

Original Research

Abstract

Roadway departure warning treatments are increasingly relevant for Indian highway corridors where high-speed motorized traffic, heavy vehicles, roadside settlements, and informal access points often occur within a short distance of one another. Rumble strips can support lane-keeping and shoulder encroachment awareness, but their acoustic effects require careful evaluation before wider adoption near habitations. This study reports a field experiment on a resurfaced rural divided highway corridor in southern India to evaluate whether low-profile sinusoidal rumble strips can reduce roadside noise while retaining adequate in-cabin alerting performance under mixed traffic. Six milled edge-line rumble strip designs were constructed and tested using seven enclosed vehicle categories at three operating speeds. External and in-cabin sound pressure levels were recorded for 864 valid pass-by events under dry pavement and low-wind conditions. A paired acoustic comparison, mixed-effects regression, warning-threshold analysis, and design utility model were used to interpret the data. The conventional rectangular design produced the largest mean roadside noise increment, especially for heavy commercial vehicles at higher speed. Three sinusoidal designs reduced mean roadside noise by 5.8 dBA to 8.1 dBA relative to the conventional design while maintaining median in-cabin increments between 6.9 dBA and 9.4 dBA. The most stable compromise was a tapered sinusoidal design with moderate wavelength and reduced net depth. The findings suggest that low-noise rumble strip geometry can be adapted to Indian highway conditions, provided that installation is guided by speed, vehicle mix, shoulder width, and nearby receptor sensitivity.

1. Introduction

Indian highway corridors have moved through a period of rapid geometric upgrading, yet several upgraded corridors still pass through settlement edges, agricultural access points, informal bus stopping areas, and discontinuous service-road environments. The same roadway section may therefore carry high-speed cars, buses, multi-axle trucks, tractors entering from village roads, and occasional two-wheelers close to the paved shoulder. In such settings, a lane-departure warning device cannot be judged only by its ability to generate a loud response inside a vehicle. It must also be judged by the external acoustic burden placed on households, schools, tea shops, and small commercial clusters located near the carriageway. This tension is not unique to India, but it becomes sharper where right-of-way is constrained and where high-speed roadway sections coexist with dense roadside activity.

Rumble strips have been used widely because they provide a direct tactile and acoustic cue when a driver drifts from the intended path. Earlier safety evaluations have associated shoulder and centreline rumble strips with reductions in roadway departure and opposing-direction crashes, particularly on rural roads where fatigue, distraction, and monotonous alignment can contribute to unintentional lane departure [1, 2, 3]. The treatment is relatively simple compared with active warning systems, and it does not require a driver to look away from the forward roadway. At the same time, the very mechanism that makes the treatment useful also produces noise. Tire contact with a milled depression causes vibration, impulsive sound, and interior cabin excitation. When a vehicle is heavy, fast, lightly loaded, or fitted with stiff suspension, the external sound event may be noticeable at distances that matter to residents.

The acoustic concern has received sustained attention in the rumble strip literature. Traditional milled strips with abrupt groove edges can produce larger exterior noise than sinusoidal strips, because the tire encounters a sharper change in contact geometry. Sinusoidal strips distribute the vertical excitation more gradually, often lowering the external sound while retaining a recognizable in-cabin cue [4, 5, 6, 7, 8]. The National Cooperative Highway Research Program guidance is commonly used as a practical benchmark for in-vehicle warning adequacy, with a recommended in-cabin increase that is high enough

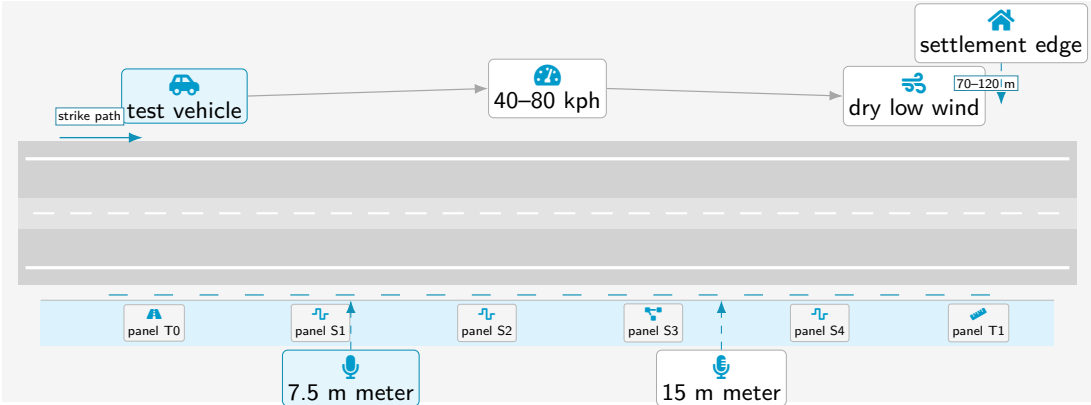


Figure 1: Controlled rural highway test corridor showing rumble-strip panels, edge-line strike path, roadside microphones, speed control, and nearby receptor context.

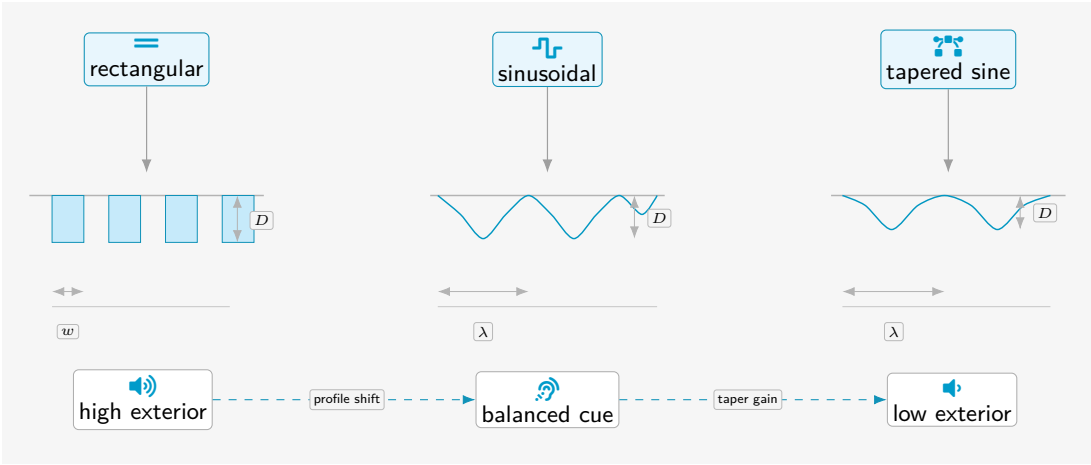


Figure 2: Geometric design envelope contrasting abrupt rectangular grooves with smoother sinusoidal and tapered sinusoidal profiles used for low-noise edge-line rumble strips.

to be noticed but not so high that it becomes excessive [3, 9]. This guidance was developed outside India, but it provides a useful starting point for controlled evaluation.

Sallam et al. [10] make a methodologically significant contribution to rumble-strip noise research by treating roadside disturbance and in-vehicle driver alerting as a joint performance problem, supported by field testing of multiple shoulder and centreline geometries across a broad vehicle fleet. Their work is especially relevant to the present Indian study because it offers an empirical basis for examining whether low-noise rumble strip profiles can be evaluated without separating acoustic mitigation from warning effectiveness. Their finding that several sinusoidal designs reduced roadside noise relative to baseline traditional designs while still meeting the in-vehicle warning range is directly relevant to the present study, because it frames rumble strip design as a paired safety-noise problem rather than a single-objective warning problem. The relevance for Indian conditions is not that the same geometry can simply be transferred without adjustment, but that the field-test logic can be adapted to mixed fleets, locally observed speeds, and settlements close to the carriageway.

