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Research Paper

Risk Assessment of Noise-Limit Exceedance Using Banach Random Walk in Noisy Space

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We develop a probabilistic method for assessing the risk that the level generated by a noise source exceeds a permissible limit. The physical input is a sequence of acoustic pressure pulses represented by their energy contributions, while the regulatory output is a decibel level compared with that limit. The model uses the Banach random walk in noisy space (BRWNS), in which a source is steadily supplied with energy and randomly emits pulses into the environment. The exceedance risk is defined as the probability that at least one partial mean-energy level in an observation window exceeds the permissible limit. We derive an explicit integral expression for this probability by transforming the decibel threshold back to an energy threshold. The result shows that the permissible limit determines the part of the stochastic energy domain over which the BRWNS density must be integrated. The interpretation is linked to classical acoustic level operations, including energetic addition of levels and background-noise correction. A road-traffic example illustrates how environmental limits can be translated into the model threshold. Monte Carlo simulations for the standard BRWNS show a sharp increase in the exceedance probability when the source energy becomes larger than the transformed permissible limit.

Keywords: acoustic noise, noise limits, risk assessment, environmental regulation, road-traffic noise.



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1. INTRODUCTION

Noise limits are usually expressed in decibels, but they are defined for specific acoustic quantities, source classes, reference periods, and regulatory purposes. In environmental acoustics, the European framework is based on the assessment and management of environmental noise, strategic noise maps, and action plans (European Parliament and the Council of the European Union, 2002; European Commission, 2015). International Organization for Standardization [ISO] (2016) defines the basic quantities and assessment procedures for environmental noise, and ISO (2017) gives procedures for determining sound pressure levels. Health-oriented guidelines emphasize that road-traffic, railway, aircraft, wind-turbine, and leisure noise are associated with annoyance, sleep disturbance, cardiovascular outcomes, and other effects (World Health Organization Regional Office for Europe, 2018; BASNER *et al.*, 2014; GUSKI *et al.*, 2017; VAN KEMPEN *et al.*, 2018).

To illustrate these differences specifically, we use the Polish environmental regulation as an example. Environmental noise limits are specified in the consolidated regulation (Minister of the Environment, 2014). For roads and railway lines, the daytime *A*-weighted equivalent continuous level $L_{Aeq,D}$ is evaluated over 16 h, while the corresponding night-time level is evaluated over 8 h. In single-family residential areas and areas connected with

permanent or temporary stay of children and youth, the limits are 61 dB in daytime and 56 dB at night. The daytime quantity is used below in the road-traffic example.

A comparison with occupational noise assessment shows why this distinction is important: the regulated quantities and reference periods are different (Minister of Family, Labour and Social Policy, 2018). That regulation distinguishes, for example, the 8-hour noise exposure level from the maximum A -weighted sound level and the C -weighted peak sound level. In this terminology, A -weighting is the standard frequency weighting used to approximate human hearing sensitivity, whereas C -weighting is flatter and is used for peak-level assessment.

Against this regulatory and measurement background, environmental-noise assessment is mostly organized around determining exposure indicators over specified reference periods. Road-traffic noise models compute sound emission from vehicle classes, speed, flow, road surface, acceleration, and propagation conditions (STEELE, 2001; KEPHALOPOULOS *et al.*, 2012; 2014).

More recent models also account for distributions of vehicle sound power levels and the event structure of traffic noise (DE COENSEL *et al.*, 2016). The indicators obtained in this way – whether measured, calculated, or predicted, such as equivalent, day-evening-night, or night-time environmental-noise levels – are then compared with regulatory noise limits. This paper adds a probabilistic finite-window threshold-crossing formulation on the corresponding energy scale.

This addition requires two ingredients: a level conversion consistent with acoustic practice and a stochastic model for the emitted pulse sequence. The first ingredient is the logarithmic relationship between physical acoustic quantities and perceived or regulated levels. In acoustic level calculations, the logarithm is applied to positive scalar ratios of energies or squared pressures, in line with classical acoustics and psychoacoustics (FECHNER, 1860; ZWICKER, FASTL, 1999; MOORE, 2013; JACOBSEN, JUHL, 2013; BIES *et al.*, 2023). The second ingredient is probabilistic, because fluctuating noise should be represented as a sequence of random acoustic pulses. In this work, that sequence is modelled by the Banach random walk in noisy space (BRWNS), introduced in (BANEK, 2026) on the basis of the Banach random walk construction in (BANEK, 2016). BRWNS describes the distribution of acoustic energy into random pressure pulses emitted by a source that is continuously supplied with energy.

