

Study of the acoustic performance of various pavements at different vehicle speeds

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Abstract: S Rapid urban expansion has increased road transportation, making traffic noise one of the most significant environmental factors affecting urban residents, particularly those living near highways or major roads. This study analyzes how vehicle-generated noise varies with speed across four different types of pavements (P1, P2, P3, and P4). The study measured noise levels in dB (A) at seven speeds, from 20 to 80 km/h in 10 km/h increments, and analyzed the data using statistical tools. The study aimed to establish the relationship between vehicle speed and pavement type and identify which factor significantly affects vehicle-generated noise; it suggests that quieter pavements are preferred in noise-sensitive areas, while speed management and pavement material can be the most effective ways to reduce traffic noise.

Keywords: Environment, vehicle noise, pavement type, speed, linear regression, noise mitigation.

1. Introduction

1.1 Customer Relationship Management (CRM)

Fast urbanization and the exponential increase in road vehicles have made traffic noise one of the most widespread environmental issues.[1] Once dismissed as a minor nuisance, noise pollution is now recognized as a serious threat to public health and quality of life. [2]. Long-term exposure to high noise levels has been associated with cardiovascular disease, hypertension, sleep problems, cognitive impairment in children, and increased stress and annoyance.[3]. Road traffic is the leading source of environmental noise in urban areas, particularly along highways and major arterial roads with high traffic volumes and vehicular speeds.[4]. Consequently, identifying the factors that contribute to vehicle-generated noise and developing effective ways to reduce it have become key research areas in transportation engineering, environmental science, and urban planning.[5][6]. Noise from a moving vehicle is a complex phenomenon caused by several sources, including the engine, exhaust system, aerodynamic flow, and, most importantly, the interaction between the tires and pavement surface. [7]. At low speeds, engine and exhaust noise usually dominate, while tire-pavement interaction becomes the main noise source as speed increases.[8] This interaction depends on several factors, including vehicle type, tire characteristics, pavement surface texture, porosity, stiffness, and aggregate properties.[9] Consequently, road acoustic performance depends not only on traffic speed but also on pavement type and condition. Pavements are broadly classified as rigid and flexible; within these categories, different mix designs and surface treatments can lead to substantial differences in noise levels. For example, porous asphalt absorbs sound and reduces tire-road noise, whereas dense-graded or rougher surfaces tend to magnify it.[10]

Therefore, pavement selection is increasingly viewed as a viable noise mitigation measure, complementing traditional strategies such as speed limits, noise barriers, and traffic management.

Although research on traffic noise is growing, comprehensive statistical analyses are still needed to assess the combined effects of speed and pavement type on noise generation.[11] Many studies have examined speed or pavement characteristics separately, or used descriptive comparisons without rigorous inferential testing. These approaches may not quantify the relative importance of each factor, determine whether differences among pavement types are statistically significant, or produce reliable predictive models. They also often overlook the

interaction between speed and pavement type.[12] A robust statistical framework combining ANOVA, post-hoc comparisons, and regression can clarify how these factors jointly influence noise levels. These insights support evidence-based pavement selection and speed-management guidelines in noise-sensitive areas. Previous studies have demonstrated the value of these methods in traffic-noise research.[13]

This study aims to address this gap by statistically analyzing vehicle-generated noise data collected on four pavement types at seven speeds ranging from 20 to 80 km/h in 10 km/h increments. The data were obtained under controlled conditions to ensure consistency and reliability. The specific objectives of the study are:

- i. To evaluate the effect of speed on noise levels for each pavement type.
- ii. To assess whether pavement type significantly affects noise generation at the same speed.
- iii. To rank the pavements according to their mean noise levels.
- iv. To determine the relative contribution of speed and pavement type to overall noise variation.
- v. To develop linear regression models relating noise to speed for each pavement.
- vi. To identify the quietest and noisiest pavements and provide practical recommendations for noise mitigation.
- vii. To evaluate whether pavement age influences noise generation.

To achieve these objectives, we conducted a two-way analysis of variance (ANOVA) without replication, followed by Tukey's Honestly Significant Difference (HSD) test to compare pavements pairwise. Linear regression modeled the relationship between speed and noise for each pavement type. Descriptive statistics summarized the central tendency and variability of data.[14]

Together, these statistical tools provide a rigorous, comprehensive way to examine the factors that influence vehicle-generated noise. Similar methodological frameworks have been used to assess pavement noise performance.[15]

The findings of this study are expected to add to the existing literature by providing quantitative evidence of the relative importance of speed and pavement type. The results will help transportation engineers, urban planners, and policymakers select appropriate pavement materials and develop effective noise-reduction strategies.