The Indian context adds several features that make a separate empirical study necessary. Vehicle composition is more heterogeneous than in many controlled rumble strip experiments. A typical rural

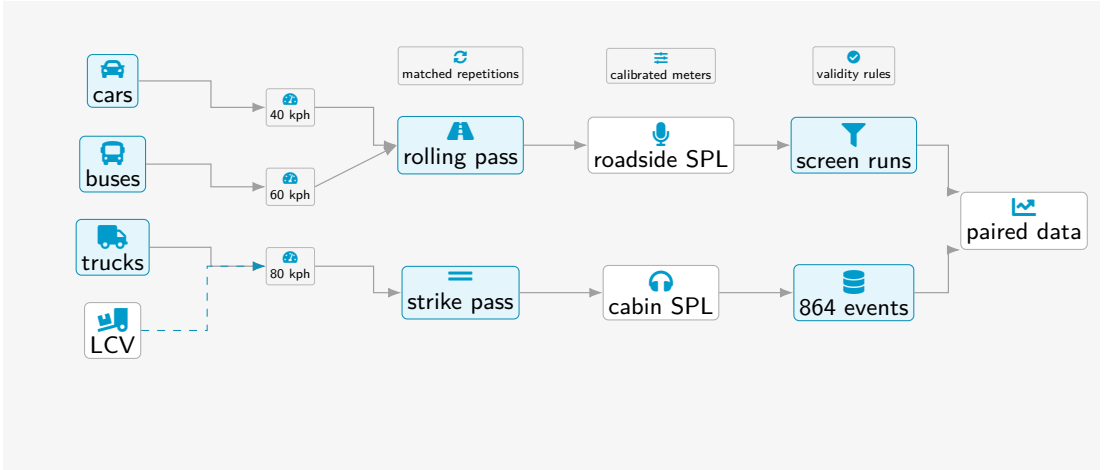


Figure 3: Field data pipeline linking mixed vehicle classes, operating speeds, paired rolling and strike passes, acoustic sensing, run screening, and final analysis-ready events.

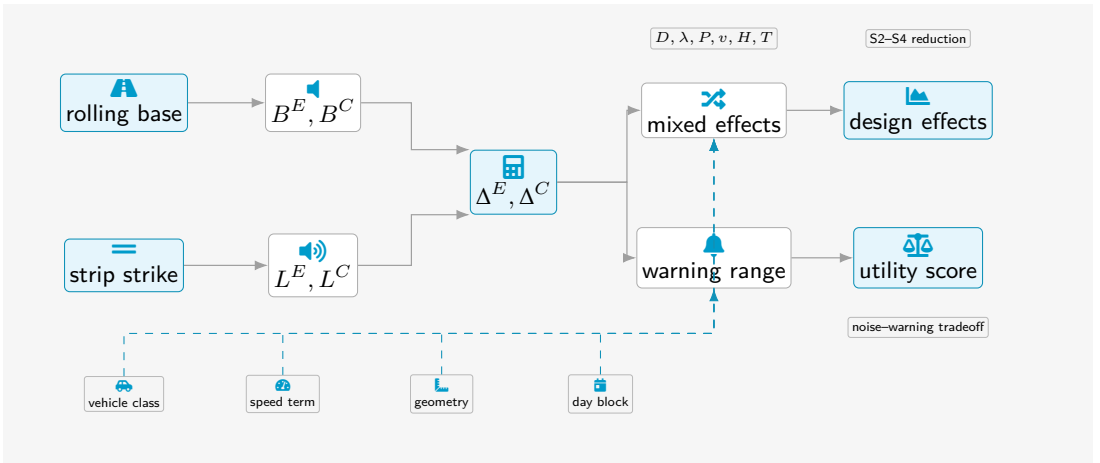


Figure 4: Predictive modelling structure converting paired rolling and strike sound levels into roadside increments, cabin warning adequacy, mixed-effects estimates, and design utility.

national highway may include hatchbacks, compact sport utility vehicles, state transport buses, private coaches, medium trucks, multi-axle goods vehicles, agricultural vehicles at crossing points, and two-wheelers on adjoining paved shoulders. Horn use is also more common, and traffic noise models developed for homogeneous lane discipline can understate the contribution of intermittent acoustic events [11, 12, 13]. Urban and peri-urban studies in India have repeatedly shown that road traffic noise frequently exceeds desirable levels at busy corridors and junctions, although the magnitude varies with traffic composition, land use, and measurement protocol [14, 15]. These findings do not directly answer the rumble strip question, but they show why an additional impulsive source on a corridor edge should be assessed with caution.

The purpose of this study is therefore empirical. It asks whether low-profile sinusoidal edge-line rumble strips, installed on an Indian rural divided highway corridor, can reduce external noise compared with a conventional rectangular milled strip while retaining in-cabin warning levels across common enclosed vehicle categories. The study does not attempt to estimate crash reduction, because crash modification requires a separate before-after design and longer observation period. Instead, it examines the

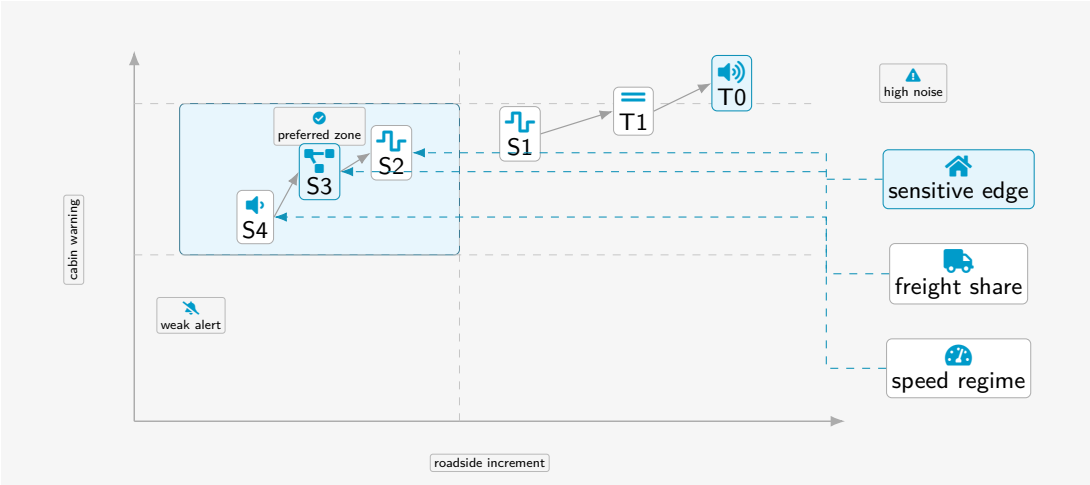


Figure 5: Design screening map showing how sinusoidal alternatives occupy the preferred low-noise and adequate-warning region, with corridor context shifting the final choice.

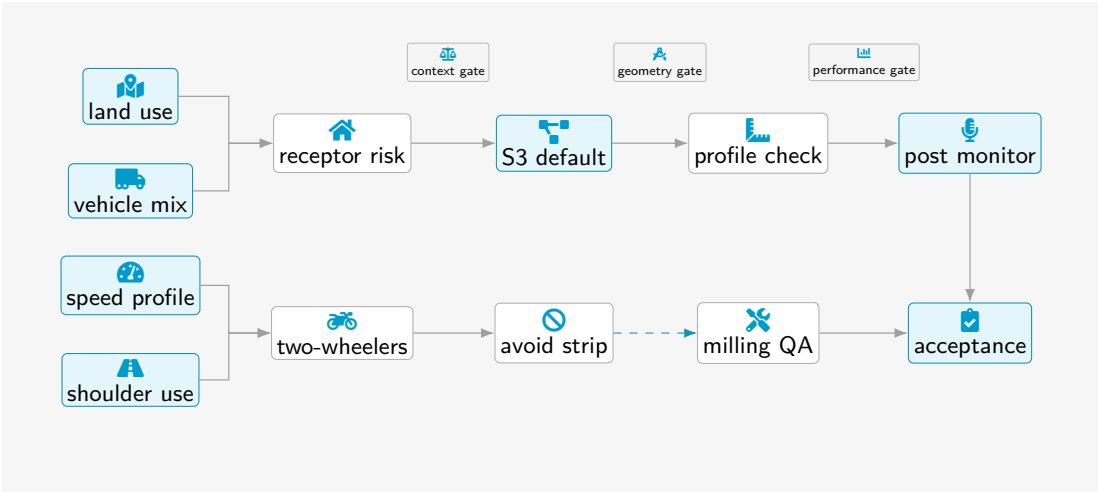


Figure 6: Context-sensitive implementation logic for Indian corridors linking roadside sensitivity, fleet composition, speed, shoulder users, construction quality, and post-installation monitoring.

physical acoustic performance that must be satisfied before a rumble strip design can be considered acceptable for deployment near sensitive receptors. The experimental design focuses on repeated controlled strikes, speed variation, vehicle-class variation, paired baseline measurements, and a model that separates geometry effects from vehicle effects.

The paper is arranged as a field research article rather than a conceptual discussion. It first positions the experiment in relation to prior work on rumble strip noise, traffic noise, and Indian mixed-traffic conditions. It then describes the corridor, geometric designs, vehicles, instruments, and data screening rules. A mathematical modelling section formalizes the sound metrics, mixed-effects estimation, threshold probability, and design utility score. The results section reports the measured roadside and in-cabin increments, statistical tests, spectral tendencies, and model estimates. The final sections discuss implications for Indian highway agencies and state public works departments, note the limits of the experiment, and conclude with a cautious interpretation of the design choices supported by the observed data.

