Traffic noise reduction using periodically spaced rectangular roughness

Alex Stronach (1)

(1) Wood Plc., Perth, Australia

ABSTRACT

A practical method for traffic noise control is to disrupt the transmission path between the source and the receiver using methods such as acoustic barriers. However, in urbanised areas, the implementation of barriers is impractical due to the limited space or the potential for obstruction of view. This paper presents alternative methods for traffic noise control by exploiting the acoustic ground effect which results in destructive interference between the direct waves travelling between the source and receiver and the reflected waves from the ground. The introduction of a porous ground surface between the source and receiver allows for the destructive interference minima to occur at lower frequencies than for an acoustically rigid surface thereby allowing for passive mitigation of acoustic signals. The frequency at which this occurs can be readily controlled via the implementation of model impedance surfaces such as periodically spaced roughness. This paper provides details of a study undertaken to explore the potential benefits of periodically rough surfaces for traffic noise mitigation.

1 INTRODUCTION

Noise disturbance is a risk to public health. Traffic noise can be constant on roads with high traffic flows and result in physiological effects as a result of stress or sleep deprivation. High noise levels can also reduce the level of natural tranquillity associated with public spaces such as parks and reserves. Noise mitigation can be achieved by either controlling the levels at the source, within the transmission path, or at the receiver.

The two primary sources of traffic noise are the vehicle engines and tyre-road interaction. The design of quiet cars that contain a running internal combustion engine can be a difficult and expensive task, with different engines requiring different mitigation and parts that will deteriorate over time (Fard *et al.,* 2013). Contrarily, electric cars have the problem that they do not emit enough noise which can put pedestrians and other drivers at risk if their sight of the vehicle is obstructed. Assuming a residential dwelling as a receiver, the control of traffic noise can be achieved via the installation of adequate sound insulation in the form of façade treatment and glazing. However, this can become expensive if high levels of sound insulation are required and can compromise other areas of the building design such as thermal efficiency and ventilation.

The preferred option is to mitigate sound within the transmission path between source and receiver. This is typically achieved through the installation of acoustic barriers. However, barriers are less effective at mitigating low frequency noise and the varying height of vehicles introduces further complications to the design. Tyre-road interaction occurs at frequencies around 1 kHz (Mahn, 2011) and thus barriers can provide a good level of attenuation at these frequencies. However, as the density of residential properties in urban areas increases, barriers become less desirable since they can obscure views. This provides the motivation for alternative means of noise mitigation, such as the exploitation of the acoustic ground effect.

Attenuation due to the ground effect arises as a result of interference between direct waves travelling between source and receiver and waves reflected by the ground surface. A means of analysis for sound propagation over such ground surfaces involves the introduction of an image source directly beneath the real source. The strength of this image source is dependent upon the reflection coefficient of the surface, surface impedance and the angle of incidence (Peters *et al*, 2011).

A frequency-dependent change of phase occurs for porous surfaces as a result of the surface impedance, defined as the ratio of the sound pressure to the normal component of particle velocity at the surface. This can lead to attenuation due to the interference between direct and reflected waves. This change of phase means that for porous surfaces, the first destructive interference occurs at a lower frequency than it otherwise would if the sound were propagating over hard ground.

2 GROUND EFFECTS IN NOISE CONTROL

Accurate models that can predict the surface impedance, and therefore the reflection coefficient of the surface, are needed to exploit the acoustic ground effect for noise mitigation. However, this is not provided within the current standards.

Firstly, ISO 9613-2:2024 (ISO, 2024) treats surfaces with low porosity as acoustically rigid and those with a high porosity as acoustically soft. This is an oversimplification since many surface properties can influence the surface impedance. A useful model for the characterization of surface impedance is the 'slit-pore model' (Attenborough *et al.*, 2016) which makes use of the porosity, flow resistivity, and layer depth to determine the surface impedance. This model allows for a surface to be simulated as one containing a number of slit-like pores with a shape factor s_0 to characterize their shape. The porosity is the ratio of the volume of the pores V_p to the total volume V_T within the material and given by:

$$\Omega = \frac{V_p}{V_T} \tag{1}$$

The flow resistivity is a measure of how readily air can flow in and out of the pores of a material. It is the ratio of the applied pressure gradient to the induced flow rate per unit thickness within a material. It is dependent on the dynamic viscosity μ of the medium, the tortuosity (or the deviation the path of the sound takes from a straight line) T, the radius r of the pore, the pore shape factor, s_0

$$R_s = \frac{12\mu T s_0}{\Omega r^2} \tag{2}$$

The attenuation achieved by such surfaces is reliant on the determination of the surface impedance and using the correct surface to achieve mitigation at the frequencies of interest. The mitigating properties of outdoor ground surfaces can be compromised by seasonal variations in weather and aridity and by extra vegetation that may be introduced. Foliage and stems in vegetation can scatter sound which can alter the intended ground effect. This makes the accurate determination of the attenuating properties of outdoor ground surfaces difficult and therefore model surfaces of known, fixed impedance is a desirable option.

3 SOUND PROPAGATION OVER ROUGH SURFACES

The focus of this paper is surfaces comprised of artificial, periodically spaced roughness. Upon interaction with surface roughness, sound is scattered with the nature of the scattering dependent upon the surface topology and the ratio of the roughness dimensions to the wavelength of incident sound. This contributes to a change in the ground effect provided enough of the reflected sound retains a phase relationship with the incident sound.

The diffraction assisted ground effect was investigated by Bashir *et al*. with measurement and simulation of excess attenuation (the ratio of the spectrum of the total sound field over the surface and the field in the absence of the surface). The excess attenuation spectra showed three distinct destructive interference maxima. The first maximum is a result of the ground effect and appears for both periodic and aperiodic arrays of roughness. This is called the roughness-induced ground effect maxima. The second destructive interference maximum is attributed to diffraction grating effects and the third to Bragg diffraction which occurs when two waves interfere constructively or destructively due to their path length difference. It is only the first destructive interference maximum that is of interest in this project.

Bougdah *et al*. also investigated the use of periodically spaced edges for road traffic noise abatement. It was found that rib-like structures can provide attenuation of up to 10 – 15 dB between 160 Hz and 1250 Hz because of the roughness-induced ground effect. However, signal enhancing effects were also observed to occur when sound propagates over periodic roughness arrays due to the generation of airborne acoustic surface waves. Surface waves arise due to the elliptical motion of air particles resulting from the vector combination of the compressional motion of sound over the surface and the vertical motion of the air particles in between the roughness elements. Energy at certain frequencies can be ‘trapped’ close to the ground as a result resulting in enhancement at certain frequencies. Enhancement effects due to quarter wavelength resonances and interference effects in the spacing between elements have also been observed (Stronach, 2019).

4 SUMMARY

It has been found that characterising the ground impedance properties is essential in determining the mitigating properties of outdoor ground surfaces. Since the weather can alter the impedance of natural outdoor ground surfaces, model rough surfaces are preferable since they can be the geometry and topography of the surface can be set to mitigate a frequency range of interest. These surfaces can also be modelled as slit-pore impedance layers. However, the topographical effects of the surface will be lost and thus the surfaces are not modelled in this way in this project.

This paper contains a presentation of a case study into the use of periodically spaced roughness for traffic noise abatement.

5 METHODOLOGY

5.1 Source Spectrum

The source spectrum has been obtained by calculating the Fast Fourier Transform (FFT) of a one-hour audio recording of freeway traffic noise. The audio file contains a large number of samples and thus the input was split into a smaller FFT sample size of 4096 points and the FFT computed for each segment. The sampling rate was calculated to be dt = 2.28x10^{-5} s and thus the time taken to compute 4096 samples is 0.093 s.