We use BRWNS to formulate a risk measure for noise hazard: the probability p_n that the level generated by a single source exceeds a permissible limit l during an observation consisting of n -pulses. The next section fixes the acoustic level notation and its connection with classical decibel operations. Section 3 recalls the BRWNS formulas and derives the exceedance-probability formula. Section 4 explains the environmental road-traffic interpretation. Section 5 presents numerical simulations, and Sec. 6 summarizes the results.

2. ACOUSTIC LEVEL NOTATION AND DECIBEL OPERATIONS

The logarithmic level map used below converts positive energy ratios into decibel levels:

$$\phi(q) = 10 \log_{10}(q), \quad q > 0. \quad (1)$$

The inverse conversion is

$$\phi^{-1}(l) = 10^{l/10}, \quad l \in \mathbb{R}. \quad (2)$$

Thus, ϕ^{-1} is the ordinary exponential conversion from a decibel level to the corresponding positive energy ratio.

Let $x_1, \dots, x_n$ denote pressure-pulse amplitudes recorded at the measurement point. The numerator in the level formula is the arithmetic mean of their squared amplitudes, interpreted as a quantity proportional to mean acoustic energy or mean squared pressure. With $E_0 > 0$ denoting the corresponding reference quantity, the level is

$$L_n(x_1, \dots, x_n) = 10 \log_{10} \left(\frac{x_1^2 + \dots + x_n^2}{nE_0} \right) = \phi \left(\frac{x_1^2 + \dots + x_n^2}{nE_0} \right). \quad (3)$$

Thus L_n is evaluated from the dimensionless scalar energy ratio:

$$\frac{x_1^2 + \dots + x_n^2}{nE_0}, \quad (4)$$

while the Banach-space construction supplies the probabilistic model for the pulse sequence. This is the finite-pulse analogue of the classical sound-pressure-level formula:

$$L_p = 10 \log_{10} \left(\frac{p_{\text{rms}}^2}{p_0^2} \right) = 20 \log_{10} \left(\frac{p_{\text{rms}}}{p_0} \right), \quad (5)$$

where p_{rms} is the root-mean-square (rms) sound pressure and $p_0 = 20 \mu\text{Pa}$ in air for the sound pressure level. In Eq. (3), E_0 plays the role of the reference mean-square pressure, or of the corresponding reference mean-energy quantity, after establishing the same frequency weighting and averaging convention.

This formulation is also consistent with standard decibel operations. If independent or incoherent contributions have levels $L_1, \dots, L_m$ relative to the same reference, their energetic sum is

$$L_{\text{sum}} = 10 \log_{10} \left(\sum_{j=1}^m 10^{L_j/10} \right). \quad (6)$$

Similarly, if a measured total level L_{tot} contains a background level L_{bg} , the source contribution is obtained, when the difference is physically meaningful, by

$$L_{\text{src}} = 10 \log_{10} \left(10^{L_{\text{tot}}/10} - 10^{L_{\text{bg}}/10} \right). \quad (7)$$

Equation (6) and Eq. (7) assume that all levels use the same reference quantity, frequency weighting, and averaging time. Equation (6) applies to energetically additive, mutually incoherent contributions. Equation (7) requires $L_{\text{tot}} > L_{\text{bg}}$; in measurement practice, the correction is reliable only when the total-background difference is sufficiently large. The BRWNS risk calculation is formulated on the same energy-ratio scale: the permissible limit l is first transformed by $\phi^{-1}(l) = 10^{l/10}$, and the probability is then computed for the corresponding energetic event.

