap}, Si}^2 dy} \right)$$

where $\sum y_{Si}$ stands for the sum over the $y_{Si}$ sources, and where $y_{Si}$ is the length of line source segment cut by the beam (of angle $d\theta$) relative to each diffracted path and expressed as (notations in Fig. 3):

![Fig. 3. Principle of decomposition of a line source into series of point sources.](image-url)
\[ y_{Si} = d_i \times d\theta / \cos \theta_i \]  

(3)

The receiver is located 50 m from the barrier. Agreement between incoherent and point sources calculations is good even when angular interval between rays is 20°. It points out that such an angular sampling is acceptable for our purpose. Comparisons on other pairs of S–R configurations also show good agreement.

Fig. 5 shows results of successive cap efficiencies [Eq. (1)] for a point source moving along the line source direction by steps of 20°.

![Graph showing efficiency vs. frequency](image1)

**Fig. 4.** Cap efficiency obtained with an incoherent line source (dotted line), a sum of point sources located every 10° (dashed) and every 20° (solid); distance source–barrier = 12 m; distance barrier–receiver = 50 m; one frequency per 3rd-octave band.

![Graph showing efficiency vs. frequency](image2)

**Fig. 5.** 3rd-octave band cap efficiency for a point source for different values of the angle of diffraction \( \theta \): 20° (solid line), 40° (dashed), 60° (dotted) and 80° (dashed-dotted); distance source–barrier = 12 m; distance barrier–receiver = 50 m.
As expected, the cap efficiency strongly depends on the diffraction angle of the path ($\theta$, in Fig. 3): in the case of a barrier considered as infinitely long, it is not correct to evaluate the efficiency by considering only the path perpendicular to the barrier. This will be confirmed in the next section when air absorption is taken into account.

3.2. Results with air absorption

Air absorption effect can now easily be taken into account on each ray, whatever complex the configuration. Values of octave band air attenuation coefficients are taken from standard XP S 31-133:2001(F) [30]. They are in accordance with values provided by ISO 9613-1 [28] given for a temperature of 15 °C and a relative humidity of 70%.

Fig. 6 shows a comparison of efficiencies calculated with coherent and incoherent line sources (no air absorption) as well as sum of point sources without and with air absorption effect.

One can observe that even when air absorption effect is taken into account, the efficiency of an infinitely long cap is somewhat different considering a sum of uncorrelated sources (corresponding to the real situation) or a single source facing the receiver (2D calculation). In the present case of a T-shaped barrier whose top is covered with 5 cm thick glasswool, the efficiency of the cap will be underestimated with a 2D calculation.

Other results also show that when summing sources from $\theta = -50^\circ$ to $+50^\circ$ only (instead of $-88^\circ/+88^\circ$), the global efficiency becomes very close to that calculated in 2D (coherent line source). It means that the transition from coherent (2D) to incoherent (2D $\frac{1}{2}$) source is mainly due to the acoustical behaviour of the absorbing cap for highly slantwise propagation. In other terms, the real impact of a such a cap on

Fig. 6. Comparison of 3rd-octave band cap efficiencies calculated with coherent (thin solid line), incoherent (dotted), sum of point sources without (dashed) and with (thick solid) air absorption; distance $S$–barrier = 12 m; distance barrier–R = 50 m.
noise reduction will strongly depend on the length of the barrier (in comparison with the observation distance). This point will be clearly illustrated through an example in Section 6.

4. Comparisons with measurements on a test-wall

4.1. Measurements setup

The test wall is a 4 m high and 19 m long barrier (Figs. 7 and 8) including seven sections (three test samples surrounded by four 2 m wide concrete sections). Posts between sections are made of steel. Central test sample is a 3 m wide altuglass plate. The two lateral 4 m wide samples are: a concrete wall and a wall made of metallic elements filled with glass wool. The five concrete sections as well as metallic part are 10 cm thick. The altuglass sample is 8 cm thick. The measurements take place in front of this central sample.

Preliminary measurements have shown that the transmitted sound energy through the barrier could be neglected in regard with the top diffracted sound energy within the frequency range of interest (125–4000 Hz octave bands). The test wall is then considered as acoustically opaque.