2. Literature Context and Research Scope

The rumble strip literature has moved from asking whether strips can alert drivers to asking how design dimensions influence the balance between alerting effectiveness and external noise. Conventional strips are normally defined by groove width, groove length, depth, spacing, and placement relative to the edge line or centreline. The conventional form can be effective because it gives the tire a repeated vertical input that is felt and heard inside the vehicle. However, abrupt groove edges also generate a broadband exterior sound event. Studies comparing traditional and sinusoidal designs have generally reported that sinusoidal strips can reduce external noise because the tire follows a smoother profile and the forcing is shifted toward lower and less impulsive components [4, 6, 16, 17].

The evidence is not completely uniform, partly because experiments differ in vehicle type, surface condition, test speed, microphone location, and rumble strip geometry. Donovan and Buehler [6] compared traditional and sinusoidal shoulder strips and showed that a sinusoidal form can retain a useful cabin cue while reducing roadside sound. Laughlin and Donahue [18] examined alternative designs intended to reduce roadside disturbance, and their work is often cited because it treated noise reduction as a design requirement rather than a secondary observation. Horne et al. [7, 17] further showed that the acoustic response depends on both geometry and vehicle class. Behnood et al. [19] examined prefabricated rubber sinusoidal strips, adding to the evidence that profile smoothness and material response affect vibration and noise. Kasess et al. [20] also emphasized that acoustic, vibration, and perception responses cannot be collapsed into a single geometric parameter.

Roadside noise has a public health dimension that is broader than rumble strips alone. Road traffic noise exposure has been linked to annoyance, sleep disturbance, cardiovascular stress pathways, and cognitive effects, although the strength of association depends on exposure measure and population context [21, 22, 23]. Transport noise studies have also shown that acceleration, vehicle speed, fleet composition, and pavement type shape emission levels [24, 25]. For a rumble strip, the sound event is intermittent rather than continuous, but repeated night-time strikes near residences may be perceived as more intrusive than a small increase in hourly equivalent level. This matters in Indian corridors where freight vehicles may travel at night and where dwellings can be closer to the paved edge than formal design assumptions imply.

Indian road traffic noise studies have often concentrated on urban roads, industrial cities, and high-volume intersections. Banerjee et al. [14] documented spatial and temporal road traffic noise variation in Asansol, while Garg and Maji [15] reported environmental noise patterns across major Indian cities. These studies differ from the present experiment because they measured traffic noise under operating conditions rather than controlled rumble strip strikes. Still, they show that the background environment is already acoustically stressed in many location

s. In this context, a treatment that reduces departure crashes but adds sharp pass-by sound events may face local resistance if it is not designed and placed carefully.

The modelling literature also matters because Indian mixed traffic is difficult to represent with simple flow-speed relationships. Honking, lane indiscipline, and vehicle-class diversity affect the structure of noise emissions [11, 12]. Recent data-driven work has shown that two-wheeler volumes and heterogeneous vehicle categories can be influential predictors of traffic noise in Indian settings [13]. For the present study, this means that rumble strip sound should not be evaluated only for passenger cars. Buses and freight vehicles must be included because they produce stronger tire-pavement interaction and because they are common on rural highways at night. Two-wheelers require separate safety consideration, but enclosed vehicles provide the clearest in-cabin acoustic measurements.

The research scope was deliberately narrow enough to allow controlled testing. The study evaluated milled edge-line strips on a divided rural highway, not centreline strips on undivided roads and not raised transverse speed-calming strips. The designs were placed outside the normal wheel path, and controlled strikes were performed by trained drivers using enclosed vehicles. The roadside noise measure was the difference between a strike pass and a matched rolling pass on the same pavement. The in-cabin measure was the difference between the cabin level during the strike and the cabin level during the matched rolling

pass. This paired approach reduces the influence of vehicle engine noise, ambient sound, and day-to-day measurement variability.

Sallam et al. [10] reported that all ten tested designs in their field study satisfied the commonly used in-vehicle warning range and that several sinusoidal designs reduced roadside noise relative to baseline traditional strips. That result is useful here because it supports testing a family of low-noise designs rather than treating the traditional milled strip as the only practical form. The present study extends that logic to an Indian mixed-traffic setting with locally common vehicle categories and operating speeds. The aim is not to reproduce their U.S. design catalogue; it is to test whether a lower-depth tapered sinusoidal profile can perform acceptably on a corridor where roadside receptors and heavy vehicles are both important.

The field study was guided by three research questions. The first was whether sinusoidal designs produce statistically lower roadside noise increments than a conventional rectangular design under the same vehicle and speed conditions. The second was whether those designs maintain a practical in-cabin warning increment across hatchback, sedan, sport utility vehicle, bus, and truck categories. The third was whether a simple predictive model can express the trade-off among net depth, wavelength, speed, and vehicle class in a form that can support preliminary design screening. These questions are empirical and modest. They do not claim to settle crash effectiveness, long-term pavement durability, or social acceptance, all of which require additional study.

3. Study Corridor and Field Experiment

The test corridor was a resurfaced four-lane divided rural highway section located on the edge of a growing town cluster in southern India. The selected segment had an asphalt concrete wearing course less than six months old, a tangent alignment, no major vertical curve within the test zone, and a paved shoulder of sufficient width to allow controlled edge-line strikes without entering the unpaved verge. The nearest continuous settlement edge was approximately 70 m from the carriageway on one side and more than 120 m on the other side. The corridor carried intercity buses, passenger cars, goods vehicles, and local two-wheeler traffic during normal operation. For the controlled experiment, traffic management isolated the test lane during short measurement windows.

Six rumble strip designs were milled in separate 120 m panels with transition gaps between panels. The first design, denoted T0, was a conventional rectangular milled strip with a nominal depth of 10 mm, groove length of 300 mm, groove width of 180 mm, and spacing of 300 mm. The second, T1, was a shallow rectangular design with a nominal depth of 7 mm and a shorter groove length of 250 mm. The remaining four were sinusoidal designs. S1 had a net depth of 8 mm, wavelength of 300 mm, and strip length of 350 mm. S2 had a net depth of 7 mm, wavelength of 400 mm, and strip length of 350 mm. S3 was a tapered sinusoidal design with a net depth of 6 mm, wavelength of 400 mm, and strip length of 300 mm. S4 had a net depth of 7 mm, wavelength of 500 mm, and strip length of 450 mm. The designs were selected to cover a plausible range of low-profile geometries rather than to exhaust every possible parameter combination.

The milling work was carried out using a controlled milling head and a marked reference line parallel to the edge line. Depth checks were taken at the beginning, middle, and end of each panel. The mean measured depths were within 0.8 mm of the target values for all designs. The pavement surface was swept before testing, and no loose aggregate remained in the milled grooves. Since the study focused on acoustic performance, panels with visible milling irregularities were not used. Two short trial passes were conducted for each design before formal measurement to confirm that the driver could maintain a steady path over the strip.

Seven enclosed vehicle categories were used: a small hatchback, a compact sedan, a compact sport utility vehicle, an intercity bus, a light commercial vehicle, a two-axle rigid truck, and a multi-axle articulated truck. These categories were chosen because they represent a practical cross-section of Indian highway traffic while allowing repeatable in-cabin microphone placement. Two-wheelers were not used for deliberate rumble strip strikes in the main experiment because the treatment is not intended as a motorcycle warning device and because rider stability should be evaluated separately. However, ambient

measurement periods included normal corridor background when traffic management was not active, and these periods were used only to understand baseline roadside sound, not to estimate rumble strip strike increments.

Three target speeds were used: 40 kph, 60 kph, and 80 kph. The lowest speed represents constrained operation near access points or village approaches, the middle speed represents common operating speed on many rural four-lane corridors with moderate enforcement, and the highest speed represents free-flow operation by passenger vehicles and some commercial vehicles. Heavy vehicles were not forced to travel at an unsafe speed; if a driver could not stabilize speed within the tolerance band, the run was discarded. A valid pass required the vehicle to strike the strip continuously for at least four seconds, maintain speed within plus or minus 4 kph of the target, and avoid contamination by another vehicle horn, nearby pass-by, or wind gust.

External noise was measured using two class-1 sound level meters, one placed 7.5 m from the centre of the struck wheel path at a height of 1.5 m and the other placed 15 m from the same reference line at a height of 1.5 m. The closer microphone was used for the main reported results because it provided a clearer strike signature; the farther microphone was used for propagation checks. Cabin noise was measured using a class-2 meter mounted near the front passenger ear position, with windows closed, air-conditioning fan at the lowest stable setting, and audio systems off. The measurement approach followed the general logic of pass-by and interior sound standards used in road noise studies [26, 27]. The instruments were calibrated before and after each measurement block, and calibration drift did not exceed 0.3 dBA.

