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Geometric and Pavement-Related Drivers of Rumble Strip Noise Generation: A Parametric Evaluation

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Abstract

Roadside and centerline rumble strips are widely deployed to mitigate run-off-road and crossover crashes by introducing tactile vibration and audible cues when tires traverse a patterned surface. The same mechanism that improves safety can also generate exterior noise that is perceived as intrusive by nearby communities, particularly where roadways pass through noise-sensitive land uses. This paper examines how rumble-strip geometry and pavement-related attributes jointly govern noise generation and its spectral characteristics, emphasizing a parametric viewpoint that can support design tradeoffs. A coupled framework is described that links tire excitation over periodic surface features to structural response in the tire–pavement system and to radiated sound quantified at a receiver through standard acoustic metrics. Geometric drivers include groove depth, width, spacing, profile shape, shoulder offset, and the spatial regularity of patterns, while pavement drivers include macrotexture, porosity, viscoelastic stiffness, surface temperature state, and construction variability. The analysis highlights that seemingly small geometric adjustments can shift dominant excitation frequencies into bands with higher human sensitivity, while pavement properties can amplify or damp specific bands through impedance, hysteretic losses, and air pumping pathways. A statistical modeling layer is used to separate systematic effects from nuisance variability associated with vehicle speed, tire type, and ambient conditions. The results motivate geometry–pavement co-optimization rather than geometry-only adjustments, and they clarify which parameters most reliably reduce A-weighted levels without eroding in-vehicle alerting performance.

1. Introduction

Rumble strips intentionally perturb the tire–road interaction to provide a salient warning stimulus. The warning is typically delivered through a combination of vibratory energy transmitted to the vehicle cabin and airborne sound radiated from the contact region and adjacent pavement. In many deployments, especially along rural highways with low background noise, the airborne component can be audible at substantial distances, and the temporal periodicity of the excitation can produce tonal or quasi-tonal content that is more noticeable than broadband traffic noise. These practical concerns create a design tension: the same geometry that maximizes alerting can also increase the exterior acoustic footprint. A technical treatment of this tension requires attention to both the excitation mechanism, which is strongly governed by rumble-strip geometry, and the transmission and radiation mechanisms, which depend on pavement texture, material state, and the acoustical environment.

A central difficulty is that rumble-strip noise is not a single-source phenomenon but a coupled outcome of mechanical impacts, stick–slip microdynamics, structural vibration, and aerodynamic pumping. When a tire encounters a groove, the local contact patch is forced to conform to a rapidly varying vertical and longitudinal profile. The forcing produces a time-varying normal load, modifies the tangential stress distribution, and can generate localized tread block deformation and release. The resulting vibration can excite tire structural modes, wheel and suspension responses, and a portion of the pavement system depending on stiffness contrast and layer bonding. In parallel, as the tread and groove form transient cavities, air flow is driven in and out of voids, producing acoustic monopole and dipole components whose relative importance depends on groove geometry and pavement porosity (1). The radiated sound field at a receiver then reflects propagation effects, including geometric spreading, ground interaction, atmospheric absorption, and potential shielding by roadside features. Because these mechanisms depend on parameters that vary across locations and over time, attributing noise levels to specific geometric features without controlling for pavement and operating state can be misleading.

The goal of this paper is to articulate, in a unified and quantitative manner, how geometric and pavement-related variables act as drivers of rumble-strip noise generation, and how their effects can be isolated and compared through parametric evaluation. The focus is not limited to any single rumble-strip standard. Instead, the analysis adopts a generalized parameterization that can represent milled grooves, rolled patterns, and formed profiles by a small set of geometric descriptors. Pavement state is similarly represented by descriptors that capture macrotexture amplitude, porosity, viscoelastic modulus, damping, and temperature dependence. The approach is aimed

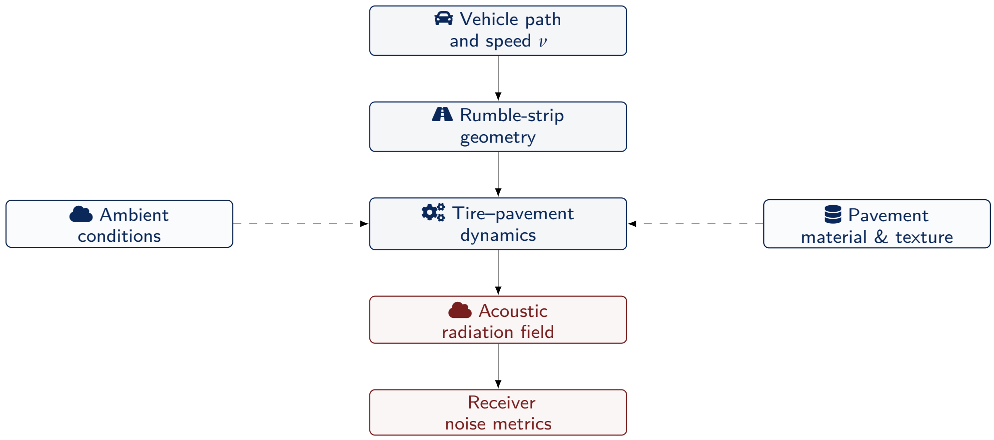

Figure 1. High-level structure of the coupled vehicle–rumble-strip–pavement–acoustic system. Geometry defines the periodic surface input, pavement and environment modify the interaction, and the combined tire–pavement dynamics feed an acoustic radiation stage whose outputs are summarized at receivers through engineering noise metrics.

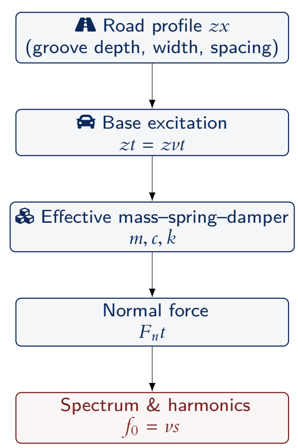

Figure 2. Kinematic and low-order dynamic chain from spatial rumble-strip profile to temporal excitation and spectral content. The periodic elevation profile is converted by vehicle speed into a base motion, filtered by an effective mass–spring–damper model to produce normal force modulation, and then mapped into a line spectrum dominated by the encounter frequency and its harmonics.

at producing engineering insights that are portable across agencies and climates, while acknowledging that absolute numerical predictions depend on local calibration.

A parametric viewpoint is particularly valuable because rumble-strip designs are often modified incrementally under constraints on milling equipment, construction tolerances, maintenance, and striping practices. Small geometric changes may shift excitation frequencies and change spectral balance, leading to different perceived loudness even if overall sound pressure level changes modestly. Moreover, geometric modifications can interact with pavement characteristics in non-additive ways (2). For example, increasing groove depth may increase mechanical impacts on a stiff, low-porosity surface, while on a porous friction course the same depth increase may be partially offset by increased aerodynamic losses into connected void space. Similarly, macrotexture that is beneficial for wet friction may increase broadband noise and mask tonal components, altering how the rumble-strip signature emerges from ambient traffic noise. These interactions motivate a model structure that can represent coupled effects rather than treating pavement as a passive boundary.

From a measurement and evaluation standpoint, rumble-strip noise is often characterized using A-weighted maximum levels, short-term equivalent levels, or octave-band spectra. While these metrics are practical, they can conflate changes in spectral composition with changes in total energy, and they can obscure the role of periodicity that drives annoyance. Therefore, this paper emphasizes frequency-domain analysis alongside overall metrics. The frequency content is linked explicitly to geometric spacing and vehicle speed through kinematic relations, then refined through contact dynamics and structural filtering. The analysis treats the time signal as a nonstationary process over the traversing event, but it leverages windowed spectral estimators to compare designs in a consistent manner.

The remainder of the paper proceeds as follows. A coupled modeling framework is presented that links geometric excitation to tire–pavement dynamics and acoustic radiation, including numerical methods that can be implemented with finite element discretization for structural components and with simplified radiation models for propagation. Then, geometric drivers

Table 1. Geometric descriptors of rumble-strip patterns and their qualitative influence on excitation and noise.