The maximum length sequence (MLS) technique is used in order to get impulse responses [24,25]. This method offers a very good background noise immunity which
allows efficient outdoor measurements assuming that the source–receiver distance is not too large. A periodic pseudo-random sequence of maximum length of binary pulses is fed through a loudspeaker 25.4 cm in diameter (Fig. 8). Signals are picked up on the other side of the test wall by means of a 1/2-inch microphone. MLS parameters were set as follow: 32 averaged measurements for each source–receiver pair of points, sequence order of 15 \((2^{15}-1)\) samples) and sample rate of 48 kHz.

The experiment took place during a sunny day of June with very little wind. We consider hereafter that the effect of wind is negligible.

The confinement of the test wall as well as its quite limited length requires us to work in the immediate vicinity of it. This constraint should also be respected for

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Fig. 8. Test-wall measurement set up at CSTB-Grenoble with loudspeaker and microphone: without (top view) and with cap (bottom view).
measurements on real built barriers along motorways. Two source positions and three locations for the receiver are considered, with and without the cap (Fig. 9). Sources and receivers co-ordinates are in meters: S1 (−4.0; 2.0), S2 (−7.3; 2.0), R1 (6.0; 3.7), R2 (12.0; 3.4) and R3 (12.0; 3.0). S1 and S2 are located on ray paths emitted from virtual sources S1’ and S2’ which correspond respectively to the 2nd and 3rd lane of a conventional 2×2 lane motorway (Fig. 2). In the same manner, R1 (or R2) and R3 represent virtual 1.5 m high receivers locate 50 and 30 m away from the barrier, respectively (or receivers at ground level 80 m and 48 m away, that is R1’ and R3’ respectively).

This approach, stating that cap efficiency is sufficiently similar for pairs S1–R1 and S1’–R1’ (that is, points S1’–S1–Q and points R1’–R1–Q are on the same lines of sight), has been imposed by preliminary calculations.

For a given pair of source–receiver, the efficiency $Eff_i$ of the T cap (i.e. T barrier compared with the straight one) for the $i$th octave band is written in dB as:

$$Eff_i = 10\log_{10} \frac{\int_{\Delta f_i} \left| \text{FFT}\left[p_{\text{ref}}(t) \times W(t - \tau_{\text{ref}})\right]\right|^2 df}{\int_{\Delta f_i} \left| \text{FFT}\left[p_{\text{cap}}(t) \times W(t - \tau_{\text{cap}})\right]\right|^2 df}$$  \hspace{1cm} (4)

Fig. 9. Position of sources (S1 and S2) and receivers (R1, R2 and R3) for measurements (a) without the cap (top sketch), (b) with the cap (bottom sketch).
where
\( p_{\text{ref}} \) is the reference impulse response (straight barrier with no cap), \( p_{\text{cap}} \) is the impulse response when the barrier is capped, \( W \) is the FFT analysis window (described hereafter), \( \Delta f_i \) is the \( i \)th octave band width, \( \tau_{\text{ref}} \) and \( \tau_{\text{cap}} \) are appropriate time shifts set so that the FFT analysis window begins 0.7 ms before the highest peak in the time responses relative to \( p_{\text{ref}} \) and \( p_{\text{cap}} \), respectively.

It is important to note that the efficiency in Eq. (4) relates to two different situations (with and without the cap) with no change of the positions of sources and receivers (Fig. 9a and b). It would have been an advantage to keep the angles of incidence and diffraction in the vertical plane by moving in the vertical direction the source and microphone by a height equal to the thickness of the cap (25 cm). In this way the virtual positions of \( S_1, S_2, R_1, R_2 \) and \( R_3 \) relative to the top edge middle point \( Q \) in the case of the single barrier would have been same as those relative to \( Q' \) (see Fig. 9b) in the case of the barrier with the cap.

The reason for choosing such fixed geometry follows the idea of characterising the real effect of adding a cap at the top of a straight barrier. The efficiency in Eq. (4) thus takes into account both the diffraction effect of the cap and the increase of the barrier’s total height due to its addition.

The FFT analysis window in Eq. (4) (also named ‘ADRIENNE window’ [23–26]) is made of three successive parts: a 0.5 ms half-Blackman window, a rectangular window and half-Blackman window. The length of the two last windows is variable with a constant ratio of 7:3. Fig. 10 shows an example of impulse responses for configuration \( S_1–R_1 \) obtained with and without the T cap, and associated FFT windows.