2. Methodology

2.1 Study Area and Pavement Selection

This study was conducted on four pavement types, designated P1, P2, P3, and P4. Were:

P1: newly constructed rigid pavement with transverse tinning

P2: newly constructed semi-dense flexible pavement

P3: old rigid pavement with transverse tinning

P4: old semi-dense flexible pavement

These pavements differ in surface characteristics, including texture, porosity, and material composition, all of which are known to affect tire-pavement interaction noise. They were selected to compare noise generation across surface types under controlled conditions. The selection included both rigid and flexible pavements, in keeping with previous research comparing noise levels on concrete and asphalt. The study section was chosen to ensure a uniform pavement surface around the measurement location, as recommended by standard pass-by measurement procedures.

2.2 Measurement Method: Controlled Pass-By (CPB)

This study used the Controlled Pass-By (CPB) method, a variant of the Statistical Pass-By (SPB) method in ISO 11819-1 for comparing traffic noise across road surfaces. Selected vehicles were driven at controlled speeds past

a fixed measurement point, enabling direct comparison of roadside noise across pavement sections while minimizing variability from mixed traffic.

The CPB method captures all noise from a moving vehicle, including exhaust, engine, aerodynamic, and tyre-pavement interaction noise, making it ideal for evaluating pavement acoustics. Previous studies have isolated and quantified tyre-pavement noise by controlling vehicle operation to eliminate engine and exhaust noise.

2.3 Measurement Setup and Instrumentation

Noise levels were measured with a sound pressure level (SPL) meter. The microphone was positioned 7.5 m from the center of the roadside lane and 1.2 m above ground level, following the measurement geometry specified in ISO 11819-1. This setup matches the European standard microphone placement for pass-by noise measurements.

A digital speedometer installed in the test vehicle was used to determine and maintain the vehicle's instantaneous speed at the measurement location. The observation was recorded when the vehicle passed exactly through the midpoint of the measurement site, and the SPL meter captured the maximum sound pressure level (L_{max}) at that instant. Using L_{max} as the primary noise metric aligns with CPB methodology, which compares roadside noise levels across road sections using specific vehicle properties and speeds.

2.4 Test Conditions and Quality Control

I applied strict quality control during data collection to ensure that the measurements were reliable and valid. Wind-related disturbance was limited to a maximum of 5 dB while readings were taken with the sound pressure level meter. Temperatures during measurement ranged from 5 °C to 30 °C. We monitored these environmental conditions because they could influence noise propagation and pavement acoustic properties. Previous research has identified pavement temperature and wind direction as factors that can affect tire-pavement interaction noise.

In this study, a four-wheeler car was used for all test runs. The vehicle was operated one at a time at the selected road section, and the maximum sound pressure level was collected for each pass-by. To ensure no other vehicle was present within the selected measurement area during data collection, two volunteers were positioned 500 m from the measurement location on either side. These volunteers signaled the approach of other vehicles and temporarily halted data collection when necessary. This procedure ensured that the measured noise levels were attributable solely to the test vehicle and not contaminated by ambient traffic noise.

2.5 Data Collection Procedure

For each pavement type, noise was measured at five speeds, spaced at 10 km/h intervals. Five readings were taken at each speed, and their mean was used in subsequent analyses. This replication helped reduce measurement variability and improve data reliability, in line with standard practice in pass-by noise studies. Measurements across multiple speeds also enabled the construction of noise-speed relationships, which are essential for understanding how pavement acoustic performance changes with vehicle operating conditions.

3. Statistical Analysis

Several statistical techniques were used to analyze the collected noise data and assess the effects of speed and pavement type. For each pavement type, we calculated descriptive statistics, including the mean, standard deviation, variance, coefficient of variation, minimum, maximum, and range. A two-way analysis of variance (ANOVA) without replication tested whether speed and pavement type significantly affected noise levels. The model assumed no interaction between speed and pavement type. Following the ANOVA, Tukey's Honestly Significant Difference (HSD) test was used for post-hoc pairwise comparisons among the four pavements. This test controls the overall Type-I error rate across multiple comparisons and identifies which pavements differ significantly. We used linear regression to model the relationship between speed and noise for each pavement type, using the coefficient of determination (R^2) to assess goodness of fit. All statistical analyses were performed at a 5% significance level ($\alpha = 0.05$).