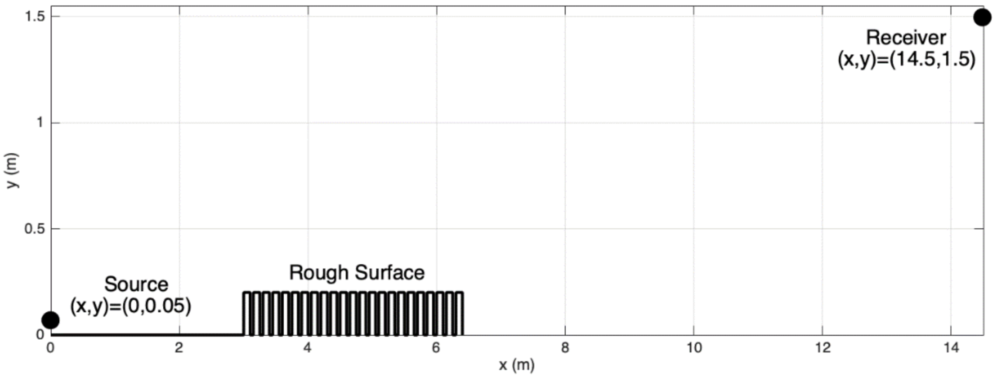
The number of 4096-sample groups required to obtain 15-minutes worth of data is therefore 9689 samples. The 15-minute traffic noise spectrum can be obtained by computing the FFT for 9689 groups of 4096 samples and calculating the average level for each frequency point.

5.2 Modelling of Roughness Elements

The sound field generated over the periodic rough surface has been obtained using the Boundary Element Method (BEM). The 2D BEM used here (Taherzadeh, 2001) has the benefit that the ground surface on which the roughness elements are placed does not require discretization. Instead, it can be modelled by defining impedance parameters such as porosity and flow resistivity which can easily characterize the surface in question. This significantly improves the computational efficiency of the model. The impedance parameters can then be defined for each element. The elements are acoustically rigid and therefore each has been assigned a porosity of Ω=0.01 and flow resistivity R_s=5×10^6 Pa s m^{-2}.

The rough surface will be situated approximately 3 m from the edge of the road and comprise 3.5 m of roughness elements. BEM simulations were run for roughness heights varying between 0.01 m and 0.10 m to determine the most suitable geometry to mitigate traffic noise around 1 kHz since this is the frequency at which tyre-road interaction is thought to be most prominent. A simulation was carried out to determine the sound spectrum in the absence of roughness, based on the assumption that the ground is acoustically rigid. This was used to determine the expected overall reduction in traffic noise levels. A typical modelling setup is shown in Figure 1.

Figure 1: Roughness elements separated by 0.05 m with a heigh of 0.2 m



In addition to roughness elements placed on hard ground, a simulation was carried out where the gap between roughness elements was filled with gravel. This was achieved by modelling the gap as being a strip which is 50% of the rectangular roughness height and assigning porosity, Ω and flow resistivity, R_s values in line with that of gravel, obtained from HOSANNA 4.1. It is thought that if the gaps between roughness elements can be filled with gravel, then they can be made to appear more aesthetically pleasing through the implementation of trees, plants or decorations.

Table 1: Impedance parameters for acoustically hard surface and gravel

Material	Porosity, Ω (%)	Flow Resisitivity, R_s (Pa s m^{-2})
Acoustically Hard Surface	1.0	5.0×10^6
Gravel	38.0	5.8×10^4

5.3 Modelling of Traffic Noise Reduction

Convolution of the traffic noise spectrum and the spectrum of the sound field over periodically spaced roughness yields the total sound field predicted over a surface with periodic roughness. When calculating the full spectrum $T(f)$, it is important to note that the spectrum is calculated between 0 and the Nyquist frequency (half the sampling frequency) since it is not possible to calculate the spectrum for negative frequencies. The fact that the solution to the Helmholtz wave equation is conjugate symmetric may be utilized to obtain the full spectrum using equation (3) below.

$$T(f) = \overline{T(-f)} \tag{3}$$

Once the full sound pressure spectrum was obtained from the BEM and the process above, the result may be combined with the traffic noise spectrum via the process of convolution to obtain the effect that the roughness elements has on the level of traffic noise. Taking the traffic nose spectrum as the source spectrum $S(f)$ and the output of the BEM as the transfer function $T(f)$, the resulting spectrum is the convolution of the two given by equation (4):

$$Q(f) = S(f) * T(f) \tag{4}$$

The sound pressure level may then be calculated using equation (5)