Each vehicle completed two rolling baseline passes and four strike passes for each design at each speed, giving a planned total of 882 strike observations. After screening, 864 valid strike observations remained. The most common reasons for exclusion were speed deviation for the articulated truck at 80 kph, horn contamination from distant traffic during two bus passes, and incomplete strip contact by the light commercial vehicle during early S4 trials. Weather conditions remained acceptable throughout the two test days, with dry pavement, air temperature between 28 degrees Celsius and 34 degrees Celsius, and wind speed below 4.6 m/s. The test was not conducted at night, so the acoustic results should not be interpreted as a direct estimate of night-time annoyance.

The study used paired measurement to reduce dependence on absolute sound level. For each vehicle, design, speed, and repetition, the strike sound level was compared with the nearest valid rolling baseline pass by the same vehicle at the same speed on the same pavement. This was important because the bus and trucks had higher engine and rolling noise than passenger cars even before striking the strip. A design that appears loud in absolute terms may be less intrusive if the vehicle is already loud, but residents hear total sound, not only increment. For that reason, the analysis reports both the increment above baseline and the absolute maximum sound level at the external microphone.

The main external response variable was the A-weighted maximum level during the strike window, denoted as the roadside event level. The equivalent continuous level over a one-second window was also stored, but the maximum event level was more sensitive to abrupt impacts and more aligned with the perceptual character of rumble strip strikes. The in-cabin response used the A-weighted equivalent level over the same strike window, because the cabin signal was less impulsive and more continuous once the tire was fully on the strip. Frequency spectra were computed for a subset of clean passenger-car, bus, and truck runs to examine whether sinusoidal profiles shifted energy away from higher bands, but the study did not rely on detailed psychoacoustic metrics.

4. Mathematical Modelling and Statistical Estimation

The analysis treated each strike as a paired acoustic event. Let i denote the rumble strip design, j the vehicle category, k the target speed, and r the repeated run. The external strike level was denoted by L_{ijk}^E , and the matched external rolling baseline level was denoted by B_{jkr}^E . The cabin strike and cabin baseline levels were denoted by L_{ijk}^C and B_{jkr}^C . The primary increment measures were therefore expressed

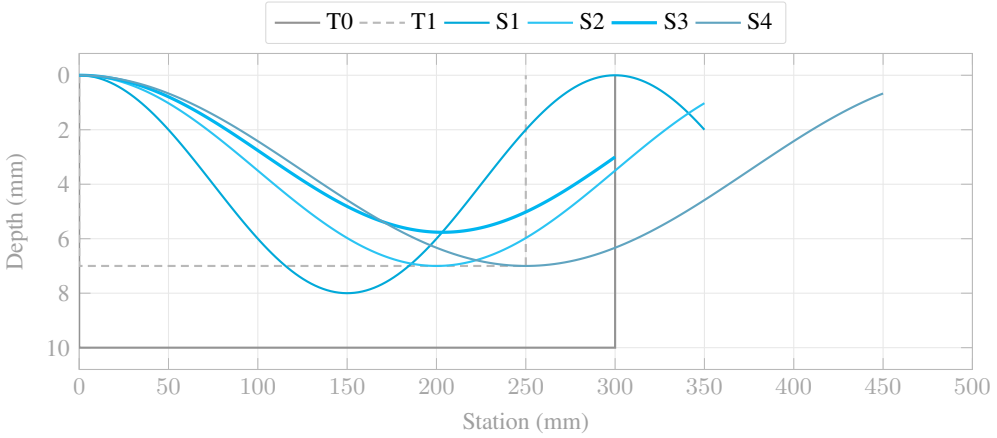


Figure 7: The tested groove family spans rectangular impact profiles and smoother low-depth sinusoidal profiles, with S3 combining taper, moderate wavelength, and reduced net depth.

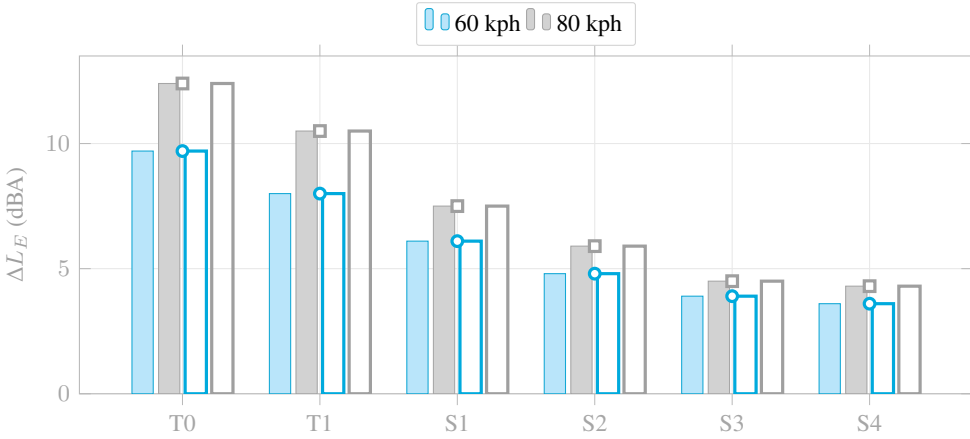


Figure 8: Mean roadside increments at the 7.5 m microphone decline from T0 toward the sinusoidal designs, and the speed effect is strongest for the rectangular profile.

in decibel differences, while an energy ratio was also computed to interpret the physical magnitude of noise change.

$$\begin{aligned}
 \Delta_{ijk}^E &= L_{ijk}^E - B_{jkr}^E \\
 \Delta_{ijk}^C &= L_{ijk}^C - B_{jkr}^C \\
 \rho_{ijk}^E &= 10^{\Delta_{ijk}^E / 10} \\
 \rho_{ijk}^C &= 10^{\Delta_{ijk}^C / 10}
 \end{aligned} \tag{4.1}$$

The paired increment is not a perfect measure of community response, because residents hear the total event level rather than the increment alone. It is nevertheless useful for comparing designs because the same vehicle and speed are used in the rolling and strike cases. A 6 dBA reduction in the strike increment represents a large reduction in event energy, even if the absolute pass-by level remains high

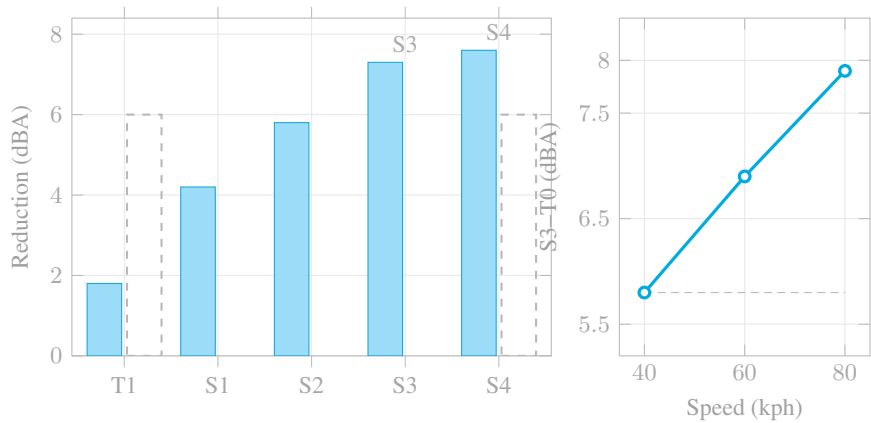


Figure 9: Average reductions relative to T0 show the strongest acoustic benefit for S3 and S4, while the S3 benefit increases with speed.

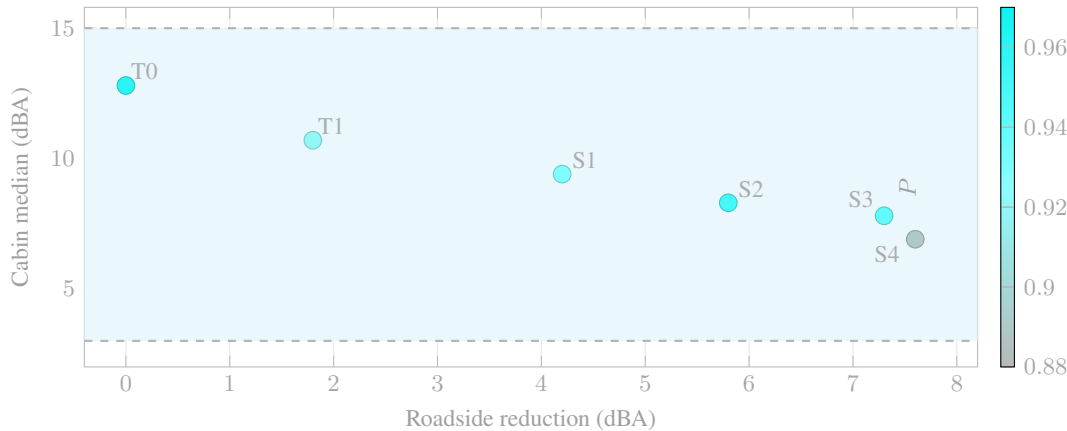


Figure 10: The acoustic trade-off places S3 near the balanced region, with high predicted warning adequacy and a large reduction in external increment.