Table 1 presents vehicle-generated noise measurements recorded on four pavement types (P1, P2, P3, and P4). The first column lists vehicle speed in kilometers per hour (km/h) at seven levels: 20, 30, 40, 50, 60, 70, and 80 km/h, increasing in 10 km/h increments. The remaining four columns contain the corresponding noise levels in A-weighted decibels [dB (A)] for each pavement type. Each row corresponds to a specific speed, and each cell represents a single noise measurement for that speed-pavement combination. The dataset therefore consists of 7 speeds $\times$ 4 pavements = 28 observations. The design is balanced, with exactly one observation per speed-pavement combination. Because there is no replication within each combination, the interaction effect between speed and pavement type cannot be estimated; consequently, the data are suitable for a two-way analysis of variance (ANOVA) without replication. The noise values range from 62.79 dB (A) for pavement P2 at 20 km/h to 80.92 dB (A) for pavement P1 at 80 km/h. Table 2 facilitates statistical analysis of the effects of speed and pavement type on vehicle noise, including descriptive statistics, ANOVA, post hoc comparisons, and regression modeling.

Table 1. Vehicle-generated noise levels dB (A) at different speeds on four pavement types (P1–P4).

Speed of vehicle	P1	P2	P3	P4
20	66.54	62.79	65.63	63.92
30	70.10	66.53	69.14	67.67
40	73.13	69.67	72.38	70.81
50	75.92	72.83	75.29	73.97
60	77.88	74.96	77.33	76.13
70	79.68	77.32	79.15	78.59
80	80.92	78.94	80.44	80.16

P1: newly constructed rigid pavement with transverse tinning

P2: newly constructed semi-dense flexible pavement

P3: old rigid pavement with transverse tinning

P4: old semi-dense flexible pavement

3.1 Descriptive statistics for each pavement

$$\text{Mean, } \bar{x} = 1/n \sum_{i=1}^n x_i$$

$$\text{Standard Deviation, } s = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n - 1}}$$

$$\text{Coefficient of Variation, } CV = \frac{s}{\bar{x}} \times 100$$

Table 2 presents descriptive statistics. (Provide a concise numerical summary)

Pavement	Mean dB(A)	SD	Variance	CV %	Min	Max	Range
P1	74.88	5.25	27.51	7.00	66.54	80.92	14.38
P2	71.86	5.86	34.33	8.15	62.79	78.94	16.15
P3	74.19	5.43	29.46	7.32	65.63	80.44	14.81
P4	73.04	5.90	34.82	8.08	63.92	80.16	16.24

3.2 Vehicular Speed-wise Average Noise Generated

Table 3 presents the average vehicle-generated noise level in dB(A) at each tested speed, computed by averaging the noise values across all four pavement types (P1, P2, P3, and P4) at that speed. The table has two columns: the first lists the vehicle speed in kilometers per hour (20, 30, 40, 50, 60, 70, and 80 km/h), and the second gives the corresponding mean noise level in dB (A). For each speed, the mean is calculated as:

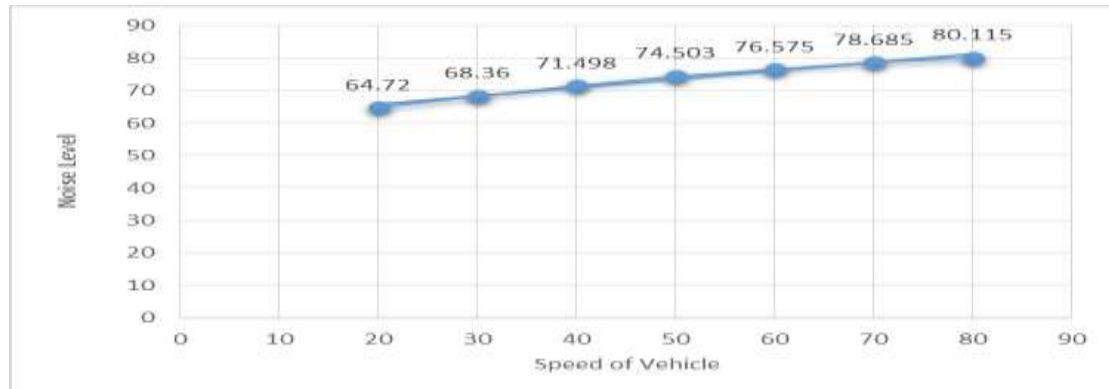
$$\bar{i} = \frac{1}{4} \sum_{j=1}^4 \text{Noise}_{(ij)}$$

Table 3 Vehicular speed-wise average noise generated

Speed km/h	Mean noise dB(A)
20	64.72
30	68.36
40	71.50
50	74.50
60	76.58
70	78.69
80	80.12

Figure 1 shows the average vehicle-generated noise level in dB(A) at each tested speed, computed by averaging the noise values obtained from all four pavement types (P1, P2, P3, and P4) at that speed. The figure has two axes: the Y-axis shows the noise level, and the X-axis shows the vehicle speed; the blue line shows the relationship between these two parameters.