In order to isolate the top edge diffraction phenomenon, the total length of the window has been chosen to reject the sound reflections on the ground on receiver side as well as diffractions on the vertical edges of the test-wall. On the source side, it is not necessary to reject the reflection on the ground since the loudspeaker is quite directive and only a small percentage of energy is spread towards the ground. The total length of the window allows to get reasonable results from 250 Hz octave band for the farther receivers (\( R_2 \) and \( R_3 \)), and from 125 Hz for \( R_1 \).

![Fig. 10. Measured time responses (solid lines) and FFT windows (dashed lines) for pair S1–R1.](image-url)
4.2. Results and comparisons

Fig. 11 shows comparisons between measurements and calculations for different pairs of points. Configurations including R1 and R2 are shown on the same graph since these receivers correspond to the same virtual zero height receiver R1'.

The agreement is very good in each case except for case S2–R1 and S2–R2 corresponding to the situations where diffraction path difference is lowest and cap effect less. These results confirm, however, the validity of the previous invoked principle when it was assumed that pairs of points S1–R1 and S1'–R1' gave similar cap efficiencies, providing that only simple top edge diffraction was taken into account.

The agreement comes also from the fact that the comparison is between results of measurements with a low wind speed and results of calculations in homogeneous atmosphere. However air conditions have to be taken into account in the case of non negligible meteorological effects. For instance, in the case of a 4 m s$^{-1}$ wind speed 2 m high, Watts [34] has measured a decrease of several dB of a 1 m wide T-shape cap efficiency compared to the case with no wind, especially for frequencies above 1000 Hz.

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Fig. 11. Comparison of the octave band T-shaped cap efficiency, in dB: measurements (solid lines) and MICADO calculations (dashed lines).
5. Analytical expressions of cap efficiency

For a simple use of our results, analytical expressions of efficiency as a function of path difference and diffraction angle have been determined for each octave band. This choice was first imposed by the following observations:

(i) For given S–R direction, frequency band and path difference, the cap efficiency is similar whatever the positions of S and R.
(ii) For large values of $\theta$, the efficiency is proportional to $\cos^{-1} \theta$.
(iii) For the highest frequencies, the efficiency is proportional to the path difference $\delta$.

These considerations have led to the following form of the cap efficiency expression:

$$\text{Eff} = A \times \frac{\delta}{\cos \theta} \left(1 - B(\theta)e^{-C(\theta)\delta}\right)$$ (5)

For the highest octave bands, the efficiency has the form:

$$\text{Eff} = A \times \frac{\delta}{\cos \theta}$$ (6)

with $A = 6, 7.5$ and $11.8$ for the 1, 2 and 4 kHz band, respectively.

Fig. 12 shows results of efficiency as a function of path difference for several diffraction angles and for many S–R configurations at 1000 Hz.

Fig. 12. Cap efficiency for a point source as a function of path difference for different diffraction angles and for many S–R configurations, at 1000 Hz; MICADO point source calculations ($0^\circ +, 40^\circ *, 60^\circ \bigcirc, 80^\circ \square$) and approximated analytical expressions (lines).
6. Global efficiency in realistic situations

It is now possible to predict the global efficiency of the studied cap in some realistic situations, taking account of ground effect, air absorption and length of the barrier. Acoustic attenuations along each path are calculated according to the New French Prediction Method (named NMPB) [29,30] whose concept is based on the ISO 9613 approach [31]. In Table 1 the global calculated cap efficiencies, in dB(A), are reported for a 4 m high barrier along a 2×2 lane motorway, for different lengths of barrier (Fig. 13). Lines sources are located 4, 7.5, 12 and 15.5 m away from the barrier. The receiver is 1.5 m high and is located at different distances behind the barrier. Terrain is grass-like flat surface behind the barrier on the receiver side. The ground impedance is determined by using the one-parameter Delany and Bazley’s model [32] with an air flow resistivity of 300 kPa s m⁻². The sound emission spectrum is determined using the standard A-weighted road traffic spectrum given by EN 1793-3 [33].

Global efficiency varies between 0.7 and 2.6 dB(A) depending on the position of receiver and length of barrier. It is now interesting to compare some of these values (Table 1) to those we would obtain by considering 2D calculations (efficiency for a coherent line source); for instance, in the case of an infinitely long barrier, global

<table>
<thead>
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<th>$d_{BR}$ (m)</th>
<th>200</th>
<th>1000</th>
<th>2000</th>
<th>$\infty$</th>
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</thead>
<tbody>
<tr>
<td>30</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.6</td>
</tr>
<tr>
<td>125</td>
<td>1.0</td>
<td>1.2</td>
<td>1.3</td>
<td>2.2</td>
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<tr>
<td>250</td>
<td>0.7</td>
<td>1.3</td>
<td>1.6</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Fig. 13. Notations for Table 1; $l_B$ is the length of the barrier; $d_{BR}$ is the perpendicular distance from the barrier to the receiver.
efficiency would be 1.2, 1.0 and 1.3 dB(A) instead of 2.6, 2.2 and 1.9 dB(A) respectively (last column of Table 1).

