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Traffic Noise Models for Curved Roads

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The paper presents two theoretical models for traffic noise level distribution on curved horizontal roads. In the case of vehicles moving on a given route, one can consider, in terms of sound field, that the granular traffic is equivalent for short periods with a quasi-continuous noise flow. When computing and modelling the noise level generated by traffic on roads with complex trajectory, it is common to treat the route as a sum of small length road segments, each being assimilated with a linear noise source. This paper started from the assumption that the route can be decomposed into a sequence of linear and arc-shaped road segments, each of which is treated as a linear respectively curved noise source. An arc-shaped road segment is modelled by a tubular vibrating surface, of circular or rectangular section. In the case of rectangular section, the vibrating blade emits complex sounds on its both vertical sides and the generated sound field can be described more clearly, qualitatively and quantitatively, through intensity distribution. The theoretical models presented in the paper have direct application to the traffic noise prediction and noise maps drawing.

Keywords: traffic noise; noise source modelling; sound field; curved road.

1. Introduction

The road traffic noise results as a combination of multiple noise emissions generated by each vehicle that transits a given road segment. There are different approaches connected with the generation of the noise field by such a complex source, consisting of a group of vehicles in motion, developed in the context of noise mapping and noise assessment (Quartieri *et al.*, 2009; Steele, 2001). The granular traffic, consisting of cars travelling on a given route, generates a noise flow that can be considered quasi-continuous for short periods. The traffic noise intensity depends on the number of vehicles per time unit, their speed and the emitted acoustic power. The noise field can be assimilated to the sound emitted by stationary incoherent extended sources, judiciously distributed along the route (Defrance, Gabillet, 1999; Defrance *et al.*, 2007; Guarnaccia, 2013; Johnson, Sanders, 1968; Lamancusa, 2009; Lighthill, Whitham, 1955). A complete acoustical study has to take into consideration the characteristics of the noise sources (Lelong, 1999) but also some other factors, such as: the exact definition of the structure and limits of the sound propagation area, reflected and diffracted sounds, the influence of sound waves on elastic structures, the soil influence, wind effects, etc.

The most common way to predict the traffic noise generated on roads with a complex trajectory, also used by different noise mapping software, treats the road as a sum of linear road segments of different lengths, each segment being assimilated with a linear noise source. The idea behind the theory presented in this paper was to decompose the road trajectory not only by linear segments but also by curved segments. Then, for the study of the traffic noise, each type of road segment is associated with a corresponding noise source: linear or curved.

The general considerations related to the noise field generated by the granular traffic on a curved road become more complex than in the case of the linear sources. The authors present two theoretical models of arc-shaped noise sources, considering that the vehicles in traffic transmit momentum, through their walls, to the molecular layer of ambient air by pulsed collision. As a result, waves are generated, travelling by successive compressions and relaxations. These wave movements are perceptible by the sense of hearing and are also called sounds.

2. Modelling the sound field generated by traffic on arc-shaped road segments

For the calculation of the spatial intensity distribution of traffic noise, one has to define the principles which justify the connection between the stochastic character of the real traffic flow and the acoustic characteristics of the sound field generated by the equivalent sources. Our models relate to the study of noise levels produced at the receptors placed in the plane of the traffic route.

We operate by statistic values of waves parameters, considered as average values in the horizontal direction, normal to the traffic. The calculus of the noise intensity and noise level of the real traffic would be consistent with that of vibrating sources having the shapes of cylindrical-tubular or blade (Cosma, Popescu, 2015).

For a uniform traffic flow $Q = N/t$, consisting of N vehicles, distributed evenly along the length of a linear road $l = vt$, each having the acoustic emission power W_0 and the velocity $\mathbf{v}$, or the corresponding mean values, the power output per unit length traffic can be written:

$$w = \frac{\sum_{i=1}^{n} W_i}{l} = \frac{NW_0}{\mathrm{v}t} = \frac{\mathrm{Q}}{\mathrm{v}} W_0, \tag{1}$$

where

$$\mathrm{v} = \frac{1}{N}\sum_{i=1}^{n} \mathrm{v}_i \qquad \text{and} \qquad W_0 = \frac{1}{N}\sum_{i=1}^{n} W_i.$$

The amplitude of the progressive wave is exponentially attenuated with the distance, due to absorption. So, the amplitude of waves with cylindrical symmetry is given by the known equation:

$$A(r) = \frac{A(0)}{\sqrt{r}} e^{-\chi r}, \tag{2}$$

where $A(0)$ is the amplitude of sound waves excited in the air at the surface of the cylindrical-tubular source and r is the distance from the source. The amplitude attenuation coefficient χ is one half of the intensity absorption coefficient ($\alpha = 2\chi$).