Parameter	Symbol	Primary role	Noise-relevant effects
Groove depth	d	Vertical deflection scale	Governs modulation of normal force; deeper cuts increase low-frequency excitation and potential contact loss on stiff, dense pavements.
Groove width	w	Encounter time $\tau_g \approx wv$	Narrow grooves shorten encounter time, increasing high-frequency content and modifying cavity volume for air pumping.
Groove spacing	s	Periodicity and $f_0 = vs$	Sets tonal families and their alignment with hearing-sensitive bands via harmonics of f_0.
Edge radius / curvature	r_e	Edge sharpness	Sharp edges generate impact-like loading and stick–slip; larger r_e smooths excitation and reduces high-frequency peaks.
Lateral offset	y_{off}	Tire path relative to lane	Changes which tires engage the strip and the source–receiver geometry, affecting both excitation and propagation.
Pattern length	L	Event duration $T = Lv$	Longer patterns yield narrower spectral lines and stronger tonality; shorter segments sound more impulsive.

are examined with attention to how depth, width, spacing, and profile shape influence contact forcing and spectral peaks. Pavement-related drivers are then analyzed, including stiffness, damping, texture, and porosity, with emphasis on how these properties alter both mechanical and aerodynamic pathways. Finally, a parametric evaluation methodology is described that combines design-of-experiments sampling, response surface modeling, and statistical inference to quantify sensitivities and interactions under uncertainty. The conclusion summarizes implications for design practice and highlights conditions under which geometry-only optimization is unlikely to deliver robust exterior noise reductions.

2. Coupled Tire–Rumble–Pavement–Acoustic Modeling

A useful starting point is to represent the rumble strip as a spatially varying surface profile imposed on the tire contact. Let the roadway elevation along the travel direction be denoted by zx, where x is the longitudinal coordinate. For a vehicle traveling at speed v, the tire experiences an effective base excitation $zt = zvt$, with derivatives scaling as $zt = vz'vt$ and $zt = v^2z''vt$. For periodic grooves with spacing s, the dominant encounter frequency in the kinematic sense is $f_0 = vs$, with harmonics arising from non-sinusoidal profiles and from nonlinear contact effects. This kinematic relation is necessary but not sufficient for predicting sound, because the amplitude and phase of the resulting force depend on how the tire deforms and how the contact patch evolves as it traverses the groove.

A compact mechanical representation treats the tire and local vehicle dynamics as a lumped or distributed system driven by base excitation. In a minimal model, the vertical dynamics are approximated by an effective mass–spring–damper system with displacement yt relative to an inertial frame and base displacement zt (3). The governing equation can be written as

$$myt \;\; c\left(yt - zt\right) \;\; k\left(yt - zt\right) = 0,$$

where m is an effective unsprung mass, k is an effective vertical stiffness, and c is an effective damping coefficient. The contact force transmitted to the pavement is then approximated as

$$F_nt = k\left(yt - zt\right) \;\; c\left(yt - zt\right),$$

with the understanding that F_nt must remain nonnegative and that contact loss can occur if excitation is severe. This representation captures a resonance-like amplification near the system natural frequency $f_n = \frac{1}{2\pi}\sqrt{km}$ and a filtering effect that shapes the force spectrum. However, it does not explicitly capture tread block dynamics, belt modes, or the spatially distributed nature of contact pressures.

To resolve spatial effects, a structural dynamics formulation can be employed for the tire and the pavement surface layer. Consider a finite element discretization of a tire cross-section or a portion of the tread and belt, with generalized coordinates collected in vector $\mathbf{u}t$. The semi-discrete equations of motion take the standard second-order form

$$\mathbf{M}\mathbf{u}t \;\; \mathbf{C}\mathbf{u}t \;\; \mathbf{K}\mathbf{u}t = \mathbf{f}_c t \;\; \mathbf{f}_b t,$$

Table 2. Principal mechanical and aerodynamic mechanisms contributing to rumble-strip noise and their characteristic frequency behavior.

Mechanism	Dominant pathway	Frequency content	Key dependencies
Normal-force modulation	Fluctuating $F_n t$	Low-to-mid frequencies near f_0 and harmonics	Depth and width, tire and pavement stiffness, vehicle speed.
Stick–slip microdynamics	Tangential slip in contact patch	Mid-to-high frequencies from rapid local events	Friction level, microtexture, edge sharpness, tread design.
Tire–wheel–suspension vibration	Unsprung mass dynamics	Resonant peaks at structural modes	Effective mass, stiffness, damping; coupling to road input spectrum.
Pavement layer vibration	Surface and slab modes	Low-to-mid frequency structural response	Layer stiffness contrast, joint behavior, viscoelastic damping.
Aerodynamic air pumping	Volume velocity Qt in grooves	Mid-to-high frequencies, often strongly A-weighted	Groove cross-section, tread sealing, surface porosity and flow resistivity.
Propagation and ground effects	Radiation above ground	Broadband with filtering	Ground impedance, receiver distance and height, shielding.

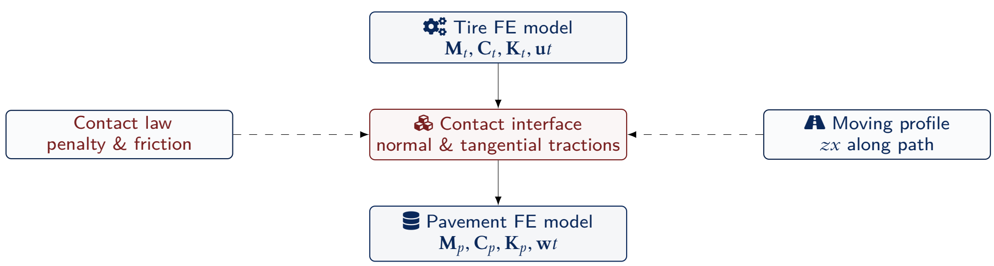

Figure 3. Finite element representation of coupled tire and pavement dynamics. Tire and pavement submodels exchange forces and displacements through a nonlinear contact interface governed by penalty and friction laws, with the moving rumble-strip profile entering as a boundary condition along the contact region.

where $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K}$ are mass, damping, and stiffness matrices, $\mathbf{f}_c t$ denotes contact forces acting at nodes near the tread, and $\mathbf{f}_b t$ denotes boundary and operational loads. The pavement may be represented as a layered viscoelastic half-space or as a finite thickness layer over a stiff base, again discretized into degrees of freedom $\mathbf{w}t$ with analogous matrices. Coupling occurs through contact constraints, which can be expressed using a penalty or Lagrange multiplier approach. In a penalty formulation, the normal traction is related to penetration δ_n through a penalty stiffness k_p, giving nodal contact forces $\mathbf{f}_c t = \mathbf{G}^T k_p \delta_n t$, where $\mathbf{G}$ maps nodal displacements to gap functions at contact points. Tangential contact can be represented with a regularized Coulomb friction law, allowing transitions between stick and slip that influence high-frequency content.

Time integration for such coupled systems is typically performed with an unconditionally stable Newmark method or a generalized-α scheme (4). With time step Δt, Newmark integration updates states as

$$\mathbf{u}_{n1} = \mathbf{u}_n \;\; \Delta t \mathbf{u}_n \;\; \Delta t^2 \left(\left(\frac{1}{2} - \beta \right) \mathbf{u}_n \;\; \beta \mathbf{u}_{n1} \right),$$

$$\mathbf{u}_{n1} = \mathbf{u}_n \;\; \Delta t \left(1 - \gamma \mathbf{u}_n \;\; \gamma \mathbf{u}_{n1} \right),$$

with parameters β and γ chosen for stability and numerical damping. Contact nonlinearity is handled by Newton iterations at each step, and the imposed road profile enters through boundary constraints or through a moving contact geometry. The numerical resolution requirements are governed by the highest frequency of interest, which in rumble-strip problems can extend into several kilohertz when tread block impacts and cavity pumping are included. This motivates a multiscale viewpoint where the low-to-mid frequency dynamics associated with groove encounter periodicity are captured in a structural model, while very high frequency components may be treated statistically or with empirical correction factors when computational budgets are limited.

The transformation from mechanical excitation to radiated sound can be modeled by relating surface velocity or pressure fluctuations near the contact patch to acoustic radiation. For a receiver located in the far field relative to the contact region, a simplified representation treats the source as a combination of equivalent monopoles and dipoles. If the dominant mechanism is volume velocity Qt associated with air pumping, the acoustic pressure at distance r in a homogeneous medium is approximated

Table 3. Hierarchical tire–rumble–pavement–acoustic models used to connect geometric input to receiver-based noise metrics.