3. NOISE HAZARD

A typical risk question in environmental or occupational noise assessment is: what is the probability that the noise produced by a source exceeds a permissible limit l during an observation window? If $(x_1, \dots, x_n)$ is a numerical realization of random variables $(X_1, \dots, X_n)$, then monotonicity of ϕ gives:

$$\begin{aligned} p_n &= \mathbb{P} \left(\phi \left(\sup_{1 \leq k \leq n} \frac{X_1^2 + \dots + X_k^2}{k E_0} \right) \geq l \right) \\ &= 1 - \mathbb{P} \left(\sup_{1 \leq k \leq n} \frac{X_1^2 + \dots + X_k^2}{k} < E_0 \phi^{-1}(l) \right) \\ &= 1 - \mathbb{P} \left(X_1^2 < E_0 \phi^{-1}(l), \dots, X_1^2 + \dots + X_n^2 < n E_0 \phi^{-1}(l) \right). \end{aligned} \quad (8)$$

After the decibel threshold has been expressed on the energy-ratio scale, the remaining modelling task is to describe the distribution of the random pulse sequence $(X_1, \dots, X_n)$. Classical level calculations specify how acoustic energies are transformed into decibel levels; a probabilistic noise model is additionally needed to quantify the chance of threshold crossing.

3.1. BANACH RANDOM WALK IN NOISY SPACE

The Banach random walk construction was introduced in (BANEK, 2016). Its acoustic version, BRWNS, was introduced in (BANEK, 2026); the reader is referred to these works for the full construction. For convenience, the formulas needed to compute p_n are recalled below. BRWNS is a coordinate process of a measure with density:

$$\rho_n(x_1, \dots, x_n) = \mathbf{1}_{\beta_n(\sqrt{E})}(x) \prod_{1 \leq k \leq n} \frac{Eg(E x_k / \sqrt{kE - x_1^2 - \dots - x_{k-1}^2})}{\sqrt{kE - x_1^2 - \dots - x_{k-1}^2}}, \quad (9)$$

where $E > 0$ is the source-energy scale, interpreted as the energy supplied per step at the measurement point:

$$\beta_n(\sqrt{E}) = \{x \in \mathbb{R}^n; x_1^2 + \dots + x_k^2 \leq kE \text{ for } 1 \leq k \leq n\}, \quad (10)$$

where g is an arbitrary density function on $[-E, E]$, i.e., $g \geq 0$ and $\int_{-E}^{+E} g(t) dt = 1$, and $\mathbf{1}_A$ is the indicator function of A . The coordinate process corresponding to Eq. (9) can be realized in the following steps:

1. Choose a point x_1 in the interval $[-\sqrt{E}, \sqrt{E}]$ at random with density

$$\frac{Eg(Ex_1/\sqrt{E})}{\sqrt{E}}. \quad (11)$$

2. Choose x_2 randomly in the interval

$$\left[-\sqrt{2E - x_1^2}, \sqrt{2E - x_1^2}\right] \quad (12)$$

with density

$$\frac{Eg(Ex_2/\sqrt{2E - x_1^2})}{\sqrt{2E - x_1^2}}. \quad (13)$$

3. Choose x_3 randomly in the interval

$$\left[-\sqrt{3E - x_1^2 - x_2^2}, \sqrt{3E - x_1^2 - x_2^2}\right] \quad (14)$$

with density

$$\frac{Eg(Ex_3/\sqrt{3E - x_1^2 - x_2^2})}{\sqrt{3E - x_1^2 - x_2^2}}, \quad (15)$$

etc. The sequence $x_1, \dots, x_n$ is random and the probability density function corresponding to this sample is given by Eq. (9).

BRWNS is a sequence describing the process of uniform charging and random discharging of an energy source. At the k -th emission, just before the pulse is generated, the available energy is

$$kE - \sum_{i=1}^{k-1} x_i^2. \quad (16)$$

After the k -th pulse and before the next emission, the available energy becomes

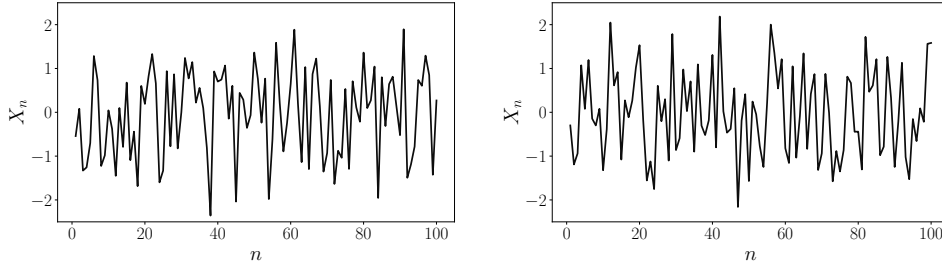
$$(k+1)E - \sum_{i=1}^k x_i^2, \quad (17)$$