$$SPL = 20\log_{10}\left(\frac{Q(f)}{p_0}\right) \tag{3}$$

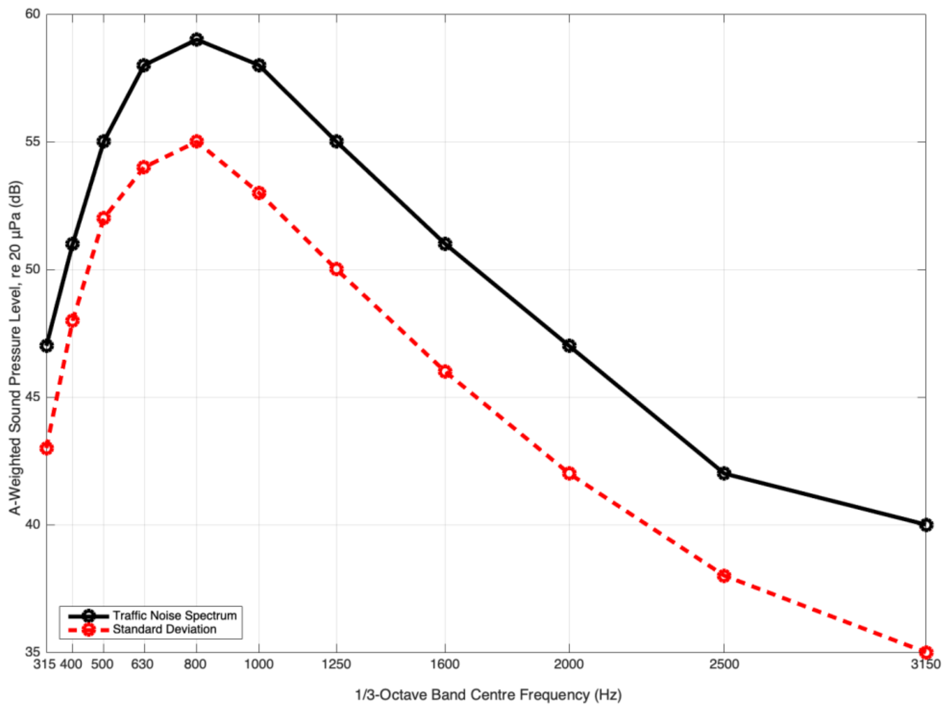
where p_0 is the reference sound pressure level of 20 μPa.

6 RESULTS

6.1 Traffic Noise Spectrum

The A-weighted traffic noise spectrum in 1/3-octave bands is shown in Figure 2 below.

Figure 2: Traffic noise spectrum

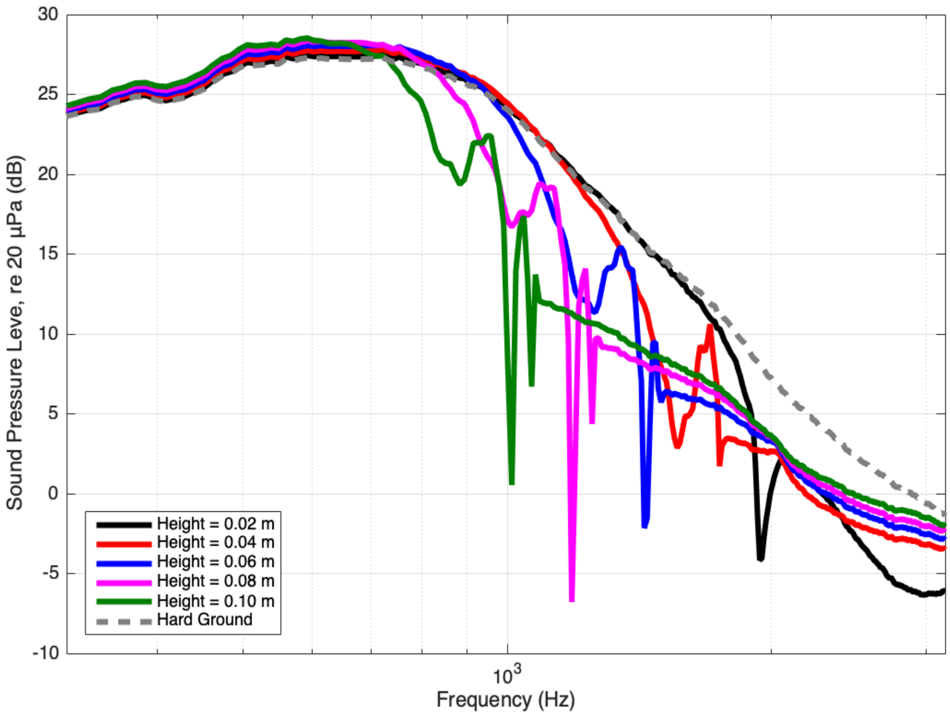


The spectrum shows a clear peak in the 800 Hz band with high noise levels also present in the 630 Hz and 1 kHz bands. The mean standard deviation across all frequency bands is calculated to be around 4 dB(A) which is consistent for the various 15-minute periods throughout the input signal and is therefore considered accurate.