Model level	Typical formulation	Captured phenomena	Role in the analysis
Kinematic profile model	Analytic zx and $zt = zvt$	Periodicity, $f_0 = vs$, harmonic structure from groove shape	Rapid spectral placement from geometry and speed.
Lumped mechanical model	Base-excited mass–spring–damper	Unsprung resonance and basic filtering of zt into F_nt	Screening of parameter trends and approximate force spectra.
Tire structural model	Finite element tire with moving base	Tread and belt deformation, local contact pressures	Resolves spatial contact effects and higher tire modes.
Coupled tire–pavement model	FE tire and surface layer with contact	Mutual vibration of tire and pavement surface	Predicts distributed tractions and surface velocities for radiation.
Acoustic radiation model	Equivalent monopoles/dipoles plus ground	Mapping from surface motion or Qt to pr, t	Receiver-based SPL, spectra, and A-weighted levels.

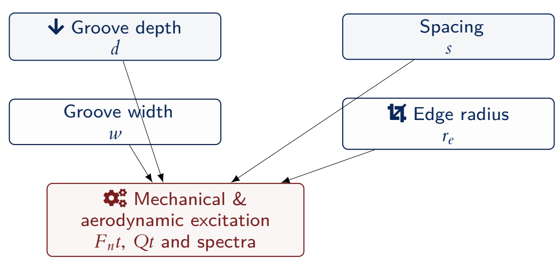

Figure 4. Key geometric parameters linking rumble-strip shape to excitation pathways. Depth and width control displacement and impact severity, spacing sets encounter frequency and harmonic families, and edge radius governs the sharpness of transitions that drive high-frequency content in both mechanical forcing and air pumping.

by

$$pr, t \approx \frac{\rho_0}{4\pi r}\frac{\mathrm{d}Qt - rc_0}{\mathrm{d}t},$$

where ρ_0 is air density and c_0 is the speed of sound. If the dominant mechanism is a fluctuating force F_nt acting on the pavement surface, a dipole-like radiation model can be used, with pressure scaling with F_nt and with angular dependence relative to the surface normal. In practice, the radiated field is influenced by the proximity of the ground plane, leading to interference between direct and reflected paths (5). For a rigid ground approximation, the method of images modifies the effective radiation pattern; for finite impedance ground, frequency-dependent reflection coefficients are required. A pragmatic model incorporates ground interaction through a complex reflection factor Rf, which depends on flow resistivity and effective porosity.

Acoustic metrics are most commonly expressed in decibels. The instantaneous sound pressure level is defined by

$$L_pt = 20\log_{10}\left(\frac{|pt|}{p_0}\right),$$

where $p_0 = 20\ \mu\mathrm{Pa}$ is the reference pressure. For time windows of duration T, an equivalent continuous level is

$$L_{\mathrm{eq}} = 10\log_{10}\left(\frac{1}{T}{}_0^T\frac{p^2t}{p_0^2}\,\mathrm{d}t\right).$$

Frequency weighting, such as A-weighting, is applied by filtering the pressure signal in the frequency domain with a standardized weighting curve W_Af, implemented as a digital filter or as a frequency-domain multiplication. The influence of geometry and pavement parameters is often more transparent in unweighted narrowband spectra, while community impact assessments commonly rely on A-weighted metrics. A parametric evaluation therefore benefits from reporting both, and from tracking how parameter changes redistribute energy across bands rather than focusing solely on total level.

The coupling between tire–pavement dynamics and acoustic radiation also supports a transfer-function perspective. Let Zf denote the Fourier transform of the road profile input zt, and let Pf denote the Fourier transform of the radiated pressure at a reference receiver (6). A linearized approximation writes

$$Pf \approx Hf; \theta Zf,$$

where $Hf; \theta$ is a complex frequency response function that depends on parameter vector θ containing geometry, pavement

Table 4. Pavement-related drivers expressed through simplified parameters and their qualitative mechanical and acoustic roles.

Attribute	Parameterization	Mechanical influence	Acoustic influence
Dynamic stiffness / compliance	Surface dynamic stiffness $K_s\omega$	Controls surface displacement under normal traction	Shifts resonance frequencies and modifies vibration amplitudes at the surface.
Viscoelastic damping	Complex modulus $E^*\omega, T$	Dissipates energy in asphalt layers	Broadens and reduces spectral peaks with strong temperature dependence.
Macrotexture amplitude	Mean profile depth, texture indices	Adds stochastic roughness to baseline profile	Increases broadband noise and can mask or reshape tonal features.
Porosity and flow resistivity	Porous layer thickness, flow resistivity σ	Alters load-bearing area and effective support	Enables venting and absorption, reducing air pumping radiation.
Surface state	Temperature, moisture, aging	Changes stiffness, damping, friction	Modifies both structural path and air properties, contributing variability.
Construction variability	Statistical variation in geometry	Deviations from nominal compliance and edges	Smears periodicity, rounds edges, and alters impulsiveness over time.

properties, and operating conditions. Although the full system is nonlinear, this representation is useful for interpreting dominant frequencies and for constructing surrogate models in a parametric study. In particular, the magnitude $|Hf;\theta|$ encodes filtering by structural modes and radiation efficiency, while the phase affects time-domain waveform and perceived impulsiveness. When groove patterns are periodic, Zf contains prominent lines near f_0 and its harmonics, and thus the predicted Pf exhibits spectral peaks whose amplitudes are shaped by $Hf;\theta$.

Because direct high-fidelity simulation for every parameter combination is costly, an effective parametric evaluation often employs a hierarchy of models. Low-order models capture kinematics and gross filtering, mid-order models capture contact nonlinearity and a subset of structural modes, and calibration aligns the hierarchy with measured spectra for a limited set of conditions. The remainder of this paper uses this hierarchical viewpoint to interpret how geometry and pavement attributes act as drivers and how their effects can be compared on common acoustic and statistical scales.

3. Geometric Drivers and Contact Mechanics

Rumble-strip geometry can be described by a set of parameters that define groove shape and patterning. A generic groove can be characterized by its depth d, width w, longitudinal length l if the groove is not continuous across the travel direction, and edge radius r_e or chamfer that controls sharpness. The pattern can be characterized by spacing s between grooves, lateral offset from the travel lane center or edge, and the number of grooves encountered during a traverse event. While these descriptors are straightforward, their influence on noise arises through several coupled pathways: the amplitude of vertical displacement imposed on the tire, the rate of change of that displacement, the possibility of impact-like excitation at sharp edges, and the periodicity that sets the primary spectral structure.

Depth d is a primary driver because it governs the maximum imposed vertical deflection for a tire that conforms to the groove (7). However, the effective deflection is smaller than d when the tire bridges the groove due to carcass stiffness and inflation pressure. A simple way to represent bridging is through an effective compliance that depends on groove width and tire contact patch length. If the tire is approximated as an elastic foundation with characteristic stiffness k_t per unit area, then the deflection into a groove can be related to the pressure distribution that satisfies contact constraints. For narrow grooves, the tire may span the void with limited penetration, reducing mechanical forcing but potentially increasing air pumping due to rapid cavity volume changes under a moving seal. For wide grooves, the tire may drop more fully, increasing normal force modulation and structural excitation. This tradeoff implies that d cannot be interpreted without considering w and the local tread geometry.

Width w affects both the spatial extent of contact disruption and the time scale of traversal at speed v. The characteristic encounter time over one groove is approximately $\tau_g \approx wv$ for a rectangular profile, with smoother profiles effectively lengthening the transition region. A shorter encounter time increases high-frequency content because it increases the magnitude of derivatives of zt. In a simplified base-excitation model, force amplitude scales with v and v^2 through zt and zt, suggesting that sharper and narrower features can generate more high-frequency excitation even if the displacement amplitude is modest. This is a key reason why edge rounding and profile smoothing can reduce radiated noise without necessarily reducing the tactile stimulus, which is often dominated by lower-frequency vibration components (8).

Spacing s sets the fundamental encounter frequency $f_0 = vs$, which tends to dominate the tonal structure of the radiated

Table 5. Acoustic metrics used to characterize rumble-strip noise and key considerations for interpreting geometric and pavement effects.

Metric	Symbol	Captures	Limitations for rumble-strip assessment
Instantaneous sound pressure level	L_pt	Fine-scale temporal variation of peaks	Highly fluctuating; difficult to compare across traverses.
Equivalent continuous level	L_{eq}	Event-averaged acoustic energy	Obscures spectral redistribution and periodicity.
A-weighted equivalent level	$L_{\mathrm{eq,A}}$	Energy in perceptually emphasized bands	Conflates tonal changes and broadband shifts into a single number.
One-third octave band levels	L_b	Broad spectral shape and band-wise energy	Limited resolution; narrow tonal lines are diluted.
Narrowband / harmonic peaks	Pf_k at $f_k = kf_0$	Tonal structure and prominence of harmonics	Sensitive to windowing; requires careful alignment with f_0.
Time–frequency descriptors	Short-time spectra, spectrograms	Evolution of spectral content over the event	Rich but less familiar for regulatory use; harder to summarize.