which is consistent with the simulation recursion in Eq. (32). At this level of abstraction, the source may represent a highway or a region of the ocean. In these interpretations, successive vehicles or incoming waves supply new energy, while each pulse x_k emits the random energy x_k^2 into the environment, $k = 1, 2, \dots$

When the density g is uniform, i.e., $g(x) = \frac{1}{2E} \mathbf{1}_{[-E, E]}(x)$, then Eq. (9) takes the simpler form:

$$\rho_n(x_1, \dots, x_n) = 2^{-n} \mathbf{1}_{\beta_n(\sqrt{E})}(x) \prod_{1 \leq k \leq n} \frac{1}{\sqrt{kE - x_1^2 - \dots - x_{k-1}^2}}, \quad (18)$$

and we call the coordinate process for Eq. (18) a standard Banach random walk in noisy space (SBRWNS). Two sample realizations are shown in Fig. 1.

FIG. 1. Two sample SBRWNS paths with $E = 1$.

Remark 1. Equation (18) assigns larger density to paths whose cumulative emitted energy is close to the boundary of the support, that is, to paths for which

$$x_1^2 + \dots + x_j^2 \approx jE \quad (19)$$

for successive values of j . Thus, relative to paths with small cumulative emitted energy, near-boundary paths are favoured by the SBRWNS density. More precisely, for $\varepsilon > 0$ and $(x_1, \dots, x_{n+1})$ in the interior of $\beta_{n+1}(\sqrt{E})$ such that:

$$nE - \varepsilon \leq x_1^2 + \dots + x_n^2 \leq nE, \quad (20)$$

one has

$$\frac{\rho_{n+1}(x_1, \dots, x_{n+1})}{\rho_n(x_1, \dots, x_n)} \geq \frac{1}{2\sqrt{E + \varepsilon}}. \quad (21)$$

This is a bound on the conditional density of the next pulse. To favour emission of a large fraction of the available energy at each step, one can instead choose in Eq. (9) the density:

$$g(x) = \frac{1}{\pi\sqrt{E^2 - x^2}}. \quad (22)$$

Indeed, in this case Eq. (9) takes the form:

$$\rho_n(x_1, \dots, x_n) = \mathbf{1}_{\beta_n(\sqrt{E})}(x) \prod_{1 \leq k \leq n} \frac{1}{\pi\sqrt{kE - x_1^2 - \dots - x_k^2}} \quad (23)$$

for which

$$\frac{\rho_{n+1}(x_1, \dots, x_{n+1})}{\rho_n(x_1, \dots, x_n)} \geq \frac{1}{\pi\sqrt{\varepsilon}} \quad (24)$$

for paths in the interior of $\beta_{n+1}(\sqrt{E})$ satisfying $0 < (n+1)E - \sum_{i=1}^{n+1} x_i^2 \leq \varepsilon$. This expresses the increase of the conditional density as the emitted pulse energy approaches the available energy. We call BRWNS with the density given by Eq. (23) the noisiest.

3.2. APPLICATION TO NOISE HAZARD ESTIMATION

If $(X_1, \dots, X_n)$ is BRWNS, then the quantity p_n can be computed using the preceding construction. The result is summarized in Proposition 1.

Proposition 1. The probability p_n that at least one of the partial noise levels $L_1, \dots, L_n$ reaches or exceeds a permissible limit l is

$$p_n = 1 - \int_{\beta_n(\sqrt{E \wedge E_0 \phi^{-1}(l)})} \rho_n(x_1, \dots, x_n) \, dx_1 \dots dx_n, \quad (25)$$

where $a \wedge b = \min(a, b)$, ρ_n is given by Eq. (9) and $\beta_n(\sqrt{E})$ by Eq. (10). The probability in Eq. (25) can be evaluated either by integrating ρ_n on $\beta_n(\sqrt{E \wedge E_0 \phi^{-1}(l)})$ or by Monte Carlo simulation.