2.1. Models of toroidal-tube and curved blade noise sources

For the noise produced by traffic on arc-shaped road segments, the modelling may be done by a set of oscillators placed on the segment of the toroidal-tube surface that has the median circle arc AB of length l and radius $\mathrm{OO}' = R$ (Fig. 1).

The curvature of the toroidal-tube source induces an alteration of the linear cylindrical symmetry. The emission being normal to the toroid's meridians, the

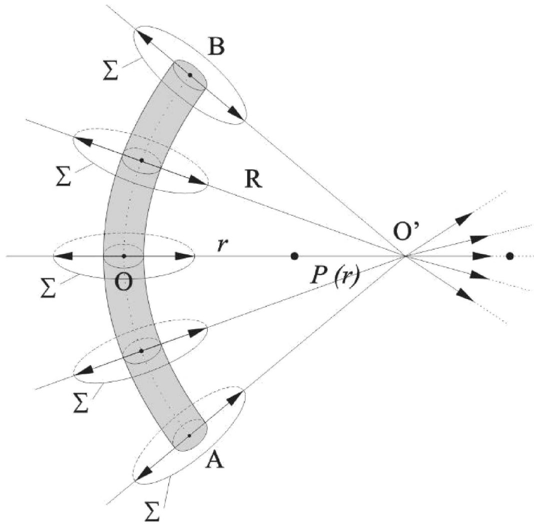

Fig. 1. Sound field of the toroidal-tube surface.

field intensities will be convergent in a small spatial region, inside of the convex curvature, and divergent in the rest of it. Spatially, the intensity of the sound field will be shaped as a prismoid or "wedge" whose edge is normal, in $\mathbf{O}'$, to the plane of the curved road (the plane of the sketch). Additionally to the field lines in Fig. 1, one can infer the spatial geometry of the wave fronts (Σ).

A model that respects the conditions imposed by the physical similarity of normal radiation can be achieved, considering a toroidal-tube emission surface having a rectangular section. This shape (Fig. 2) will be more appropriate for traffic noise emitters. They may be assimilated to vibrating tapes, which become sources of corresponding sounds. This model presents interest in the plane of the curved road. It will be more adequate to consider only the emission from the both lateral faces that vibrate in the plane of the curved road.

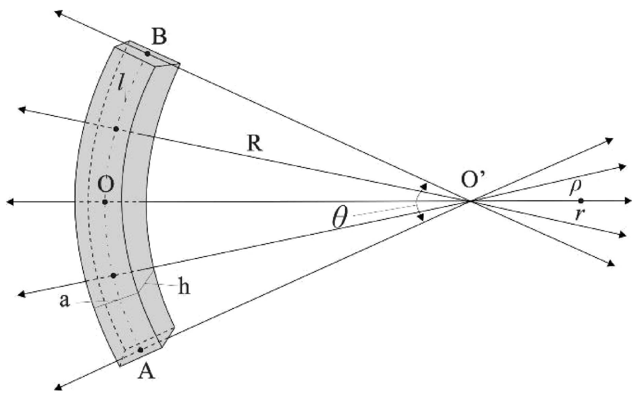

Fig. 2. Toroidal-tube vibrating surface with rectangular section.

In Fig. 2, a curved tubular source with a rectangular section is considered. Its median circle arc is of radius R and length l. The rectangular section is of height h and finite thickness a, negligible versus the observation distance r. Because the intention is to model the sound field in the plane of the circular road, we consider that the emission is from both vertical lateral parts of vehicles, in radial direction. This can also be generated by curved vibratory blades or strips.

Since the normal emission powers from both sides of the curved blade are equal and opposite, the sound field can be considered equivalent with the divergent one generated by a *virtual source*. This is a linear source, perpendicular to the route plane, having the height h equal with the blade's width. It is positioned in the curvature center O′ of the traffic trajectory, and only emitting radially back and forth in the dihedral angle corresponding to the plane angle $\theta = l/R$.