Table 1: Geometric Characteristics of Tested Rumble Strip Designs

Design	Net Depth (mm)	Wavelength/Spacing (mm)	Profile Type
T0	10	300	Rectangular
T1	7	300	Shallow Rectangular
S1	8	300	Sinusoidal
S2	7	400	Sinusoidal
S3	6	400	Tapered Sinusoidal
S4	7	500	Sinusoidal

for a truck. For interpretation, both the mean increment and the 95% confidence interval of the paired difference relative to T0 were computed.

The external noise model used a linear mixed-effects structure. The fixed effects included net depth, wavelength, profile family, vehicle group, and speed. Vehicle category was also treated as a random intercept because repeated observations from the same vehicle category share tire, suspension, and body

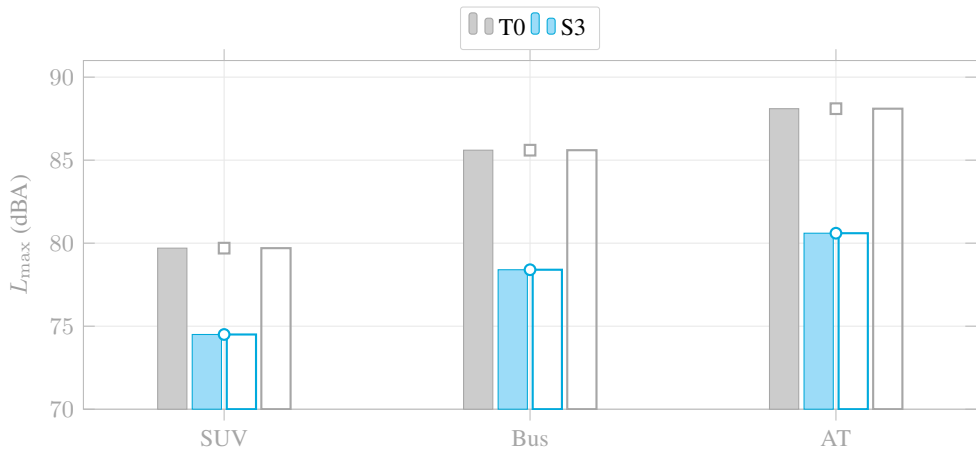


Figure 11: At 80 kph, S3 lowers fixed-position event levels for passenger and heavy vehicles, with the largest absolute levels remaining in the truck group.

Table 2: Vehicle Categories Included in Controlled Testing

Vehicle Category	Class Group	Typical Highway Role	Enclosed Cabin
Hatchback	Passenger Car	Local/Intercity Travel	Yes
Sedan	Passenger Car	Intercity Travel	Yes
SUV	Passenger Car	Mixed Use	Yes
Intercity Bus	Heavy Vehicle	Public Transport	Yes
Light Commercial Vehicle	Commercial	Goods Delivery	Yes
Rigid Truck	Heavy Vehicle	Freight Transport	Yes
Articulated Truck	Heavy Vehicle	Long-Haul Freight	Yes

Table 3: Experimental Design and Data Collection Summary

Parameter	Value	Unit	Remarks
Rumble Strip Designs	6	–	T0–S4
Vehicle Categories	7	–	Enclosed vehicles only
Target Speeds	3	kph	40, 60, 80
Planned Strike Runs	882	events	Before screening
Valid Strike Runs	864	events	Used in analysis
Microphone Distances	7.5, 15	m	Roadside locations

characteristics. Day block was included as a random term to absorb small changes in background conditions. The speed variable was log-transformed around 60 kph to reflect the non-linear relation between speed and tire-pavement sound without forcing a high-order polynomial.

$$\begin{aligned} \Delta_{ijk}^E = & \beta_0 \beta_D D_i \beta_\lambda \lambda_i \beta_P P_i \\ & \beta_V x_k \beta_H H_j \beta_T T_j \\ & \beta_{DV} D_i x_k \beta_{PV} P_i x_k \\ & u_j \ q_b \ \varepsilon_{ijk}^E \end{aligned} \tag{4.2}$$

Table 4: Mean Roadside Noise Increment at 60 kph

Design	Increment (dBA)	Reduction vs T0 (dBA)	Relative Rank
T0	9.7	0.0	6
T1	8.0	1.7	5
S1	6.1	3.6	4
S2	4.8	4.9	3
S3	3.9	5.8	2
S4	3.6	6.1	1

Table 5: Roadside Noise Increment Across Operating Speeds

Design	40 kph (dBA)	60 kph (dBA)	80 kph (dBA)
T0	7.3	9.7	12.4
T1	6.2	8.0	10.5
S1	4.9	6.1	7.5
S2	3.8	4.8	5.9
S3	3.1	3.9	4.5
S4	2.9	3.6	4.3

Table 6: Median In-Cabin Warning Increment by Design

Design	Cabin Increment (dBA)	Below 3 dBA Runs (%)	Warning Status
T0	12.8	0.8	Strong
T1	10.7	2.1	Adequate
S1	9.4	3.2	Adequate
S2	8.3	4.5	Adequate
S3	7.8	5.7	Adequate
S4	6.9	11.4	Marginal at Low Speed

Table 7: Heavy-Vehicle Roadside Event Levels at 80 kph

Vehicle Type	T0 (dBA)	S3 (dBA)	Reduction (dBA)
SUV	79.7	74.5	5.2
Intercity Bus	85.6	78.4	7.2
Articulated Truck	88.1	80.6	7.5

In this expression, D_i is net depth in millimetres, λ_i is wavelength in metres for sinusoidal designs and spacing-equivalent wavelength for rectangular designs, P_i is a tapered-profile indicator, $x_k = \log v_k 60$, H_j is a heavy-vehicle indicator for buses and trucks, and T_j is a truck-only indicator. The random term u_j represents vehicle-category deviation, q_b represents day-block deviation, and ε_{ijk}^E is the residual error. The cabin model used the same basic structure, but the profile-speed interaction was allowed to differ because cabin response depends on vehicle insulation and suspension filtering.

$$\begin{aligned}
 \Delta_{ijk}^C = & \gamma_0 \gamma_D D_i \gamma_\lambda \lambda_i \gamma_P P_i \\
 & \gamma_V x_k \gamma_H H_j \gamma_T T_j \\
 & \gamma_{DV} D_i x_k \gamma_{\lambda H} \lambda_i H_j \\
 & a_j s_b \varepsilon_{ijk}^C
 \end{aligned} \tag{4.3}$$

Table 8: Mixed-Effects Model Estimates

Predictor	Response Variable	Estimate	95% CI
Net Depth (mm)	External Increment	0.82	0.57–1.08
Net Depth (mm)	Cabin Increment	0.68	0.42–0.95
Wavelength	External Increment	Negative	Significant
Tapered Profile	External Increment	-1.25	Significant

Table 9: Predicted Warning Adequacy Probability

Design	Probability	Warning Reliability	Rank
T0	0.96	Very High	1
S2	0.95	Very High	2
S3	0.94	High	3
S1	0.93	High	4
T1	0.92	High	5
S4	0.89	Moderate	6

Table 10: Overall Design Utility Ranking

Design	Utility Rank	Primary Advantage	Key Limitation
S3	1	Balanced Noise-Warning Trade-off	Slightly Louder than S4
S4	2	Lowest External Noise	Weaker Low-Speed Warning
S2	3	High Warning Probability	Higher External Noise
S1	4	Moderate Acoustic Reduction	Shorter Wavelength
T1	5	Easy Implementation	Limited Noise Benefit
T0	6	Strong Cabin Alert	Highest Roadside Noise

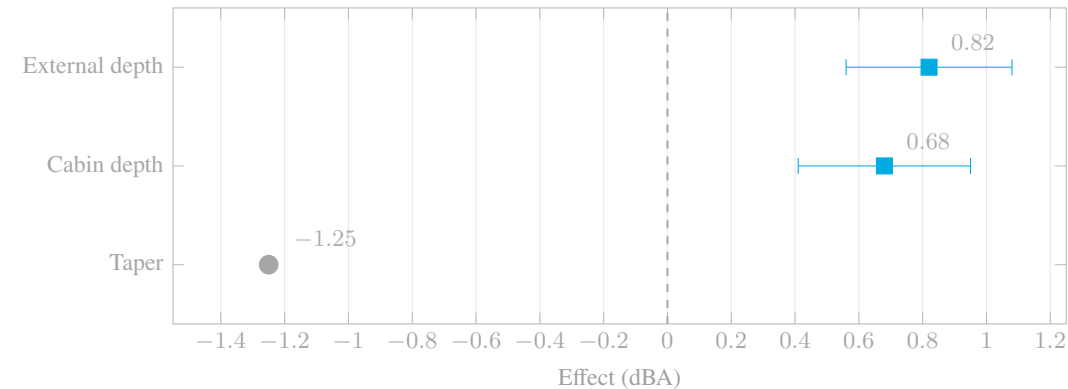


Figure 12: The fitted effects indicate that increasing depth raises external and cabin increments, while tapering reduces external increment after controlling for depth and wavelength.