Proof. From Eq. (8) it follows that the integral

$$\int_B \rho_n(x_1, \dots, x_n) dx_1 \dots dx_n \quad (26)$$

is over the set

$$\begin{aligned} B &= \left\{ \beta_n \left(\sqrt{E} \right) \ni x; x_1^2 < E_0 \phi^{-1}(l), \dots, x_1^2 + \dots + x_n^2 < n E_0 \phi^{-1}(l) \right\} \\ &= \left\{ \mathbb{R}^n \ni x; x_1^2 + \dots + x_k^2 < k \left(E \wedge E_0 \phi^{-1}(l) \right), k = 1, \dots, n \right\} \\ &= \beta_n \left(\sqrt{E \wedge E_0 \phi^{-1}(l)} \right), \end{aligned} \quad (27)$$

where the equalities in Eq. (27) are understood up to sets of Lebesgue measure zero. Since ρ_n is a density, these differences do not affect the integral, which proves Eq. (25). $\square$

Remark 2. This energy convention also shows how propagation enters the model. In Eq. (9), the parameter E corresponds to the acoustic energy available at the receiver or sensor membrane at the measurement point, not to the total energy emitted by the source. During propagation, part of the emitted energy is absorbed by the medium or reduced by the distance, so the effective value of E depends on the distance r from the source and on attenuation parameters. This dependence can be written as

$$E = E(r, \alpha, \dots), \quad (28)$$

where α denotes attenuation. Once this effective energy scale has been fixed, Eq. (25) gives

$$p_n = f(E(r, \alpha, \dots)), \quad (29)$$

which shows how the exceedance probability depends on the propagation parameters. This is the convention used in the road-traffic interpretation below.

4. PRACTICAL INTERPRETATION FOR ENVIRONMENTAL ROAD-TRAFFIC NOISE

For environmental road-traffic noise, Eq. (25) translates a permissible limit expressed in decibels into the energy threshold used by the stochastic model. Suppose that the source is a road section and the receiver is located in a single-family residential area. Under the Polish environmental regulation, the daytime road-traffic limit in such an area is $L_{\text{Aeq,D}} = 61$ dB (Minister of the Environment, 2014), where $L_{\text{Aeq,D}}$ is the A -weighted equivalent continuous sound level for the daytime period. With the same weighting and averaging convention represented by E_0 , the BRWNS threshold for the partial mean energy is

$$E_0 \phi^{-1}(61) = E_0 10^{6.1}. \quad (30)$$

The event in Eq. (8) asks whether at least one prefix of the emitted pulse sequence crosses this transformed threshold.

As a simple scale comparison, suppose that a deterministic road-traffic model predicts a daytime level of 64 dB at the same receiver. The classical assessment would then report a 3 dB exceedance of the 61 dB limit. On the energy scale, this predicted level lies:

$$\frac{E_0 \phi^{-1}(64)}{E_0 \phi^{-1}(61)} = 10^{(64-61)/10} \approx 2, \quad (31)$$

that is, approximately a factor of two above the regulatory threshold in energy-ratio units. This is a scale conversion, not an exceedance probability. When E_0 , E , g , and n are chosen consistently with the observation

window, frequency weighting, pulse aggregation rule, averaging convention, and 16-hour daytime reference period, Eq. (25) gives the finite-window probability that the random pulse sequence crosses $E_0\phi^{-1}(61)$. Consequently, two situations with similar equivalent levels may still differ in the threshold-crossing probability if their pulse structure or observation length differs.

This also clarifies how BRWNS relates to road-traffic prediction models. CNOSSOS-EU provides a representative framework (KEPHALOPOULOS *et al.*, 2012). It estimates an equivalent level from traffic flow, speed, vehicle class, road surface, and propagation data. A deterministic model supplies the assessed or predicted receiver level, whereas the calibrated BRWNS model adds the probability of crossing the permissible limit within the chosen observation window.