The total sound power W, radiated through each side of the blade's surface $S_0 = hl = h\theta R$, will cross all areas $S = h\theta\rho$, seen under the same angle θ. The sound intensity at different distances ρ, from the curvature center O′ where the virtual source is located, will be:

$$I(\rho) = \frac{W}{S} = \frac{W}{h\theta\rho}. \tag{3$_1$}$$

For $\rho = R$, at the surface of the vibratory curved blade, we obtained the emission intensity I_0:

$$I_0 = \frac{W}{h\theta R} = \frac{W}{S_0} = \frac{W}{hl} = \frac{w}{h}, \tag{3$_2$}$$

where $w = W/l$ is the sound power emitted in the horizontal plane, per unit length of the real source, and $I_0 = W/hl$ is the intensity of the sound field "created" by the virtual source in the position of the vibrating blade.

Reporting the last two equations, we can write the sound intensity distributions:

$$\begin{aligned} I(\rho) &= \frac{w}{h}\frac{R}{\rho} = I_0\frac{R}{\rho}, \\ I(r) &= \frac{w}{h}\frac{R}{r-R} = I_0\frac{R}{r-R}, \end{aligned} \tag{4}$$

where w, I_0, and distances ρ and R are considered, in the algebraic sense, related to virtual source; $r = \rho + R$ being the distance reported to the lamellar real source.

The generality and versatility of relation (4) consists in its applicability to any curvature radius of the equivalent vibratory blade, and to any traffic, inclusively to straight road segments (Cosma, Popescu, 2015), where the radius of curvature $R \to \infty$. Without absorption and diffusion, the sound intensity remains constant, $I(\rho) = I_0 = w/h$, i.e., the sound flow does not spread, remaining with the same section lh of the vibrating blade.

2.2. Level of noise generated by the curvilinear traffic

The sound field generated by curved vibratory blades can be described more clearly, qualitatively and quantitatively, through intensity distribution. By operating with this model, we can better observe the similarities and differences as compared to the normal emission and reflection of light rays on the concave and convex faces of the cylindrical mirrors.

The level of sound radiated in the horizontal plane by a curved lamellar source of W power output, on each side of the area $S_0 = lh$, according to (4) will be:

$$\begin{aligned} L(r) &= 10\log\frac{I(r)}{I_{\text{ref}}} = 10\log\frac{I_0}{10^{-12}}\frac{R}{(r-R)} \\ &= 10\log\frac{I_0}{10^{-12}} - 10\log\frac{|r-R|}{R} \\ &= L_{I_0} - 10\log\frac{|r-R|}{R}. \end{aligned} \tag{5$_1$}$$

If we relate the positions in the sound field to the virtual source by $\rho = r - R$:

$$L(\rho) = L_{I_0} - 10\log\frac{|\rho|}{R}. \tag{5$_2$}$$

A traffic flow $Q = N/t$, consisting of N vehicles with an individual horizontal acoustic power W_0 and speed $\mathbf{v}$, or the same average values, will have the power output per unit of length: $w = NW_0/l = NW_0/vt = W_0Q/v$.

The level of noise intensity generated at a curved road related to traffic parameters according to the Eq. (4) will be:

$$\begin{aligned} L(r) &= 10\log\frac{w}{hI_{\text{ref}}}\frac{R}{r-R} = 10\log\frac{W_o}{hI_{\text{ref}}}\frac{\text{Q}}{\text{v}}\frac{R}{r-R} \\ &= L_{W_0} + 10\log\frac{\text{Q}}{\text{v}} - 10\log\frac{|r-R|}{R}, \end{aligned} \tag{6}$$

where the sum of the first two terms represents the power level per unit length of the traffic. With Eqs. (6) we can evaluate the *noise intensity level*, which in fact, for normal conventional weather conditions, is not significantly different from the noise level related to pressure.

3. Special aspects for the noise assessment of the real traffic

The noise assessment of the real traffic, considering the models presented above, is more restrictive in geometrical shapes, as compared to the case of extensive sources: spherical with 3D symmetry or linear with 2D cylindrical symmetry (Cosma, Popescu, 2015). For any real shape of emitting surface, only vertical parts of vehicles are considered in modelling the traffic.