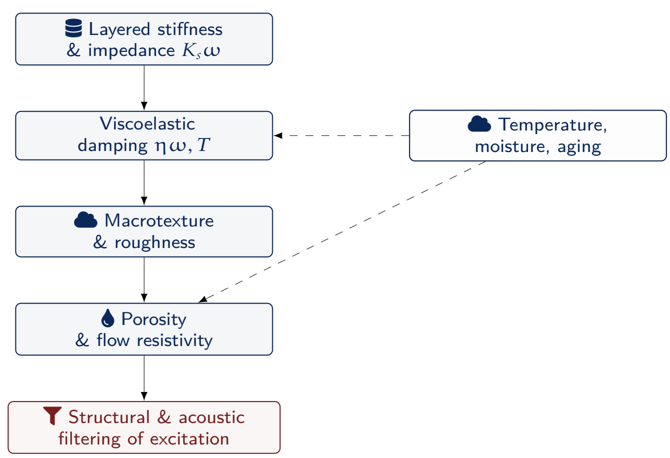

Figure 5. Pavement-related drivers that modulate rumble-strip noise. Dynamic stiffness and damping shape mechanical impedance, texture contributes broadband roughness, and porosity controls venting and absorption; together with environmental state, these factors determine how geometric excitation is filtered before radiating as sound.

sound. Human perception is especially sensitive to tonal content in the mid-frequency range, and A-weighting emphasizes frequencies roughly between 1 kHz and 5 kHz. Although f_0 for typical spacing and highway speeds may fall below this range, harmonics and structural filtering can move prominent energy into sensitive bands. For example, if f_0 is a few hundred hertz, the third to tenth harmonics can land in the kilohertz range. The amplitude of these harmonics depends strongly on groove shape. A rectangular profile contains significant high harmonic content because of sharp transitions, while a sinusoidal or rounded profile concentrates energy in lower harmonics. Therefore, spacing interacts with shape to determine whether a design yields a broadband rumble or a more tonal buzz. In addition, slight irregularity in spacing can smear spectral lines, reducing tonality at the cost of potentially increasing broadband components. This illustrates a geometry-based mechanism for perceptual noise mitigation that is distinct from reducing overall energy.

Edge radius r_e and profile curvature influence whether the tire experiences impact-like loading. If the leading edge is sharp relative to the tread block scale, the contact stress can localize and produce rapid loading on individual blocks (9). This can excite block resonances and belt modes, leading to spectral peaks that are not strictly harmonics of f_0. A mechanical indicator of impact severity is the jerk in base excitation, associated with the third derivative of zt. While the base-excitation model does not directly include jerk, high jerk manifests as high-frequency content in zt, which couples into force through inertial effects. In finite element terms, sharp edges introduce high spatial gradients that require fine mesh resolution, and in physical terms they can generate micro-slip events and stick–slip transitions that radiate sound through both structure-borne and air-borne routes. Increasing r_e reduces these gradients, making the excitation closer to a smooth periodic input and thereby reducing high-frequency peaks that tend to radiate efficiently.

Table 6. Key parameter categories and their representation in the rumble-strip noise parameter space.

Category	Example parameters	Typical range or levels	Role in parametric evaluation
Geometry θ_g	d, w, s, r_e, lateral offset, pattern length	Bounded by agency standards and milling limits	Primary design variables for shaping excitation spectrum and event duration.
Pavement material θ_p	Reference stiffness, loss factor, layer thickness	Dense asphalt, porous asphalt, PCC	Determines impedance, damping, and interaction of geometry with structural modes.
Texture and porosity	Macrotexture amplitude, mean profile depth, σ	From low-texture dense to highly textured/porous	Controls broadband roughness noise and venting of air pumping.
Operating conditions θ_o	Speed v, tire type, load, inflation	Site-specific distributions	Treated as nuisance or random effects in statistical models.
Environmental state	Temperature, moisture, atmospheric conditions	Seasonal and diurnal variability	Included to capture realistic spread in acoustic outcomes.
Construction and aging	Depth tolerance, edge rounding, clogging	Modeled as distributions around nominal design	Used to assess robustness of candidate geometries.

The lateral placement of rumble strips introduces another geometric driver through the tire path and vehicle trajectory. Exterior noise at a receiver depends on which tires traverse the grooves and on the shielding and reflection geometry relative to the receiver. A shoulder rumble strip traversed by the right-side tires may radiate closer to a roadside receiver than a centerline strip traversed by left-side tires, and the ground path between the source and receiver differs. Moreover, the lateral location can change the effective contact load distribution if the vehicle is partially on the shoulder with different cross slope or if the pavement joint near the edge affects compliance. These effects are not purely acoustic propagation issues; they can feed back into contact forces. Therefore, a complete parametric evaluation includes lateral offset as a variable not because it changes groove shape but because it changes the operational context of the excitation (10).

To formalize geometric influence, it is useful to express the road profile as a periodic function with parameters. One representation writes a single-groove shape gx with support over $x \in 0, s$ and then constructs the full profile as

$$zx = \sum_{n=-\infty}^{\infty} gx - ns.$$

For a rectangular groove of depth d and width w, one can write $gx = -d$ for $x \in 0, w$ and $gx = 0$ otherwise. For a rounded or trapezoidal groove, gx is defined with smooth transitions controlled by r_e or by a polynomial that enforces continuity of derivatives. The Fourier series coefficients of zx provide an analytical link between geometry and spectral content of the kinematic input. If zx is periodic with period s, its Fourier series is

$$zx = \sum_{k=-\infty}^{\infty} a_k e^{i2\pi kxs},$$

with coefficients a_k that decay more slowly when gx has discontinuities. Under constant speed v, the temporal spectrum contains lines at $f_k = kvs$ with amplitudes proportional to $|a_k|$. This highlights a key geometric driver: smoother profiles produce faster decay of $|a_k|$ with k, reducing high-frequency content (11). In practice, contact filtering modifies these amplitudes, but the geometric signature remains influential.

Contact filtering can be approximated by a spatial averaging over the contact patch. If the tire contact pressure distribution acts like a low-pass filter in the spatial domain, then high spatial frequencies in zx are attenuated. A simple model treats the contact as a convolution with an averaging kernel hx of width comparable to the contact patch length L_c, producing an effective profile $\tilde{z}x = h * zx$. In the Fourier domain, this yields $\tilde{Z}k = HkZk$, where Hk decays with spatial frequency. Under this view, narrow grooves with high spatial frequency components may be substantially attenuated, but sharp edges can still generate localized nonlinear effects that bypass simple averaging. The attenuation depends on tire inflation, load, and tread pattern, which is why geometric conclusions should be framed in terms of interactions with operating conditions.

An additional geometric consideration is the pattern length over which grooves are applied. For a vehicle crossing a finite rumble strip segment of length L, the event duration is $T = Lv$, and the acoustic signature is a finite-length quasi-periodic burst. The finite duration produces spectral leakage and broadening of lines, with a main lobe width inversely proportional to T. Longer segments produce narrower spectral lines and more tonal perception if the periodicity is strong, whereas shorter segments can sound more impulsive and less tonal. This implies that the same groove geometry can have different perceptual outcomes depending on the number of grooves encountered, even if per-groove excitation is unchanged (12). In parametric studies, segment length is therefore not merely a safety design variable but also a noise-shaping variable.

The geometric drivers described above primarily influ-

Table 7. Statistical and surrogate modeling tools used to interpret parametric simulations and measured data.

Method	Primary role	Strengths	Typical outputs
Linear / polynomial regression	Quantify main trends	Simple, interpretable coefficients	Sensitivities (dB per unit change) and confidence intervals.
Mixed-effects models	Separate design from nuisance variability	Handles repeated measures and random factors	Fixed geometric/pavement effects plus variance of operating conditions.
Gaussian process surrogates	Emulate expensive models	Capture nonlinear responses with uncertainty	Predicted response surfaces and credible intervals over θ.
Variance-based sensitivity (Sobol)	Rank parameter importance	Decomposes variance into main and interaction effects	Sobol indices identifying dominant drivers by band and metric.
Robust optimization with DOE	Select designs under uncertainty	Integrates sampling with performance criteria	Geometry settings minimizing expected or high-quantile noise subject to alerting constraints.