6.2 Comparison of Full Spectra for Different Roughness Heights

BEM simulations were conducted for roughness heights varying between 0.01 m and 0.10 m. The results for the roughness with even values for height are presented in Figure 3 below and compared with the spectrum after propagation over acoustically hard ground. This is presented to demonstrate the various effects that occur following sound interacting with periodic roughness such as surface waves and the roughness-induced ground effect.

Figure 3: Comparison of the sound field over roughness with varying height.



The first thing to note is the increased levels at lower frequencies between 400 Hz and 700 Hz. This is a result of surface wave generation due to the compressional nature of the sound interacting with the vertical to-and-fro motion of the air particles in the gaps between roughness elements. The frequency at which the surface wave propagates is mostly unchanged by the change in roughness height although it can be seen to become narrower as the height is increased and thus a narrower range of frequencies are enhanced via its formation.

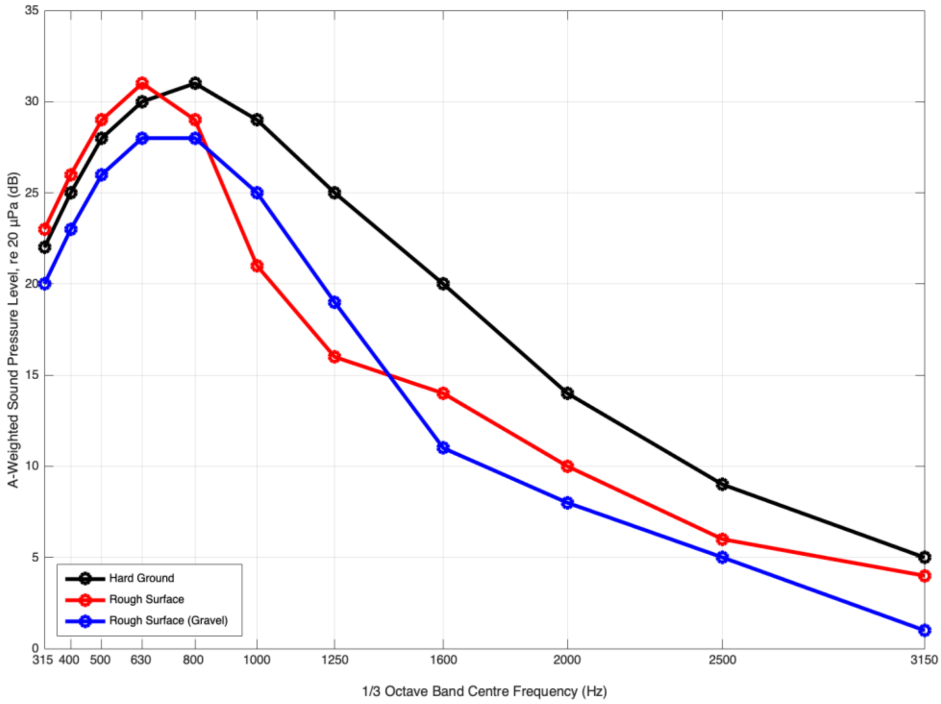
Secondly, the roughness-induced ground effect is observable as a sharp minimum in the spectrum. The frequency at which this occurs can be seen to decrease with increasing roughness height. The amount by which the ground effect frequency decreases is also reduced with increasing roughness height which indicates that lower frequency noise could potentially be difficult to mitigate unless large roughness heights are available.

A roughness height of 0.10 m is shown to effectively reduce noise levels at 1 kHz.

6.3 Traffic Noise Over Roughness

The results in Figure 4 show the results of traffic noise propagation over an acoustically hard surface, periodic roughness, and periodic roughness with gravel in the gaps.