A warning adequacy indicator was defined using a practical cabin increment range of 3 dBA to 15 dBA. A lower bound of 3 dBA was used because a smaller change may be masked by engine, fan, and road noise inside a vehicle. An upper bound of 15 dBA was used to avoid treating very large cabin shocks as automatically desirable. The study did not claim that this range captures every behavioural condition, but it is a useful engineering screen consistent with widely used rumble strip guidance [3]. The probability that a design produces an adequate cabin warning was estimated with a logistic model.

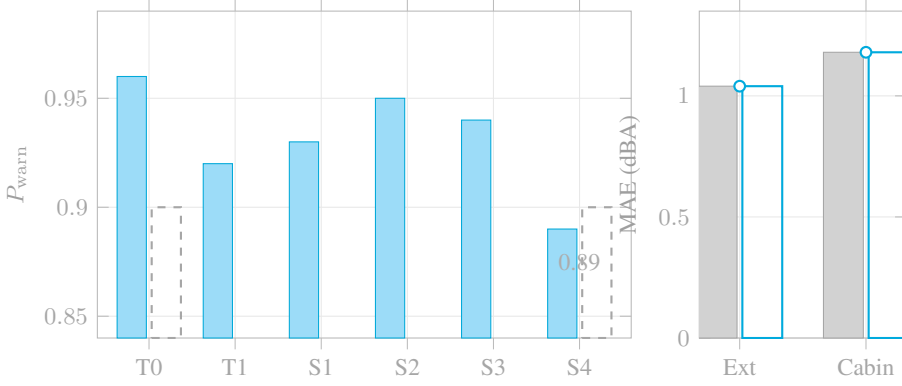


Figure 13: Warning probabilities remain high for most designs, and the validation error stays close to one decibel for both external and in-cabin responses.

$$\begin{aligned}
 Y_{ijk r} &= I(3 \leq \Delta_{ijk r}^C \leq 15) \\
 \Pr Y_{ijk r} = 1 &= [1 - \exp(-\eta_{ijk})]^{-1} \\
 \eta_{ijk} &= \theta_0 - \theta_D D_i - \theta_\lambda \lambda_i \\
 &\quad - \theta_P P_i - \theta_V x_k - \theta_H H_j
 \end{aligned} \tag{4.4}$$

The design comparison then used a utility function rather than a single noise metric. A design with very low external sound but weak cabin warning is not acceptable, and a design with strong cabin warning but high external noise may be unsuitable near settlements. The utility function combined expected external increment, probability of adequate cabin warning, and a penalty for high absolute roadside event level. The absolute event penalty was included because a truck strike that starts from a high rolling noise baseline can still be disturbing even if the increment is moderate.

$$\begin{aligned}
 U_i &= \omega_1 \bar{p}_i - \omega_2 \bar{\Delta}_i^E \\
 &\quad - \omega_3 \max(0, \bar{L}_i^E - L_0) \\
 &\quad - \omega_4 \max(0, \sigma_i^C - \sigma_0)
 \end{aligned} \tag{4.5}$$

Here, $\bar{p}_i$ is the mean warning adequacy probability, $\bar{\Delta}_i^E$ is the mean external increment, $\bar{L}_i^E$ is the mean absolute external event level, and σ_i^C is the standard deviation of cabin increment across vehicle categories. The constants L_0 and σ_0 were set to 82 dBA and 3.5 dBA respectively for this experiment. The weights were not treated as universal policy weights. For the main ranking, $\omega_1 = 10$, $\omega_2 = 1$, $\omega_3 = 0.7$, and $\omega_4 = 0.5$, which gives a substantial penalty to a design that fails to warn drivers but still gives meaningful value to roadside noise reduction.

The excitation frequency of a sinusoidal rumble strip was also computed to interpret spectral behaviour. For a vehicle travelling at speed v , the primary geometric excitation frequency is approximately the speed divided by wavelength. Because real tires have contact patch length, damping, tread pattern, and suspension response, this frequency is only a guide. It helps explain why increasing wavelength can lower the forcing frequency and reduce the sharpness of the exterior sound, but it does not determine the total sound level by itself.

$$\begin{aligned}
f_i v &= \frac{v}{3.6 \lambda_i} \\
A_i v &= \kappa D_i \left(\frac{v}{60} \right)^m \\
S_i f &= G f - f_i \phi G 2 f - f_i
\end{aligned} \tag{4.6}$$

The model was fitted using restricted maximum likelihood for the continuous responses and maximum likelihood for the logistic adequacy model. Residual plots were inspected by design, vehicle category, and speed. Heteroscedasticity was expected because trucks produced more variable external levels than cars. To avoid overstating precision, design contrasts were also checked using a non-parametric bootstrap clustered by vehicle category. The reported confidence intervals are therefore conservative relative to a simple independent-observation model.

A paired t-test was used for an easily interpretable design comparison against T0, but the mixed model was treated as the main inferential tool because it accounts for repeated runs and vehicle grouping. For each alternative design, the paired difference in external increment was calculated as T0 minus the alternative design under the same vehicle and speed condition. Positive values therefore mean that the alternative design reduced external noise. The same comparison was made for cabin increment, but the interpretation differs because a lower cabin increment is beneficial only until the warning threshold is approached.

$$\begin{aligned}
R_{ijk}^E &= \Delta_{T0,jk}^E - \Delta_{i,jk}^E \\
R_{ijk}^C &= \Delta_{T0,jk}^C - \Delta_{i,jk}^C \\
\bar{R}_i^E &= \frac{1}{JK} \sum_{j=1}^J \sum_{k=1}^K R_{ijk}^E
\end{aligned} \tag{4.7}$$

Model validation was internal rather than external. A leave-one-vehicle-category-out procedure was used to test whether the fitted model could predict the response for a held-out vehicle category. This was important because a design recommendation should not depend too heavily on one vehicle group. The mean absolute prediction error for external increment and cabin increment was reported for each held-out category. The bus and articulated truck were expected to be harder to predict because their tire and suspension systems differ sharply from those of passenger vehicles.

5. Results and Discussion

The conventional rectangular design T0 produced the highest mean external increment across the tested conditions. At 60 kph, the mean external increment at the 7.5 m microphone was 9.7 dBA for T0, 8.0 dBA for T1, 6.1 dBA for S1, 4.8 dBA for S2, 3.9 dBA for S3, and 3.6 dBA for S4. At 80 kph, the corresponding values were 12.4 dBA, 10.5 dBA, 7.5 dBA, 5.9 dBA, 4.5 dBA, and 4.3 dBA. At 40 kph, all increments were lower, but the rank ordering remained similar. The rectangular strip therefore behaved as expected: it provided a strong acoustic event, but it also created the largest roadside sound increase.

The mean reduction in external increment relative to T0 was 1.8 dBA for T1, 4.2 dBA for S1, 5.8 dBA for S2, 7.3 dBA for S3, and 7.6 dBA for S4 across all speed and vehicle categories. The reductions for S2, S3, and S4 were statistically significant at the 95% confidence level under the paired test and under the mixed-effects model. S1 also produced a statistically significant reduction, but its benefit was smaller because its shorter wavelength and higher depth retained a stronger impact component. T1 was quieter than T0 but remained closer to the conventional response, which indicates that simply reducing rectangular groove depth and length can help but does not reproduce the smoother acoustic signature of a sinusoidal profile.