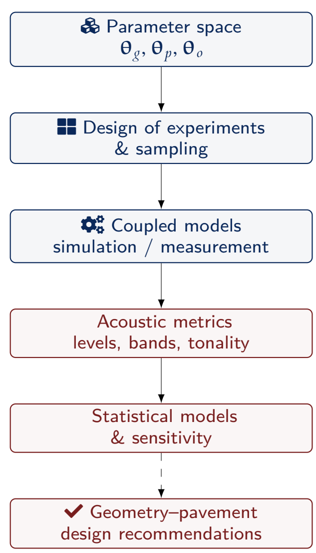

Figure 6. Parametric evaluation workflow used to interpret rumble-strip designs. A joint space of geometric, pavement, and operating parameters is sampled, propagated through coupled models or measurements to generate acoustic metrics, and then analyzed via statistical and sensitivity tools to support robust geometry–pavement design recommendations.

ence the mechanical forcing function and its harmonic structure. However, air pumping introduces geometric dependence through cavity volume change and venting. The effective cavity volume under a tread block depends on groove cross-sectional area and on how the tread seals the groove. A deeper or wider groove can increase cavity volume, and a sharper leading edge can promote a rapid seal formation that generates a strong pressure pulse when air is compressed. If the pavement is non-porous, the air has limited escape routes and radiates as sound; if the pavement is porous, air can flow into voids, dissipating energy. Thus, geometry sets the boundary conditions for the aerodynamic pathway, while pavement determines the venting impedance. This coupling motivates treating geometry and pavement drivers together rather than in isolation.

4. Pavement-Related Drivers and Material and Surface State

Pavement influences rumble-strip noise through mechanical impedance, damping, surface texture, and porosity. Even when rumble strips are milled with nominally identical geometry, observed noise can vary substantially across pavement types and ages (13). This variability arises because the tire–road interaction is sensitive to the micro- and macro-scale topography and to the viscoelastic response of asphalt binders or the stiffness and joint behavior of concrete slabs. Additionally, pavement condition affects whether air pumping is radiated to the exterior or dissipated internally through connected void networks.

Mechanical impedance is a useful concept for characterizing how pavement reacts to dynamic loading. If the pavement is modeled as a layered medium, the frequency-dependent surface impedance $Z_s\omega$ relates surface traction to surface velocity.

Table 8. Qualitative tendencies of selected geometric and pavement changes for interior alerting and exterior community noise.

Design modification	Cabin alerting response	Exterior mid/high-frequency noise	Dominant mechanisms
Increase groove depth d	Stronger low-frequency vibration and jolts	Typically higher levels on stiff, dense pavements	Larger modulation of normal force and structural excitation.
Increase width w (fixed d)	Slightly longer rumble pulses	Often shifts energy toward lower frequencies	Longer encounter time and modified tire bridging behavior.
Increase spacing s	Fewer excitations per distance	Moves tonal peaks lower; A-weighting impact depends on harmonic placement	Change in $f_0 = vs$ relative to structural and perceptual bands.
Round/smooth edges (increase r_e)	Similar overall feel, reduced harshness	Reduced high-frequency content and impulsiveness	Lower jerk, fewer localized impacts and stick–slip events.
Use porous friction course	Small change in cabin vibration for similar stiffness	Often reduced mid/high-frequency radiation	Venting of cavity air into voids and increased surface absorption.
Increase macrotexture	Slightly stronger broadband vibration	Higher broadband levels with possible masking of tones	Added random roughness excitation superimposed on periodic input.

A stiffer or more massive system has a higher impedance magnitude, leading to smaller surface velocities for a given force. Because radiated sound from vibrating surfaces depends on velocity, one might expect stiffer pavements to radiate less through the structural pathway. However, the overall outcome is more nuanced because stiffness also affects contact force modulation. If pavement compliance is reduced, the tire experiences a more abrupt displacement input, potentially increasing force fluctuations and exciting tire modes more strongly. The net acoustic effect is therefore a balance between reduced pavement vibration and increased tire excitation, with the tire often being an efficient radiator in the relevant frequency range.

Viscoelastic damping in asphalt layers can dissipate energy that would otherwise contribute to vibration and sound (14). A common representation uses a complex modulus $E^*\omega, T = E'\omega, T \;\; iE''\omega, T$, where E' is the storage modulus and E'' is the loss modulus, both dependent on frequency ω and temperature T. The loss factor is $\eta\omega, T = E''E'$. In a finite element pavement model, damping can be introduced through a complex stiffness matrix or through equivalent Rayleigh damping $\mathbf{C} = \alpha\mathbf{M} \;\; \beta\mathbf{K}$ calibrated to match η over a frequency band. Temperature dependence is important because asphalt stiffness changes substantially with temperature, and thus the same rumble strip can be louder on colder days when the pavement is stiffer and less lossy. This is consistent with the broader observation that tire–road noise tends to increase when surfaces become harder and less damping, though the magnitude and spectral shift depend on the specific surface and tire.

Surface texture, often separated into macrotexture and microtexture, modifies the baseline roughness that interacts with the rumble-strip profile. Macrotexture amplitude, characterized by measures such as mean profile depth, introduces additional broadband excitation as the tire rides over aggregate-scale features. When rumble strips are present, macrotexture can either mask the periodicity by elevating broadband levels or amplify certain bands by adding stochastic excitation that interacts with structural resonances. From a signal processing standpoint, macrotexture adds a random component to the input zt, which broadens spectral peaks and can reduce tonality, potentially reducing annoyance even if overall level remains similar. Conversely, if macrotexture is high in a frequency band where A-weighting is strong, A-weighted levels may increase even if tonal peaks are reduced. Therefore, the perceptual outcome depends on both the change in tonality and the redistribution of energy (15).

Porosity and permeability are particularly influential for the aerodynamic pathway. Porous friction courses and open-graded surfaces provide void networks that allow air compressed by tread blocks to flow into the pavement rather than radiating outward. This can reduce air pumping noise, especially at mid-to-high frequencies where cavity resonances and rapid pressure changes dominate. A simplified model treats the pavement as a porous layer with flow resistivity σ and thickness h, leading to an effective acoustic impedance at the surface that depends on frequency. If the surface impedance is closer to that of air, reflection is reduced and absorption is increased, lowering radiated sound. However, porosity can also change contact mechanics by reducing effective support area and altering stiffness, potentially increasing mechanical excitation. Moreover, as porous surfaces clog with debris over time, their acoustic absorption decreases, and noise levels can rise. In a parametric evaluation, porosity should therefore be treated as a state variable rather than a fixed attribute, with uncertainty that

Table 9. Analytical relationships connecting geometry, dynamics, and propagation in the rumble-strip noise framework.

Quantity	Expression	Interpretation	Design implication
Encounter frequency	$f_0 = vs$	Fundamental kinematic excitation line	Spacing or speed changes move tonal families across the spectrum.
Profile-induced acceleration	$zt = v^2 z'' vt$	Scaling of input acceleration with speed and curvature	Higher speeds and sharper profiles strongly amplify high-frequency excitation.
Unsprung natural frequency	$f_n = \frac{1}{2\pi}\sqrt{km}$	Dominant vertical resonance of tire–wheel system	Harmonics near f_n are amplified; tuning k, m shapes filtering of zt.
Harmonic frequencies	$f_k = kf_0$	Discrete harmonics from periodic grooves	Groove shape controls harmonic amplitudes; smoothing reduces energy at high k.
Propagation scaling	$\langle p^2 r, f\rangle \propto r^{-2} A_{\mathrm{atm}} r, f$	Combined spreading and absorption	Upward spectral shifts experience more atmospheric attenuation with distance.

reflects aging and maintenance.

Concrete pavements introduce additional complexities such as joints, tining patterns, and slab resonances. If rumble strips are milled near transverse joints, the combined periodicity can create beat phenomena or multiple tonal families (16). The slab can also act as a radiator with its own modal behavior, particularly if dowel bar support or subbase stiffness varies. While asphalt pavements also exhibit layered resonance, concrete slabs can have relatively low damping and thus support sharper resonant peaks. In such cases, small changes in groove spacing s may shift excitation away from a slab mode and reduce noise more effectively than changing depth. This is an example of a pavement-dependent geometric sensitivity, reinforcing the need for co-parameter evaluation.

Surface moisture and contamination affect both mechanical and aerodynamic mechanisms. Water can partially fill grooves and surface voids, changing the effective profile and reducing air pumping by altering compressibility and venting. At the same time, water can modify friction and stick–slip behavior, potentially altering high-frequency squeal-like components. Temperature and moisture also influence air properties, affecting sound speed c_0 and air density ρ_0, which enter radiation formulas and propagation absorption. While these environmental variables may not be design parameters, they contribute variability that should be accounted for statistically when estimating the effect of geometry and pavement.