Figure 1: Graphical representation of vehicle-generated noise level in dB (A) and speed of vehicle



3.3 Two-way ANOVA for Analyzing Speed and Pavement Effects

In this case, two-way ANOVA was used because the same speeds were tested across all four pavements; a two-way ANOVA without replication seems appropriate.

Table 4: Two-way ANOVA summary of vehicle noise by speed and pavement type.

Source	df	SS	MS	F	p-value
Speed	6	754.483	125.747	1017.0	< 0.001
Pavement	3	37.002	12.334	99.76	< 0.001
Error	18	2.225	0.1236		
Total	27	793.710			

The analyses show that both vehicle speed and pavement type have a highly significant effect on noise levels ($p < 0.001$). Speed is the dominant factor, accounting for approximately 95.1% of the total variation in noise, while pavement type accounts for about 4.66%. Together, the factors explain about 99.7% of the total variation, indicating an excellent model fit and confirming that vehicle speed and pavement characteristics strongly influence noise levels.

Tukey HSD ranking for pavements.

ANOVA indicates only that at least one pavement mean differs from the others; it does not identify which pavements differ. Tukey's Honestly Significant Difference test is a post hoc multiple-comparison procedure conducted after ANOVA to compare all pairs of pavement means while controlling the overall Type I error rate.

$$HSD = q_{\alpha, k, d, f_{Error}} \sqrt{MSE}$$

Where:

- q = critical value from the studentized range distribution
- $\alpha = 0.05$
- $k = 4$ pavements
- $df_{Error} = 18$
- $MSE = 0.1236$
- $n = 7$ observations per pavement
- By using $q_{0.05, 4, 18} = 4.00$

$$\text{HSD} = 4.00 \sqrt{\frac{0.1236}{7}} \approx 0.53 \text{ dB (A)}$$

According to the Assessment rule, if $|\bar{Y}_i - \bar{Y}_j| > \text{HSD}$, the two pavement means are significantly different at the 5% level.

3.4 Tukey ranking table

Table 5. Tukey HSD ranking of pavement types by mean noise level dB (A).

Pavement	Mean dB(A)	Tukey group
P1	74.89	a
P3	74.20	b
P4	73.04	c
P2	71.87	d

The table presents mean noise levels for the four pavement types and their Tukey HSD groupings. All four pavements have different Tukey letters (a, b, c, d), indicating that each pavement is significantly different from every other pavement at the 5% significance level. The noise ranking is $P1 > P3 > P4 > P2$. P1 is the noisiest pavement (74.89 dB (A)), and P2 is the quietest (71.87 dB (A)). The minimum significant difference (HSD) was approximately 0.53 dB (A). This confirms that pavement type has a statistically significant effect on vehicle-generated noise, and the differences among all pavement pairs are meaningful.

From the above analyses, it can be concluded that all four pavements have different Tukey letters; significance:

- P1 is significantly different from P3, P4, and P2.
- P3 is significantly different from P1, P4, and P2.
- P4 is significantly different from P1, P3, and P2.
- P2 is significantly different from P1, P3, and P4.

Therefore, the final noise ranking is: $P1 > P3 > P4 > P2$

➤ P1 = noisiest pavement

➤ P2 = quietest pavement

3.5 Linear regression: Noise vs. Speed for each pavement

Model: $\text{Noise} = a + b \times \text{Speed}$

$$b = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sum (x_i - \bar{x})^2}$$

$$a = \bar{y} - b\bar{x}$$

$$R^2 = 1 - [\text{SS}_{(\text{tot})} / \text{SS}_{(\text{res})}]$$

Table 6: Linear regression equations and (R^2) for vehicle-generated noise versus speed.

Pavement	Regression equation	R^2
P1	Noise = $62.908 + 0.2395 \times \text{Speed}$	0.973
P2	Noise = $58.413 + 0.2690 \times \text{Speed}$	0.984
P3	Noise = $61.801 + 0.2479 \times \text{Speed}$	0.973
P4	Noise = $59.486 + 0.2710 \times \text{Speed}$	0.984

After analysis, all four pavements show a strong positive linear relationship between vehicle speed and noise level, with R^2 values above 0.97. This indicates that speed accounts for more than 97% of the variation in noise for each pavement. P2 and P4 show slightly steeper increases in noise as speed rises, while P1 has the highest overall noise levels across the tested speeds.