Figure 4: Spectrum of traffic noise over hard ground, periodic roughness, and periodic roughness with gravel in the gaps.



Firstly, the surface wave is visible in the frequency bands between 315 Hz and 630 Hz as an increase in the sound pressure level to that in the absence of roughness. The enhancement in these frequency bands is eradicated by the presence of gravel within the gaps due to the fact the interactions that would otherwise occur between the incident sound and the air within the gaps is disrupted.

The noise level is reduced by 2 dB(A) in the 800 Hz band in the presence of roughness and by 3 dB(A) when gravel is introduced into the gaps. However, in the 1 kHz band the level is reduced by 8 dB(A) without gravel and only 4 dB(A) with gravel. This indicates that whilst the gravel is useful in reducing the enhancement at low frequency due to the disruption of the surface wave generation, the reduction achieved in the band corresponding to noise generated by tyre-road interaction is compromised.

The $L_{Aeq,15min}$ may be calculated by summing over all the levels and dividing by the number of frequency bands. This calculating yields the following values in Table 2.

Table 2: Impedance parameters for acoustically hard surface and gravel

Material	$L_{Aeq,15min}$ (dB)
Acoustically Hard Surface	25
Rough Surface	21
Rough Surface (Gravel in Gaps)	20

There is a 4 dB(A) reduction achieved when periodic roughness is introduced, and 5 dB(A) achieved if the gap is filled to 50% of the roughness height with gravel.

7 CONCLUSIONS AND FURTHER WORK

Simulations using the Boundary Element Method of the total sound field over a periodically rough surface were convolved with a traffic noise spectrum obtained from a recording of traffic noise and the resulting spectra compared with that for sound propagation over acoustically hard ground. Whilst more accurate measurements would improve the sound pressure levels reported, the model developed in this paper has proven effective when investigating the potential reduction achievable by rough surfaces.

It has been shown that a reduction of up to 8 dB(A) in the 1 kHz 1/3-octave band is achievable with a roughness height of 0.10 m. However, insertion of gravel in the gaps decreases the reduction achieved to 4 dB(A). This occurs despite the surface reducing signal enhancement at lower frequencies due to the generation of a surface wave and making the surface more aesthetically pleasing.

Future work will involve the use of measured traffic noise data and a variation of the material within the gaps Model rough surfaces may also be constructed to measure the effect of traffic noise reduction achievable by rough surfaces in practice.

REFERENCES

Attenborough. K., Bashir. I., Taheradeh. S. (2011), '*Applicable Ground Models*', FP7 HOSANNA Deliverable 4.1

Attenborough. K., Li. K.M., Horoshenkov. K (2007), *'Predicting Outdoor Sound,'* Taylor & Francis, UK

Bashir. I., Taherzadeh. S., Attenborough. K. (2012), 'Diffraction assisted rough ground effect: Models and data,' *J. Acoust. Soc. Am*, 133(3), 1281 – 292

Boughdah. H., Ekici. I., Kang. J. (2006), 'A laboratory investigation of noise reduction by rib-like structures on the ground,' *J. Acoust. Soc. Am*, 120(6), 3714 – 3722

Fard. S.M., Kessissoglou. S., Samuels. S., Burgess. M, (2013), 'A review of road traffic barriers for low frequency noise,' *Proceedings of Meetings on Acoustics (ICA 2013 Montreal)*, 19, 1 – 6.

ISO 9613-2:2024, *'Attenuation of sound propagation outdoors – Part 2: General method of calculation'*

Mahn. J. (2011), 'Road Traffic and Aircraft Noise Spectrums,' Acoustics Research Group Report: Department of Mechanical Engineering, University of Canterbury, Christchurch, No. 73.

Peters. R.J., Smith. B.J., Hollins. M. (2011), *'Acoustics and Noise Control (Third Edition),'* Pergamon Education Limited, UK

Stronach, A., (2020). An Investigation of the Sound Field Above a Surface With Periodically-Spaced Roughness. PhD thesis, The Open University.

Taherzadeh.S., Li. K.M., Attenborough. K. (2001), 'A Hybrid BIE/FFP Scheme for Predicting Barrier Efficiency Outdoors', *J. Acoust. Soc. Am*, 110 (2)