If results are needed in terms of global efficiency of a 4.25 m high T-shaped barrier compared to a 4.25 m high straight barrier (same total height), the increase in height due to the height of the cap must be taken into account. Then, all results given in Table 1 should be decreased by 0.5 dB(A) on average. A more precise corrective value can be obtained for given octave band and situations ($d_{BR}$ and $l_B$ fixed) by calculating with GTD or BEM the efficiency of a 4.25 m high straight barrier compared to a 4 m high one.

7. Concluding remarks

In this paper, a T-shaped barrier with an absorbing cap has been investigated. A first approach has been achieved by using the MICADO software able to achieve 2D and 2D $\frac{1}{2}$ calculations [22]. A measurement procedure using a MLS technique has also been presented. From 2D $\frac{1}{2}$ MICADO results, it has been possible to determine the acoustical efficiency of the cap for different diffraction angles and path differences, in order to introduce it in a ray tracing method where all effects are taken into account [27].

The following conclusions can be drawn from measurements and calculation results:

(i) MLS measurements made close to the barrier show a good agreement with 2D $\frac{1}{2}$ MICADO calculations (for a point source). This validates the BEM approach for such a problem: MICADO then may be used for other various simulations (such as longer range reception, slantwise point source–receiver configurations, incoherent line source, etc.).

(ii) As expected, results of point source measurements are close to 2D MICADO calculations (coherent line source) in terms of cap efficiency. The agreement could be increased using a more sophisticated model of cap impedance.

(iii) Results of cap efficiency obtained for a coherent line source (or a point source facing the receiver) are noticeably different from those corresponding to an incoherent line source which is typical of road traffic noise. The present measurement method cannot be used directly for the certification of road barrier caps, as any other impulsive method where source-receiver direction is perpendicular (or almost perpendicular) to the screen. The present measurement method can only be used for the certification of road barrier caps in a laboratory (i.e. on a test-wall) as well as in situ (already built barriers along roads) providing that slantwise propagation effects are introduced.

(iv) In this way, the testing and setting of a diffracting product can be made by means of 2D BEM calculations as well as point source measurements. However, the real behaviour of a device under road traffic noise conditions should be given through 2D $\frac{1}{2}$ BEM calculations (with incoherent line sources).

(v) Values of 3rd-octave or octave band efficiency (such as those shown in Figs. 5 and 11) could be determined for a point source as a function of the diffraction
path difference as well as the diffraction angle; these results could then be used for the implementation of T-shaped cap effect in a ray tracing program by means of simple analytical formulae.

(vi) From 1000 Hz octave band, tested T-shaped cap efficiency is proportional to the diffraction path difference and inversely proportional to the cosine of diffraction angle.

(vii) Between 300 and 500 Hz, and for angles of diffraction less than 50°, the studied cap shows a negative efficiency. This dip in efficiency disappears for larger angles of diffraction.

(viii) Behind a barrier looking perpendicularly to it, if the masked angle is bigger than 140°, 2D calculations give results which are up to 1.4 dB(A) less than those from a 2D \frac{1}{2} approach; cap efficiency will then be underestimated.

(ix) If the masked angle is less than 120°, the 2D approach gives similar results as 2D \frac{1}{2} calculations: in this configuration, measurements of the cap efficiency carried out close to the top edge (and perpendicularly to it) seem to be usable in calculations.

(x) One may finally say that:
• in a real situation where the T-shaped barrier is of finite length, the efficiency of such a cap will be between 1 and 2 dB(A), mainly depending on the value of the masked angle and path difference;
• a 2D calculation corresponding to an infinite coherent line source (with an infinite long barrier) will give an efficiency about 1 dB(A) less;
• with a 2D \frac{1}{2} infinite incoherent line source (with an infinite long barrier) more representative of a road traffic noise, the efficiency will be between 2 and 3 dB(A).

Work on the determination of the acoustical efficiency of other caps is in progress.

References