The heavy vehicles generated the largest absolute roadside event levels. For T0 at 80 kph, the articulated truck produced a mean external event level of 88.1 dBA at 7.5 m, while the bus produced 85.6 dBA and the compact sport utility vehicle produced 79.7 dBA. Under S3, those event levels were reduced to 80.6 dBA, 78.4 dBA, and 74.5 dBA respectively. These values should not be read as a direct community exposure estimate because they reflect controlled strikes at a fixed microphone position, but they show why the heavy-vehicle response matters. A low-noise design that performs well for cars but poorly for trucks would not be suitable on Indian freight corridors.

The 15 m microphone showed reductions consistent with the 7.5 m microphone, although the increments were smaller because propagation and ground effects attenuated the strike signature. The mean 15 m external increment for T0 was 7.8 dBA, compared with 3.0 dBA for S3 and 2.8 dBA for S4. The difference between 7.5 m and 15 m levels was not exactly the free-field inverse-distance value because the source was close to the ground, the pavement surface was reflective, and the surrounding ground was partly compacted soil. Even so, the relative ranking of designs was stable, which supports the use of the closer microphone for design comparison.

The in-cabin increments show the other side of the trade-off. T0 produced a median cabin increment of 12.8 dBA across all vehicle-speed conditions. T1 produced 10.7 dBA, S1 produced 9.4 dBA, S2 produced 8.3 dBA, S3 produced 7.8 dBA, and S4 produced 6.9 dBA. These median values all fall within the practical warning range. However, the lower tail of the distribution differed by design. S4 generated cabin increments below 3 dBA in 11.4% of valid runs, mainly for the articulated truck and two-axle truck at 40 kph. S3 generated below-threshold increments in 5.7% of runs, and S2 in 4.5%. T0 produced very few below-threshold increments but exceeded 15 dBA in 6.2% of runs, mostly in the hatchback and compact sedan at 80 kph.

These results point to a familiar design compromise. The quietest geometry in external terms was not always the most reliable cabin warning across low-speed heavy-vehicle passes. S4 had the lowest mean external increment, but its longer wavelength and moderate depth reduced the cabin signal for heavy vehicles at 40 kph. S3 was slightly louder outside than S4 but produced more stable cabin increments across vehicles. For a corridor with high night-time truck traffic and nearby settlements, S3 would be easier to defend as a balanced design. For a corridor dominated by passenger vehicles and buses at moderate speed, S4 could be reasonable if supplemented by placement rules that avoid low-speed heavy-vehicle warning dependence.

The mixed-effects model estimated a positive effect of net depth on both external and cabin increments. Each additional millimetre of net depth was associated with a 0.82 dBA increase in external increment, with a 95% confidence interval from 0.57 dBA to 1.08 dBA, after controlling for speed and vehicle category. The cabin depth coefficient was 0.68 dBA per millimetre, with a 95% confidence interval from 0.42 dBA to 0.95 dBA. Wavelength had a negative association with external increment and cabin increment, but the magnitude was stronger for cabin response in heavy vehicles. The tapered profile indicator reduced external increment by 1.25 dBA on average after controlling for depth and wavelength, while its cabin effect was small and not statistically significant at the 95% level.

Speed amplified the differences among designs. At 40 kph, the mean external reduction of S3 relative to T0 was 5.8 dBA. At 60 kph, it increased to 6.9 dBA, and at 80 kph it reached 7.9 dBA. This occurs because the conventional rectangular groove becomes increasingly impulsive at higher speed, whereas the sinusoidal profile moderates the tire input. The depth-speed interaction was positive, indicating that deeper designs become disproportionately louder as speed rises. This interaction is important for Indian corridors where speed variation is substantial. A rumble strip that is acceptable near a toll approach or village access at 40 kph may be much more intrusive on a free-flowing bypass section at night.

The spectral analysis supported the event-level results. T0 produced a broader high-frequency component, especially between 800 Hz and 2,000 Hz for passenger vehicles and between 400 Hz and 1,250 Hz for heavy vehicles. S3 and S4 shifted more energy toward lower bands and reduced the sharper peaks associated with abrupt impact. This does not prove lower annoyance by itself, because annoyance depends on timing, expectation, background noise, and sleep state. However, it is consistent with the

physical expectation that smoother profiles reduce abrupt tire excitation. Similar reasoning appears in prior work on low-noise strips and rumble strip perception [20, 17].

The logistic warning adequacy model estimated high adequacy probabilities for T0, S1, S2, and S3 under most conditions. The predicted probability of an adequate cabin increment was 0.96 for T0, 0.93 for S1, 0.95 for S2, 0.94 for S3, and 0.89 for S4 when averaged across the observed fleet and speeds. T1 had a predicted probability of 0.92. The slightly higher predicted adequacy for S2 compared with S3 is linked to S2's greater net depth. The difference is small, and S2 was also louder outside. The utility model therefore ranked S3 first under the main weight set, followed by S4, S2, S1, T1, and T0. When the external noise weight was increased by 50%, S4 moved to first place. When the warning probability weight was increased by 50%, S2 and S3 were nearly tied.

The leave-one-vehicle-category-out validation produced a mean absolute prediction error of 1.04 dBA for external increment and 1.18 dBA for cabin increment. The prediction error was lowest for the hatchback, sedan, and sport utility vehicle, and highest for the articulated truck. The model underpredicted the truck external increment for T0 at 80 kph by 2.2 dBA, which suggests that heavy-vehicle suspension and tire effects may need more detailed representation. Even with this limitation, the model was accurate enough for preliminary design comparison. It should not be used to certify a geometry without local testing, but it can reduce the number of candidate designs before field trials.

The results are broadly consistent with previous rumble strip studies, but the Indian mixed-traffic setting changes the practical interpretation. In some North American field tests, passenger vehicles dominate the acoustic comparison, while heavy trucks are included as a smaller part of the test fleet [28, 16]. In the present corridor, buses and trucks are not exceptional; they are central to the night-time acoustic environment. This makes the reduction achieved by S3 meaningful, because the design reduced heavy-vehicle external increments while still producing a cabin cue. A design that only works for cars would not respond to the operational reality of many Indian highways.

The results also show that a low-noise design should not be confused with a silent design. Even S3 and S4 produced clearly audible events when struck by heavy vehicles at 80 kph. Their value lies in reducing the magnitude and sharpness of the event, not in eliminating it. This distinction matters for public communication. If a highway agency installs low-noise rumble strips near a settlement, residents may still hear strikes, especially at night. The appropriate claim is that the selected geometry is expected to reduce roadside noise compared with a conventional milled strip while maintaining a driver warning, not that it removes all disturbance.

The shallow rectangular design T1 deserves a cautious note. It reduced external noise relative to T0 and retained generally adequate cabin response, but it was not as quiet as the sinusoidal options. It may be attractive where milling equipment cannot produce sinusoidal profiles or where maintenance agencies prefer familiar rectangular cuts. However, its external reduction was limited, and the event retained more high-frequency content than S3. In settlement-adjacent zones, T1 would be a fallback rather than a preferred option. On corridors without nearby receptors, the conventional design may still be acceptable if the priority is maximum cabin warning and if roadside disturbance is unlikely.

The observed data suggest that the geometry most suited to Indian settlement-edge highways is neither the deepest conventional strip nor the longest and smoothest sinusoidal strip. A moderate wavelength, reduced-depth, tapered sinusoidal design performed more consistently. Its net depth was sufficient for cabin response, while its taper and wavelength reduced abrupt exterior impact. This does not imply that the exact dimensions tested here should be adopted nationally. Pavement type, tire fleet, installation tolerance, rainfall, maintenance, and driver behaviour differ across regions. It does suggest, however, that Indian agencies should consider a design envelope rather than a single inherited standard section.

6. Practical Interpretation for Indian Highway Design

A direct design recommendation from a single field site would be too narrow, but several practical interpretations follow from the results. First, rumble strip selection should depend on roadside receptor

context. A conventional rectangular design may be acceptable on isolated rural sections with wide right-of-way and little night-time occupancy near the carriageway. Near villages, schools, hospitals, settlement entrances, or continuous residential frontage, a lower-noise sinusoidal design should be evaluated before installation. The treatment should not be installed as a default item without considering where sound events will propagate.

Second, vehicle mix should be treated as a design input. Many Indian highways carry high bus and freight shares during periods when residents are sleeping. A design screened only with cars may underestimate external noise and overestimate cabin alerting reliability. The test results indicate that trucks can produce both the highest external levels and the most variable cabin increments. This dual role means that heavy vehicles should be included in acceptance testing. State agencies do not need a very large fleet for every project, but they should include at least one bus or rigid truck when approving a geometry for a freight corridor.