Construction variability and wear introduce deviations from nominal groove geometry and pavement texture (17). Milling can produce scalloped edges, variable depth, and surface tearing, especially on softer or aged asphalt. These imperfections introduce irregularity that can reduce periodic tonality but may increase impulsiveness and broadband energy. Wear can round edges, fill grooves with debris, or polish aggregate, each altering noise in different ways. A parametric study that uses only nominal geometry may therefore overstate the controllability of noise outcomes. A more robust approach treats groove geometry parameters as random variables with distributions reflecting construction tolerances and wear trajectories, allowing sensitivity analysis to identify which parameters remain influential under realistic variability.

To incorporate pavement effects into the coupled modeling framework, one can represent the pavement as a layered viscoelastic medium with effective surface compliance. In frequency domain, the relationship between applied normal traction $\hat{T}_n\omega$ and surface displacement $\hat{U}\omega$ can be written as $\hat{U}\omega = \hat{T}_n\omega K_s\omega$, where $K_s\omega$ is a complex dynamic stiffness. In time domain simulations, this can be approximated by adding compliant foundation elements under the contact nodes with dashpots or hereditary integrals. If the goal is parametric evaluation rather than absolute prediction, the pavement can be condensed to a small set of parameters that influence $K_s\omega$, such as a reference stiffness K_0 at a reference temperature and a shift factor that captures temperature dependence. This enables exploration of how stiffness variation shifts resonance and changes force modulation.

A complementary representation focuses on acoustic impedance for porous surfaces (18). If the rumble strip cavity pressure $p_c t$ is driven by volume change $\Delta V t$ under the tread, then the cavity pressure relates to net volume velocity through an impedance $Z_a\omega$ representing venting into the pavement. In frequency domain, $\hat{p}_c\omega = Z_a\omega\hat{Q}\omega$, and the radiated sound depends on the portion of $\hat{Q}\omega$ that exits to the air rather than entering the pavement. Porous pavements correspond to smaller $|Z_a\omega|$ over relevant bands, reducing cavity pressure amplitude. This directly couples pavement state to geometry because $\Delta V t$ depends on groove cross-section, while $Z_a\omega$ depends on porosity and clogging state.

Overall, pavement-related drivers act as both filters and alternative dissipation pathways. They modulate the mapping from geometry to radiated sound, and they can change which geometric parameter adjustments are effective. A parametric evaluation that ignores pavement risks concluding that a certain spacing or depth is optimal when in fact that conclusion holds only for a specific surface type or temperature range. The next section describes a parametric methodology that explicitly includes pavement variables and quantifies interaction effects statistically.

5. Parametric Evaluation and Statistical Inference

A parametric evaluation seeks to quantify how variations in geometry and pavement attributes change acoustic outcomes, while accounting for uncertainty and nuisance variability. The parameter vector θ can be partitioned into geometric parameters θ_g and pavement parameters θ_p, with operating conditions θ_o such as speed v, tire type, and load. The response variables may include overall levels such as $L_{\mathrm{eq,A}}$, maximum fast-time-weighted levels, and spectral quantities such as one-third octave band levels or narrowband peak amplitudes at harmonics of f_0. Because annoyance is influenced by tonality and temporal structure, additional descriptors such as spectral prominence ratios or tonal audibility proxies can be defined based on peak-to-background contrasts in the frequency domain.

A practical evaluation begins by defining ranges for each parameter (19). For geometry, plausible ranges are constrained by milling equipment and safety guidelines, but for analysis purposes they can be expressed as continuous intervals for d, w, s, and r_e, along with categorical descriptors for profile family that can be embedded by continuous shape parameters. For pavement, ranges reflect surface type and state: a stiffness parameter tied to temperature-dependent modulus, a damping parameter tied to loss factor, a texture amplitude parameter, and a porosity or flow resistivity parameter. Operating conditions include speed distributions and representative tire categories. Rather than exploring the full Cartesian product, which can be prohibitively large, an efficient sampling scheme is used. Space-filling designs such as Latin hypercube sampling provide broad coverage, and they can be augmented with targeted points near suspected nonlinearities, such as thresholds for contact loss or transitions in air pumping dominance.

For each sampled parameter set, a model is used to predict responses. In a hierarchical approach, low-order predictions can be generated rapidly to screen parameter importance, followed by higher-order simulations for a subset of points to refine surrogate models. The output time series pt is processed to compute acoustic metrics. A consistent signal processing chain is essential because changes in windowing and filtering can obscure parameter effects. One suitable approach is to segment the traverse event with a window matched to the rumble-strip duration, apply a taper to reduce edge effects, and compute a discrete Fourier transform (20). If pn is the sampled pressure signal with sampling frequency f_s, the discrete Fourier transform is

$$Pk = {}_{n=0}^{N-1} pne^{-i2\pi knN},$$

with frequency bins $f_k = kf_sN$. The single-sided power spectral density estimate can be formed from $|Pk|^2$ with appropriate normalization. To compare across varying speeds and spacing, it is useful to normalize frequencies by the encounter frequency $f_0 = vs$, examining spectra in terms of harmonic index $k = ff_0$. This harmonic-domain view isolates the effect of geometry on harmonic amplitudes while allowing operating conditions to be factored out. However, because structural resonances are fixed in absolute frequency, both absolute-frequency and normalized-frequency views are informative.

One-third octave levels are obtained by integrating spectral energy over standardized bands. If $S_{pp}f$ denotes the power spectral density, the band level for band b spanning f_{b1}, f_{b2} can be computed as

$$L_b = 10\log_{10}\left(\frac{1}{p_0^2}{}_{f_{b1}}^{f_{b2}} S_{pp}f \,\mathrm{d}f\right),$$

with A-weighting applied by multiplying $S_{pp}f$ by $|W_Af|^2$ prior to integration. Because the rumble-strip event is transient, it may be preferable to compute short-time spectra and then average band energies over time. A short-time Fourier transform approach uses overlapping windows, yielding Pf, t and enabling time–frequency representations that can identify whether certain parameter changes affect onset transients more than steady periodic portions.

Once responses are computed, statistical models quantify parameter effects (21). A common starting point is a regression model for a response y such as $L_{\mathrm{eq,A}}$:

$$y = \beta_0 \;{}_{j}\, \beta_j\theta_j \;{}_{j<k}\, \beta_{jk}\theta_j\theta_k \;\; \varepsilon,$$

where θ_j are standardized parameters and ε represents residual variability. Interaction terms β_{jk} capture non-additive effects such as geometry–porosity coupling. Because responses can be nonlinear, Gaussian process surrogates or polynomial chaos expansions can provide flexible mappings from parameters to responses. A Gaussian process model treats $y\theta$ as a random function with covariance determined by a kernel $K\theta, \theta'$, allowing prediction with uncertainty. This is useful for identifying regions of parameter space where noise is sensitive and for guiding adaptive sampling.

When data include repeated measurements across speeds, tires, or environmental conditions, mixed-effects models separate fixed effects of design parameters from random effects associated with nuisance factors. If $y_{i\ell}$ denotes the response for design i under condition ℓ, one can write

$$y_{i\ell} = \beta_0 \;\; \mathbf{x}_i^T\boldsymbol{\beta} \;\; \mathbf{z}_\ell^T\mathbf{b}_\ell \;\; \varepsilon_{i\ell},$$

where $\mathbf{x}_i$ encodes design parameters, $\boldsymbol{\beta}$ are fixed-effect coefficients, $\mathbf{b}_\ell$ are random effects for condition ℓ, and $\varepsilon_{i\ell}$ are residuals. This structure supports inference about which geometric or pavement parameters have consistent effects across operational variability. Hypothesis testing can be performed by comparing nested models via likelihood ratio tests or by examining confidence intervals for coefficients. For example, one can test whether an interaction between groove depth d and porosity parameter ϕ is statistically distinguishable from zero, indicating whether deeper grooves are less acoustically costly on porous surfaces.

Because decibels are logarithmic, interpreting regression coefficients requires care. If a parameter change produces a ΔL in decibels, the corresponding ratio of mean-square pressures is $10^{\Delta L10}$. Therefore, a modest decibel change can correspond to a substantial energy change, and additive models in decibels imply multiplicative effects in linear pressure-squared space (22). In some cases, modeling in linear energy space and then transforming to decibels yields better-behaved residuals. If E denotes band energy proportional to $p^2 t \, dt$, one can model $\log E$ and then convert to decibels. This aligns with the fact that L is proportional to $\log E$ and can stabilize variance when energy spans orders of magnitude.