For a random granular traffic, instead of the general values defined in (1), one may consider the mean values of the power emission per unit length of the traffic:

$$w_m = \frac{1}{n}\sum_{i=1}^{n} w_i = \sum_{i=1}^{n} w_i p_i, \tag{7}$$

where w_i are the n random discrete values with p_i probability or statistical weight, $p(x)$, for continuous variables, which is called the repartition or distribution function.

The psychophysical restraints state that temporal and locative analysis of noise levels, such as measure of pollution, make sense only by statistical mean values. As the harmful physiological effects of noise exposure are cumulative, they can be evaluated by the energy dose of noise $D = It$ ($\mathrm{J}\cdot\mathrm{m}^{-2}$ or Pa^2 s) (Cosma, Popescu, 2010). The practical unit used in sound exposure meters is Pa^2 h. The *noise exposure level*, numerically equivalent to the total noise energy level, is also used.

The noise exposure level may be relevant only in terms of mean equivalent values. For the punctual scalar effective observables of local traffic noise sources, one should work with statistical mean value (arithmetic average). So, for continuous monitoring of traffic noise, the level is:

$$L_m = \frac{1}{t-t_0}\int_{t_0}^{t_1} L(t)\,\mathrm{d}t, \tag{8}$$

where the defined integral represents the area bounded by the time axis and the graph of the recorded quantities at the moments t_0 and t_1.

Optimisation of the traffic speed may be taken into account to avoid bottlenecks. An asymmetric Poisson distribution is considered for speed limited traffic, and a normal Gaussian distribution will fit for the free traffic speeds. Usually in such cases, the assessment of traffic noise is analysed statistically (Berg *et al.*, 2000; Berg, Woods, 2001; Stefano *et al.*, 2001; Tong Li, 2007).

4. Numerical applications

The variation with distance of the noise level emitted by the traffic on a curved road, given by relations (5) and (6), can be better understood by presenting a numerical case study and graphical representation. For this purpose, we will deem a 200 m long convoy, consisting of 10 lorries with laterals of 10m long and 2.5 m height, going with 72 km/h on a road with curvature radius $R = 500$ m. If the sound power output of each lateral side is 1 watt, the noise level depending on the distance in the air, without and with absorption ($\alpha = 0.1\cdot 10^{-2}\ \mathrm{m}^{-1}$), will be expressed by relations:

$$L_0(r) = 100 - 10\log\frac{|500-r|}{500}$$

and

$$L_a(r) = 100 - 0.01\,|r| - 10\log\frac{|500-r|}{500}\ \mathrm{dB}.$$

The calculated power level per unit length of the traffic for the considered noise source is 100 (dB).

The curves in Fig. 3 show the influence of divergent propagation by comparison, without and with absorption, on the noise levels $L_0(r)$ and $L_a(r)$. We notice that in the centre of the curvature, for $r = 500$ m, an indefinite maximum is reached though it is affected by absorption. For $r = 0$, when the absorption is not considered, the value is 100 dB, that is the same with the emission from the concave side of the road.

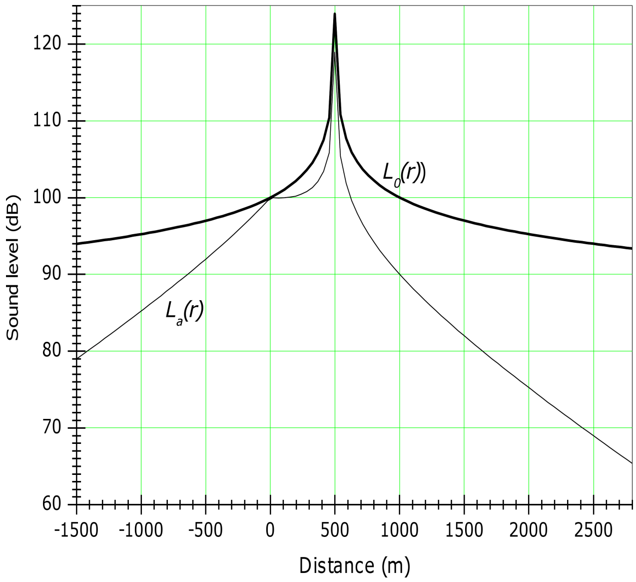

Fig. 3. Divergent propagation, influence of absorption.