Figure: 2 Prediction noise level in relation with speed of vehicle

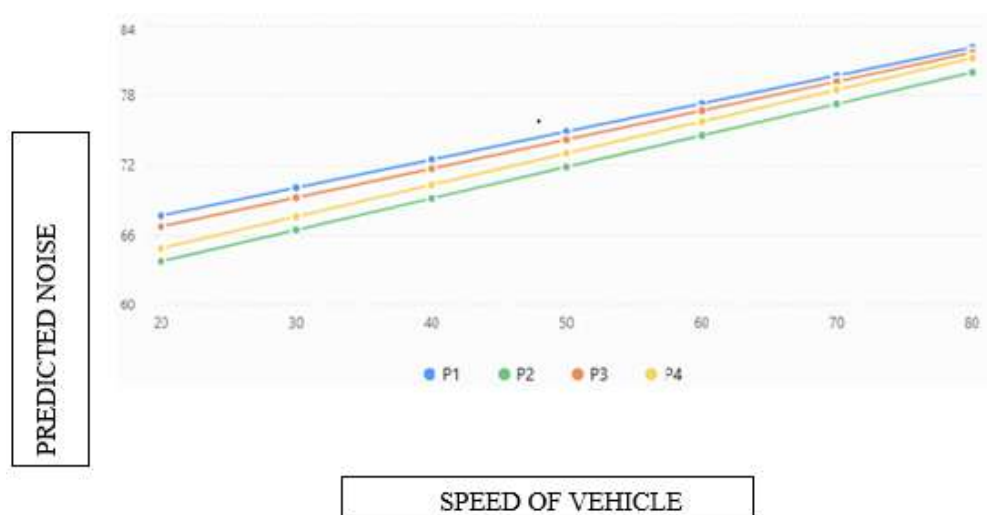
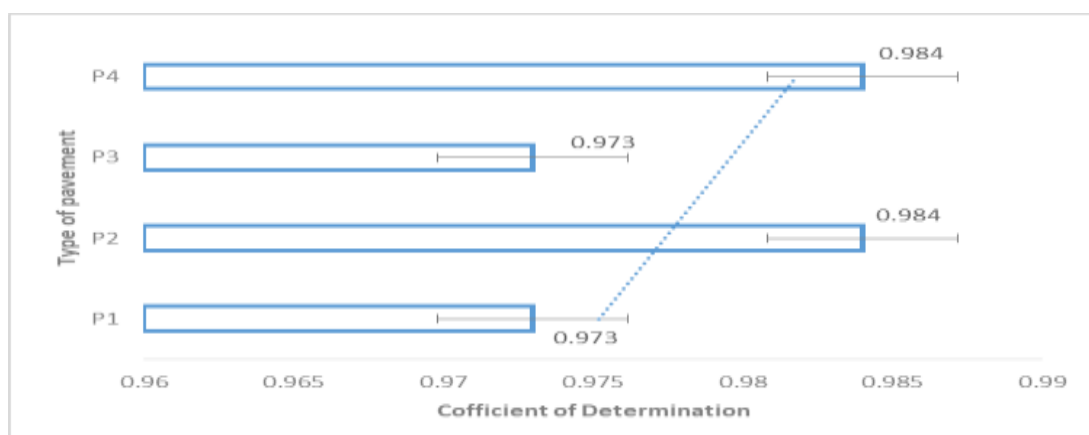


Figure: 3 Bar chart with error bar representing coefficient of determination for all pavements



4. Discussion

This study evaluated how vehicle speed and pavement type affect vehicle-generated noise. The analysis used noise measurements recorded at seven speeds (20–80 km/h) across four pavements (P1–P4). The results clearly show that both speed and pavement type significantly affect noise levels, with speed being the dominant factor. The two-way ANOVA showed that speed had a highly significant effect on noise ($F(6, 18) = 1017.0$, $p < 0.001$). Speed alone accounted for approximately 95.1% of the total variation in the data. Mean noise levels rose steadily from 64.720 dB (A) at 20 km/h to 80.115 dB (A) at 80 km/h, an average increase of about 0.257 dB (A) per km/h, or 2.57 dB (A) per 10 km/h. This strong positive relationship aligns with the physics of tire-road interaction and vehicle aerodynamics. As speed rises, tire impacts with pavement asperities become more frequent and intense, while aerodynamic noise grows more prominent, increasing overall sound pressure levels.