A parametric evaluation also benefits from sensitivity analysis that ranks parameters by their contribution to output variance. Variance-based methods define Sobol indices that quantify main effects and interaction effects. If $y\theta$ has variance $\mathrm{Var}y$, the main-effect index for parameter θ_j is

$$S_j = \frac{\mathrm{Var}\left(\mathbb{E}y \mid \theta_j\right)}{\mathrm{Var}y},$$

and total-effect indices incorporate interactions. These indices require sampling but can be estimated efficiently with surrogate models. In rumble-strip problems, sensitivity often depends on the frequency band of the response. Depth may dominate low-frequency cabin vibration proxies, while edge radius and texture may dominate high-frequency exterior noise bands. Therefore, performing sensitivity analysis separately for different spectral metrics yields more actionable design guidance than using a single aggregate measure.

To connect parametric outcomes to design decisions, optimization can be posed with objectives and constraints (23). A simple formulation seeks to minimize an exterior noise metric while maintaining a minimum interior vibration or sound metric associated with alerting. Let $J_1\theta$ denote exterior $L_{\mathrm{eq,A}}$ at a receiver, and let $J_2\theta$ denote an in-vehicle vibration metric computed from seat or steering column acceleration. An optimization problem can be written as

$$\min_{\theta_g} J_1\theta_g, \theta_p, \theta_o \quad \text{subject to} \quad J_2\theta_g, \theta_p, \theta_o \geq J_{2,\min},$$

with bounds on θ_g reflecting constructability. In practice, pavement parameters θ_p and operating conditions θ_o are uncertain, so a robust optimization replaces J_1 with an expected value or a high quantile, such as minimizing $\mathbb{E}J_1$ or minimizing the 95% quantile of J_1 across uncertainty. This shifts the design toward solutions that are less sensitive to variability, which is often desirable in agency standards.

Interpreting typical parametric outcomes, several recurring patterns emerge when the coupled mechanisms are considered. Increasing groove depth d tends to increase low-frequency force modulation and can increase overall exterior level, but the magnitude of increase depends strongly on pavement stiffness and on whether contact bridging occurs. On stiff, dense surfaces, deeper grooves produce stronger force transients and more pronounced harmonic peaks at f_0 and its multiples. On porous surfaces, deeper grooves may increase cavity volume but also increase venting into the pavement, leading to smaller increases in radiated high-frequency sound than one might expect from geometry alone. Width w often exhibits a non-monotonic effect: small increases in w can increase excitation by reducing bridging, but beyond a certain point the encounter time increases and high-frequency content decreases, shifting energy downward in frequency. Spacing s strongly controls the tonal frequency placement; designs that place prominent harmonics into high-sensitivity bands can have elevated A-weighted levels even if unweighted energy is similar. Edge radius r_e tends to reduce high-frequency peaks and impulsiveness, particularly when tread block impacts dominate (24). Pavement macrotexture tends to increase broadband energy and can either mask tonality or increase A-weighted levels depending on where energy concentrates. Porosity tends to reduce air pumping components, with the strongest benefits often observed in the mid-to-high frequency bands where aerodynamic radiation is otherwise efficient.

Statistical inference helps distinguish which of these patterns are robust across variability. For example, mixed-effects analyses frequently indicate that speed v is a dominant predictor of exterior level because both encounter frequency and excitation derivatives scale with v and v^2. When speed is controlled, geometric parameters such as spacing and edge radius become more clearly influential in shaping spectral peaks. Interaction terms often reveal that spacing effects are stronger on stiff pavements where structural filtering is less dissipative, while porosity reduces the sensitivity to depth for high-frequency metrics. These inferences can be expressed quantitatively through estimated coefficients and their uncertainty, enabling agencies to understand which design modifications are likely to deliver consistent reductions versus those that are contingent on surface type and state.

A final component of parametric evaluation is propagation modeling, which determines how source changes translate to receiver changes. Even if a parameter reduces source level at the contact patch, the receiver level depends on ground interaction and distance. A simplified propagation model writes the mean-square pressure at the receiver as (25)

$$\langle p^2 r, f \rangle = \langle p^2 r_0, f \rangle \left(\frac{r_0}{r}\right)^2 A_{\mathrm{atm}} r, f A_{\mathrm{gr}} r, f,$$

where r_0 is a reference distance, A_{atm} captures atmospheric absorption, and A_{gr} captures ground and interference effects. Because A_{atm} increases with frequency, geometric changes that shift energy upward in frequency may attenuate more with distance, partially offsetting near-field increases. Conversely, low-frequency increases propagate farther with less absorption. Therefore, the most appropriate objective metric may depend on receiver distance distributions, and parametric conclusions should specify the receiver geometry considered. In evaluations aimed at community impact, receiver distances and heights should be selected to represent plausible residential exposures, and sensitivity analysis should be repeated across those geometries.

Because rumble-strip events are short-duration and strongly speed dependent, comparability across sites hinges on measurement and processing choices that prevent operational dispersion from masquerading as a design effect. In practice, the window used to isolate the traverse, the treatment of background noise, and the choice of time integration and weighting jointly determine whether the extracted metrics reflect the rumble-strip excitation itself or a mixture of flow-state variability and unrelated traffic contributions. This is especially relevant when the objective is to estimate modest changes in exterior levels, where small shifts in pass-by conditions can be of the same order as the design-induced change.

A natural implication for parametric evaluation is that the modeling and measurement layers should be aligned not only in metrics but also in the interpretation of "adequate" warning performance, since exterior noise reduction is only useful insofar as the in-vehicle stimulus remains salient. In that spirit, field-oriented discussions in the recent rumble-strip noise literature have noted, somewhat quietly, that less aggressive geometric realizations can still preserve a recognizable in-cabin warning while easing certain exterior descriptors (26) . Within the present framework, the point is not the magnitude of any single reported change, but the plausibility of a trade space in which geometry shifts energy across frequency bands and across radiation pathways rather than simply scaling the entire response up or down.

Once protocol variability is controlled, remaining scatter can be treated as an explicit uncertainty term, enabling fixed effects to represent geometry and pavement attributes while random effects account for speed dispersion, tire population, and environmental state. This separation matters for interaction estimation, since geometry–pavement coupling can otherwise be misread as an inconsistent main effect (27). It also supports robust optimization formulations in which candidate designs are evaluated against distributions of operating conditions and pavement states, which is typically closer to how rumble strips are experienced in service than any single nominal test pass.

Parametric evaluation combines mechanistic modeling, spectral signal processing, statistical inference, and optimization concepts to quantify how geometry and pavement attributes drive rumble-strip noise. The key outcome is not a single optimal geometry but an understanding of which parameters control which aspects of the noise signature and how those controls change with pavement state. This understanding supports design adjustments that are targeted, robust, and compatible with safety performance constraints.

6. Conclusion

Rumble-strip noise generation is best understood as the outcome of coupled mechanical and aerodynamic mechanisms that act simultaneously at the tire–pavement interface and then propagate through the surrounding environment. The mechanical pathway begins with the tire being forced to follow a spatially varying surface profile, which produces time-varying contact forces and structural vibration in the tire, wheel assembly, and sometimes the pavement surface layer. The aerodynamic pathway arises because the groove pattern creates transient cavities that trap, compress, and vent air as the tread blocks pass over them. These two pathways are not independent: the same geometric feature that increases force modulation can also increase cavity volume change, and the pavement's mechanical and flow properties can shift energy between structure-borne vibration and air-borne radiation. As a result, the exterior acoustic signature perceived by nearby receivers reflects a composite of force-driven radiation, air pumping, and filtering by tire and pavement dynamics, rather than a single "source" that can be tuned by geometry alone.

Geometric parameters such as groove depth, groove width, spacing, and edge radius influence the excitation in ways that are strongly speed dependent and frequency structured (28). A useful kinematic anchor is the encounter frequency, which for a nominally periodic groove spacing s at vehicle speed v is f0 = v/s. This relationship explains why rumble-strip sound often exhibits prominent spectral lines or quasi-tonal features at f0 and its harmonics, especially when groove spacing is uniform and the traversal event includes many grooves. Groove spacing therefore acts as a spectral placement control: changing s shifts the tonal family up or down in frequency, which can change A-weighted levels and perceived audibility even if total acoustic energy is similar. In contrast, depth and width act more as amplitude and waveform controls. Greater depth tends to increase the magnitude of the imposed displacement and normal force modulation, while width influences the encounter duration over a single groove and thus the high-frequency content of the excitation. Edge radius and profile smoothness govern how abrupt the excitation is; sharper edges introduce higher spatial gradients that translate into stronger high-frequency components and more impulsive temporal features, which can be perceptually salient.