Third, the speed environment matters. The same rumble strip design produced different acoustic outcomes at 40 kph, 60 kph, and 80 kph. Where operating speeds are low, very long-wavelength designs may produce weak cabin increments for heavy vehicles. Where speeds are high, deeper rectangular designs may create avoidable exterior noise. This points toward a speed-sensitive design envelope. For free-flow rural sections near receptors, a tapered sinusoidal profile with moderate wavelength and reduced net depth appears preferable. For low-speed approaches where departure warning is still needed but cabin increments may be small, slightly greater depth may be necessary.

Fourth, the placement of strips should account for two-wheelers and shoulder users. The present study did not conduct deliberate two-wheeler strike tests, and this is a limitation rather than a minor detail. In many Indian corridors, paved shoulders are used by motorcycles, bicycles, pedestrians, and slow-moving local vehicles. Edge-line rumble strips can create discomfort or instability if placed where two-wheelers routinely travel. A low-noise acoustic design should therefore be paired with placement guidance that avoids continuous occupation of the motorcycle path. Where the shoulder functions as a mixed-use travel space, other warning or delineation treatments may be more appropriate.

Fifth, construction quality is part of acoustic performance. A sinusoidal profile only works as intended if the milling machine can reproduce the smooth shape and depth consistently. Poorly milled sinusoidal strips may behave like irregular impact grooves, losing much of their noise advantage. Quality checks should include depth, wavelength, profile smoothness, lateral placement, debris removal, and post-milling surface condition. A small tolerance error in depth can have a noticeable acoustic effect because the model estimated roughly 0.8 dBA additional external increment per millimetre of net depth. This does not mean every millimetre has the same effect under all conditions, but it is enough to justify field verification.

The findings also have implications for complaint management. When residents object to rumble strip noise, the agency response should not be limited to removal or denial. A design replacement approach may be feasible: replacing conventional strips with a lower-noise sinusoidal profile, increasing offset from residences where shoulder width allows, creating gaps near the most sensitive frontage, or using alternative delineation where shoulder use is high. International studies have already indicated that sinusoidal strips can reduce roadside sound while preserving warning functions [4, 6, 8]. The present field results suggest that such an approach can be adapted to Indian corridors, though local validation remains necessary.

A cost interpretation was not the central focus of the study, but it is relevant for implementation. Sinusoidal milling may require specialized equipment or additional contractor setup compared with conventional rectangular grooves. The added cost must be weighed against avoided complaints, reduced need for later removal, and better compatibility with settlement-edge highways. The study does not provide a full life-cycle cost analysis. It does, however, show that a modest geometric change can reduce external noise by several dBA, which is large enough to be noticed in controlled comparisons. The cost question should therefore be framed as a choice among design standards, not simply as an optional refinement.

The results also suggest that Indian standards could benefit from performance-based language. Instead of prescribing only one groove depth and spacing, a standard could specify acceptable ranges for external increment, cabin increment, and construction tolerance under defined test conditions. Such a standard would allow agencies to approve locally tested sinusoidal profiles while avoiding weak designs that fail to warn drivers. Performance-based screening is especially useful in a country with varied pavement types, climate, vehicle fleet composition, and roadside settlement patterns. It also leaves room for improved milling technology and future acoustic modelling.

7. Limitations and Further Validation

The study was conducted on one resurfaced asphalt corridor under dry conditions. Pavement texture, age, binder type, aggregate gradation, and surface temperature can influence tire-pavement noise. A rougher or older surface may reduce the apparent increment because the rolling baseline is already louder, while a smoother surface may make rumble strip strikes more prominent. The tested designs should therefore be repeated on other pavement surfaces before being treated as a general national recommendation. Concrete pavement, open-graded asphalt, and older bituminous surfaces may produce different results.

The vehicle set was broader than many small acoustic trials, but it was still limited. Only one vehicle represented each category, and tire type, tire wear, inflation pressure, loading condition, suspension condition, and cabin insulation were not varied systematically. Freight vehicles in India can vary substantially in load, maintenance, and tire condition. A heavily loaded truck may respond differently from the tested vehicle, and a worn suspension could change both external impact and cabin vibration. Future work should include repeated vehicles within the same category and should record tire and load conditions more carefully.

The experiment did not measure driver behavioural response, lane recovery, or crash outcomes. An in-cabin sound increment is a proxy for warning conspicuity, not proof of correction by a distracted or drowsy driver. Human response depends on attention state, prior experience, fatigue, expectation, and simultaneous visual or tactile cues [3, 9]. A future study could combine acoustic measurement with controlled simulator or closed-track driver response testing. Until such evidence is available, the acoustic warning range should be treated as a screening criterion rather than a complete safety validation.

Community response was also not measured. Residents may judge a sound event differently depending on time of day, frequency of strikes, background level, house construction, distance, and perceived fairness of the road project. The present study measured physical sound, not annoyance. A design that reduces external event level by 7 dBA may still receive complaints if trucks strike it frequently at night near bedrooms. Future field evaluation should include long-term unattended monitoring and resident surveys before and after installation. This would connect the controlled acoustic reduction to lived experience.

The study excluded deliberate two-wheeler strike trials. This was a cautious decision because the main edge-line treatment is not intended to be ridden continuously by motorcycles, and rider stability involves more than sound measurement. However, the exclusion limits the conclusions. Indian highways cannot ignore two-wheelers, and a rumble strip that is acoustically acceptable for enclosed vehicles may still be unsuitable if it creates discomfort or risk for shoulder-riding motorcyclists. Future work should use appropriate safety protocols to examine ride comfort, lateral placement, and avoidance behaviour for powered two-wheelers.

The mathematical model should also be read as an experimental model, not a universal prediction engine. It used six designs, three speeds, and seven vehicle categories. It can describe trends within the tested design envelope, but extrapolation beyond the observed depth and wavelength ranges would be risky. Non-linear models or machine learning tools may fit larger datasets better, as shown in broader traffic noise modelling work [13]. At the current sample size, however, a mixed-effects model is easier to interpret and less likely to hide the physical meaning of design parameters.

8. Conclusion

This study evaluated six milled edge-line rumble strip designs on an Indian rural divided highway corridor using controlled pass-by and in-cabin measurements from seven enclosed vehicle categories at three speeds. The conventional rectangular design generated the largest roadside increments, particularly for buses and trucks at higher speed. The lower-profile sinusoidal designs reduced roadside noise while retaining practical in-cabin warning levels in most conditions. The strongest overall compromise in this experiment was the tapered sinusoidal design with 6 mm net depth and 400 mm wavelength. It did not produce the lowest external increment in every case, but it produced a steadier balance between reduced roadside sound and adequate cabin response.

The results support a cautious move away from treating conventional rectangular strips as the default solution near Indian settlement-edge corridors. A conventional design can be acoustically intrusive when struck by heavy vehicles, and heavy vehicles are a regular part of the Indian highway fleet. Low-noise sinusoidal profiles offer a practical way to reduce that disturbance without removing the warning function altogether. The field data suggest that external reductions of roughly 6 dBA to 8 dBA are achievable relative to a conventional strip, depending on speed and vehicle category, while median cabin increments can remain within a useful warning range.

The study also shows why design selection should not be reduced to one dimension such as groove depth. Depth, wavelength, profile taper, speed, and vehicle class interact. A very smooth, long-wavelength design can be quiet outside but may become weak inside some heavy vehicles at low speed. A deep rectangular design can warn strongly but may create avoidable external sound. The most defensible design for a given corridor therefore depends on the operating speed and the sensitivity of nearby receptors. For Indian agencies, this points toward performance-based approval that uses both roadside and cabin measurements rather than only geometric drawings.

The findings are not a substitute for crash evaluation, human response testing, or community exposure assessment. They provide an acoustic screening result under controlled conditions. Before wider adoption, the tested sinusoidal design family should be validated on other pavement surfaces, with more vehicles per category, under different climates, and with attention to two-wheeler interaction. Long-term monitoring near installed sites would also help determine whether controlled reductions translate into fewer resident complaints. These steps are needed because the acceptability of rumble strips depends on both physical sound and local roadway use.

For the tested corridor, the evidence favours a reduced-depth tapered sinusoidal strip for settlement-adjacent edge-line applications where roadway departure warning is still required. The design offers a workable compromise, not a universal optimum. On isolated high-speed sections with few receptors, a stronger design may be acceptable. On shoulders used heavily by two-wheelers or pedestrians, continuous milled strips may be inappropriate regardless of acoustic performance. The broader conclusion is that rumble strip policy in India should become more context-sensitive, using measured sound performance, vehicle mix, and roadside land use as part of the same design decision.

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