The linear regression models for each pavement further confirmed this trend. All four pavements showed a strong linear relationship between speed and noise, with R^2 values above 0.97. The slopes ranged from 0.2395 dB (A) per km/h for P1 to 0.2710 dB (A) per km/h for P4. Although P2 and P4 had slightly steeper slopes, P1 remained the noisiest pavement at every speed. The high R^2 values indicate that speed is an excellent predictor of noise for each pavement type, and that the linear model can be reliably used for predictions within the tested speed range.

Pavement type also had a statistically significant effect on noise ($F(3, 18) = 99.76$, $p < 0.001$), accounting for about 4.66% of the total variation. Although this is less than the proportion explained by speed, pavement type remains practically important because road design can control it. Mean noise levels were ranked as follows: $P1 > P3 > P4 > P2$

P1 was the noisiest (74.881 dB (A)), and P2 was the quietest (71.863 dB (A)). The difference between the noisiest and quietest pavements was about 3.02 dB (A), which is perceptible to the human ear and meaningful in urban noise management.

The Tukey HSD post-hoc test further showed that all four pavements differed significantly ($HSD \approx 0.53$ dB (A)). This means that each pavement type has a distinct noise signature, and the ranking is not due to chance. The consistent ranking across all speeds ($P1 > P3 > P4 > P2$) indicates that the relative acoustic performance of these pavements is stable and independent of speed. This is a valuable finding because it suggests that a quieter pavement will remain quieter than a noisier one regardless of traffic speed.

The differences among pavements can be attributed to variations in surface texture, porosity, aggregate size, and stiffness. Porous asphalt pavements, for example, absorb sound and reduce tire-road noise, while dense-graded or rougher surfaces tend to amplify noise. Although the exact mix designs of P1–P4 are not specified here, the statistical results clearly demonstrate that pavement selection can be an effective noise mitigation strategy.

Relative importance of speed and pavement type

The ANOVA results show that speed is the dominant factor, explaining 95.1% of the variation, compared with 4.66% for pavement type. Together, the factors explain 99.7% of the total variation. This indicates that speed management is the most effective way to reduce traffic noise, while pavement selection provides a smaller but still statistically significant and practically relevant benefit. In noise-sensitive areas, the two strategies can be combined by enforcing lower speed limits and choosing quieter pavements, such as P2.

Limitations

The study has several limitations. First, because only one noise measurement was available for each speed–pavement combination, it was not possible to estimate the interaction between speed and pavement type. However, the consistent ranking across speeds suggests that this interaction is likely small. Second, the data include only four pavement types and a limited speed range of 20–80 km/h. Third, the study did not control for vehicle type, tire condition, or environmental conditions. Future studies that include replication and additional variables could

help generalize these findings.

5. Conclusion

This study statistically analyzed vehicle-generated noise data from four different pavements at seven speeds. The following conclusions can be drawn:

- i. Speed significantly increases vehicle noise on all four pavements. The relationship is strongly linear, with $R^2 > 0.97$ for each pavement. Noise increases by approximately 2.57 dB (A) for every 10 km/h increase in speed.
- ii. Pavement type significantly affects noise even at the same speed. The noise ranking is consistent across all speeds: $P1 > P3 > P4 > P2$. P1 is the noisiest pavement, and P2 is the quietest.
- iii. Tukey HSD confirms that all four pavements are significantly different from each other in terms of noise, with a minimum significant difference of about 0.53 dB(A).
- iv. Speed is the dominant factor, explaining about 95.1% of the total variation in noise, while pavement type explains about 4.66%. The combined model explains 99.7% of the variation.
- v. The difference between the noisiest and quietest pavements is about 3.02 dB (A), which is perceptible and practically important for noise reduction.

Based on these findings, it is recommended that:

- a) Quieter pavements such as P2 should be preferred in noise-sensitive areas such as residential zones, hospitals, and schools.
- b) Speed limits should be enforced as the most effective measure to reduce traffic noise.
- c) Combining low-noise pavements with speed management can yield the best results.

Future research should replicate this study to examine interaction effects, consider a broader range of pavement types, and include variables such as vehicle class and tire characteristics. The present study provides robust statistical evidence that speed and pavement type significantly affect vehicle-generated noise, and that pavement selection is a practical tool for mitigating noise in road infrastructure planning.

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