The noise level is affected to a little extent by the road width. Thus, for a road width of 6 m and radius of curvature $R = 500$ m, if we add for the convex and respectively subtract $a/2 = 3$ m, for the concave edge, there is a negligible difference between the noise levels at the two margins of the road:

$$\Delta L = L_{\text{in}} - L_{\text{ex}} = 10\log\frac{R+a/2}{R-a/2}$$

$$= 10\log\frac{500+3}{500-3} = 0.05\ \mathrm{dB}.$$

The use of these models for predicting noise levels becomes more credible through experimental proofs and adjustments to the traffic characteristics. Thus, for a given road having a certain curvature radius, the noise level is recorded under standard conditions and the most probable value for the considered period is chosen.

Knowing the absorption coefficient, corresponding to the average frequency and air humidity, one can get the noise variance $L(r)$ for $r < 0$ and for $r > 0$ in the convex, respectively concave region of the road. Equations (5) will be supplemented by the term $\alpha|r|$, due to the atmospheric absorption, and the dependence of noise level on distance will be:

$$L(r) = L_{I_0} - 10\alpha\,|r| - 10\log\frac{|r-R|}{R}.$$

For the experimental values of level L_{I_0}, recorded with a sound level meter in two different traffic situations, and considering the absorption coefficients $\alpha_1 \neq \alpha_2$ suitable to weather conditions, the graphs of noise levels in adjacent zone of the same curved road of radius $R = 400$ m are drawn as shown in Fig. 4.

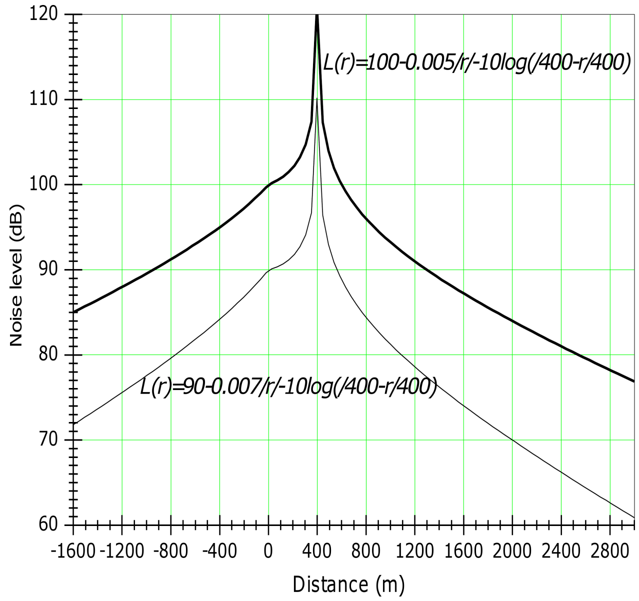

Fig. 4. Traffic noise levels in two different conditions.

The advantage of adding the values of original, experimentally obtained L_{Io} to the analytical formula (5) consists in removing the difficulties and errors in choosing the parameters for evaluation of the noise power per unit length of traffic flow and average traffic speed on the considered road.

By correlating the traffic composition with the corresponding graphs, one can establish the influence of different factors on the traffic noise levels and their distribution.

5. Conclusions

Our study on modelling the level of noise generated by traffic sources highlights the complexity of acoustical and mathematical correlations between the observables that characterise sound fields. Starting from an analysis of emission and propagation of noises produced by a real discontinuous traffic on curved roads, we have developed two theoretical models for equivalent sources consisting of toroidal-tube surfaces or curved vibrating blades. Having a high degree of generality and versatility, the curved vibrating blade model enables the study of spatial noise intensity distribution, considering a certain virtual source, generating in the trajectory plane an equivalent field with the real source.

The calculus of traffic noise level through a stated formula, starting from the considered acoustical and geometrical parameters, allows the prediction of sound level and drawing of noise maps (Czyzewski *et al.*, 2011; Popescu *et al.*, 2011). This also gives the possibility to find the noise level distribution using a single sonometric recording. Correlated with the stochastic mean values, the study above allows the prediction of noise exposure dose, an essential physiologic descriptor of noise effects.

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