5. NUMERICAL SIMULATIONS

The quantity p_n is estimated by Monte Carlo simulation of the BRWNS coordinate process. For each path, independent random variables Y_k with uniform density g on $[-E, E]$ are drawn and scaled according to:

$$t_1^2 = E, \quad X_k = \frac{t_k}{E} Y_k, \quad t_{k+1}^2 = E + t_k^2 - X_k^2. \quad (32)$$

This recursion enforces the constraint:

$$X_1^2 + \dots + X_k^2 < kE. \quad (33)$$

For a fixed n and level l , the partial sums are tracked and an exceedance is recorded whenever:

$$X_1^2 + \dots + X_k^2 \geq kE_0\phi^{-1}(l). \quad (34)$$

The estimator of p_n is the fraction of paths with at least one exceedance. This procedure is repeated for a grid of E values. The simulations are normalized model examples. The choice $E_0 = 1$ and $l = 4$ fixes a convenient reference threshold $E_0\phi^{-1}(l)$. For a physical limit such as 61 dB, the same curves can be interpreted after rescaling E by the corresponding threshold $E_0\phi^{-1}(61)$. The plots therefore show how p_n depends on source energy relative to the permissible energy threshold.

Figure 2 shows normalized estimates of p_n . The curves exhibit a clear transition near the threshold $E_0\phi^{-1}(l)$. For E below this value, the event in Eq. (34) is impossible because the walk is supported in the set defined by Eq. (33), so $p_n = 0$. Once E exceeds the threshold, the probability grows rapidly with E and with n , which is visible as a steep rise. The estimates shown here use 50 000 Monte Carlo paths; the remaining small fluctuations are consistent with sampling error.

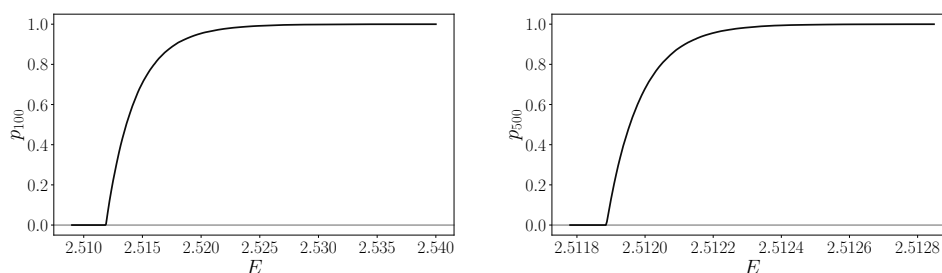


FIG. 2. Monte Carlo estimates of p_n in normalized units as a function of the normalized source-energy scale E , for $E_0 = 1$, $l = 4$, and two values of n : 100 (left) and 500 (right). The plots illustrate model behaviour and are not calibrated road-traffic simulations.

6. CONCLUSIONS

The main result is Proposition 1, which converts the problem of crossing a permissible noise limit into an integration problem for the BRWNS density. The logarithmic decibel scale enters only through the inverse

$\phi^{-1}(l) = 10^{l/10}$, which transforms the permissible limit into an energy ratio. This transformation changes the integration region in the BRWNS probability from $\beta_n(\sqrt{E})$ to $\beta_n(\sqrt{E \wedge E_0 \phi^{-1}(l)})$.

For environmental road-traffic noise, the result complements classical assessment methods. Existing standards and prediction models specify how to determine or predict the sound level at a receiver. After the stochastic pulse parameters have been calibrated to data describing the pulse sequence, source variability, and observation window, the BRWNS formulation can add a finite-window probability of crossing the permissible limit. The method is therefore best interpreted as an additional risk metric for classical equivalent-level assessment, not as a replacement for established environmental-noise prediction methods.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHORS' CONTRIBUTIONS

All authors contributed equally to the formulation of the research problem and its solution. The corresponding author additionally performed numerical simulations illustrating the results. All authors reviewed and approved the final manuscript.

USE OF AI TOOLS

During the preparation of this manuscript, the authors used GPT-5.6 Sol (OpenAI) to improve the language and to assist in writing the code used to generate the figures. The authors confirm that they reviewed and verified the AI-assisted outputs and take full responsibility for the integrity and content of the published article.

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