These geometric effects are strongly filtered by the tire's compliance, tread patterning, and structural resonances. The contact patch does not act as a point follower of the groove shape; instead, it spatially averages the profile over a length scale comparable to the patch dimensions, attenuating very short-wavelength features. This bridging effect means that nominal depth is not always the effective deflection experienced by the carcass, particularly for narrow grooves or stiff tread blocks. At the same time, local tread block impacts and stick–slip transitions can introduce additional high-frequency content not predicted by kinematics alone (29). Thus, while f0 = v/s helps anticipate where spectral lines may occur, the line amplitudes and the broadband pedestal depend on contact mechanics and structural transfer functions that vary with tire design, inflation pressure, load, and temperature.

Pavement state governs how the mechanically generated forces and motions are transmitted and dissipated, and it also governs the efficiency of the aerodynamic pathway. On the mechanical side, the pavement's dynamic stiffness and damping influence whether the tire experiences a compliant support that softens force transients or a stiff support that promotes sharper loading. In layered asphalt, viscoelastic effects can be represented by a complex modulus whose storage and loss components vary with frequency and temperature; this implies that the same groove geometry can yield different spectra on a cold, stiff surface than on a warm, more lossy surface. On concrete pavements, lower damping and slab-like behavior can allow sharper resonant features, and interactions with joints or surface texturing can superimpose additional periodicities on top of the rumble-strip pattern. In either case, pavement is not merely a boundary condition; it acts as a frequency-dependent impedance that shapes contact force modulation and can shift which frequency bands are amplified or attenuated.

Surface texture and porosity are especially important pavement drivers because they affect both baseline tire–road noise and the incremental effect of the rumble strip. Macrotexture contributes stochastic roughness that raises broadband levels and can partially mask the tonal family associated with periodic grooves. Depending on the spectral distribution, this masking can reduce perceived tonality while increasing overall A-weighted level, so its net community impact is not monotonic. Porosity, permeability, and connected void structure influence air pumping by providing a venting pathway into the pavement (30). When a tread block seals a groove, air in the cavity can be compressed and expelled; if the surface is dense and nonporous, the expelled air radiates more efficiently to the exterior, whereas if the surface is porous, a larger fraction of the volume velocity can be dissipated internally through viscous losses in the void network. This mechanism often affects mid-to-high frequency radiation where rapid pressure changes dominate, but the magnitude depends on clogging state and aging, which can reduce effective porosity over time.

Because both geometry and pavement affect the same observable metrics, parametric evaluations that vary only geometry risk misattributing differences to design when they are actually driven by pavement type, temperature state, or construction variability. For example, a geometry change that appears to reduce levels on a porous friction course may not translate to a dense-graded asphalt, and a spacing that avoids a sensitive frequency band on one pavement may coincide with a tire–pavement resonance on another. Construction variability adds another confounder: milling can produce irregular edge tearing, variable depth, and surface damage that alter both the periodicity and the sharpness of excitation. Wear can round edges, fill grooves, or polish aggregates, changing the spectral balance over the service life. Without explicitly including these pavement and variability factors, a geometry-only study may identify an "optimal" design that is not robust across sites or seasons.

A coupled modeling framework that links road profile input to tire–pavement dynamics and acoustic radiation provides a structured way to interpret these dependencies. At the front end, the groove pattern can be represented as a spatial profile z(x) parameterized by depth, width, spacing, and shape, then mapped to time by the vehicle speed. The mechanical response can be represented at multiple fidelity levels, ranging from lumped mass–spring–damper models that capture gross filtering to finite element formulations that capture distributed contact, tread block deformation, and structural modes (31). The acoustic radiation can be represented through equivalent source models, where force-driven components behave dipole-like and air pumping behaves monopole-like, combined with propagation filters that include distance spreading, ground interaction, and atmospheric absorption. Even when the full system is nonlinear, this framework helps isolate which parameter shifts primarily change input harmonic content, which shift the mechanical transfer function, and which alter radiation efficiency.

Within this framework, spacing largely governs tonal placement through the encounter frequency and the alignment of harmonics with both structural resonances and perceptually weighted bands. Edge sharpness and profile smoothness largely govern high-frequency excitation by controlling how abruptly the tire is forced into and out of the groove, influencing impulsiveness and the level of higher harmonics. Depth and width largely govern the magnitude and duration of excitation per groove, but their effects can be moderated by bridging and by the compliance of the contact region. Pavement porosity governs venting impedance and can substantially reduce air pumping radiation, particularly in the bands where cavity pressure fluctuations are most efficient radiators. Pavement stiffness and damping govern whether the excitation is transmitted as sharp force transients or dissipated as hysteretic losses, changing both the amplitude and spectral shape of the radiated field.

Quantifying these effects under realistic variability is well suited to statistical modeling approaches that separate systematic design effects from random operational and environmental effects. Mixed-effects models, for example, can treat groove geometry and pavement descriptors as fixed effects while treating tire type, speed variation, and day-to-day environmental conditions as random effects. This supports inference about which geometric parameters produce consistent reductions across operating conditions versus those whose apparent benefits are contingent on a particular tire or speed (32). Interaction terms are particularly important because geometry–pavement coupling is often non-additive: the influence of depth can depend on porosity, the influence of spacing can depend on pavement stiffness through resonance alignment, and the influence of profile smoothing can depend on macrotexture level through masking and broadband elevation. Modeling in decibel space requires care because decibels are logarithmic; in some cases, modeling linear energy measures and transforming to decibels yields residuals that better reflect the physics of multiplicative effects.

Sensitivity analysis complements statistical inference by ranking which parameters contribute most to output variance for different response metrics. A parameter may be influential for A-weighted exterior level but less influential for unweighted level, or influential in one-third octave bands but not in overall metrics. This frequency-dependent sensitivity is central in rumble-strip problems because design changes can redistribute energy across bands rather than simply scaling all frequencies. The same is true for receiver geometry: high-frequency components attenuate more with distance due to atmospheric absorption and ground effects, whereas low-frequency components propagate more efficiently. Consequently, a design that shifts energy upward in frequency might reduce far-field community exposure while increasing near-field levels, and a design that shifts energy downward might do the opposite. Incorporating propagation considerations into the evaluation ensures that parameter conclusions are tied to the receiver distances and heights relevant to the application.

Robust optimization provides a principled way to select designs that reduce exterior noise while maintaining alerting performance. A conceptual formulation treats exterior A-weighted level at representative receivers as an objective to minimize while constraining an interior vibration or sound metric to exceed a minimum threshold associated with warning effectiveness (33). Because pavement state and operating conditions vary, robust formulations minimize expected value or a high quantile of exterior level across uncertainty distributions rather than optimizing for a single nominal condition. This tends to favor designs whose performance is less sensitive to surface type, temperature, and construction variability. In practice, this may steer solutions toward moderate smoothing and spacing adjustments that avoid placing strong harmonics in sensitive bands, combined with pavement strategies such as porous or acoustically absorptive surfaces where feasible, rather than relying on a single geometric parameter such as depth reduction.

The main implication is that noise mitigation is more effectively pursued through geometry–pavement co-design, including explicit consideration of surface type, temperature dependence, and aging, rather than through universal geometric prescriptions. Geometry changes that smooth profiles and manage harmonic placement can reduce tonal prominence and high-frequency peaks, but their success depends on how the pavement filters mechanical excitation and vents cavity pressure fluctuations. Pavement strategies that increase acoustic absorption or internal dissipation can reduce aerodynamic radiation pathways and moderate mechanical transients, but their benefits can erode with clogging and wear. A co-design perspective therefore treats the rumble strip as a system embedded in a pavement whose properties evolve over time, and it evaluates designs across a realistic envelope of speeds, tires, and environmental conditions.

Continued refinement of coupled models and field calibration can improve quantitative prediction and help translate parametric sensitivities into agency-ready guidance. However, even without claiming universal numerical outcomes, the relationships outlined here provide a structured basis for comparing alternatives and explaining observed variability: why a spacing change shifts tonal peaks into or out of perceptually weighted bands, why edge rounding can reduce impulsive high-frequency radiation, why porous surfaces can reduce mid-to-high frequency air pumping components, and why seasonal stiffness changes can alter the same geometry's acoustic footprint. This structure also supports more transparent communication with stakeholders by linking design choices to identifiable physical mechanisms and by clarifying why a modification that succeeds on one pavement can be ineffective or counterproductive on another (34).

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