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Research Article

The statistical modeling of traffic characteristics and noise levels on urban roads with rigid pavement

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Abstract

Urban road traffic noise is a serious environmental issue that directly affects people's health and quality of life in big cities. This study statistically investigates the relationship between traffic noise levels and pavement surface condition on urban roads with rigid pavement in Najaf City, Iraq. Field data were collected on three urban road segments with Pavement Condition Index (PCI) values of 65, 77, and 86, representing fair, good, and very good conditions. A total of 432 observations were obtained during daytime peak periods (06:00–18:00) under dry weather. At each observation, traffic noise levels (dB) were measured at the roadside using a calibrated Class 1 sound level meter in accordance with ISO 1996-1:2016. Concurrently, traffic volume and vehicle classification were extracted from video recordings; vehicle speeds were derived from time–distance analysis and checked against accelerometer readings; and PCI values were computed from ASTM D6433 condition surveys supported by drone imagery. The statistical analysis comprised analysis of covariance (ANCOVA), Spearman's rank correlation, and linear regression modelling. The results indicate that pavement condition significantly affects noise levels, with lower PCI values associated with higher noise levels. Although the bivariate correlation between speed and noise is modest (r ≈ 0.3), the ANCOVA results show that pavement condition moderates the speed–noise relationship. The findings highlight the importance of incorporating pavement quality indicators, such as PCI, into local noise prediction models to support more reliable urban planning and pavement management decisions.

1. Introduction

Transportation networks are vital for urban development; however, the rapid growth in vehicle usage has led to road traffic noise becoming one of the most prevalent forms of urban pollution, with well-documented health impacts, including cardiovascular diseases and cognitive disorders [1-4]. Despite its seriousness, noise pollution is often overlooked compared to air and water pollution. To address this, statistical tools and software, such as R, have been effectively employed to analyze traffic noise using field data [5]. Additionally, numerous global models, ranging from traditional equations to machine learning, have been developed to predict noise levels [6,7]. However, the predictive power of these models is limited when they ignore local conditions, especially pavement characteristics. Surface roughness, pavement type, and degradation significantly impact noise levels from tire-road interaction and mechanical vibrations [8,9]. Previous studies have shown that a decrease in PCI (deteriorated pavement) is generally associated with higher road traffic noise levels, lower operating speeds, and reduced traffic capacity. In contrast, pavements with a higher Pavement Condition Index (PCI) (good or very good condition) tend to generate lower noise levels and allow higher speeds and flow rates [10,11].

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In cities like Najaf, Iraq, where religious tourism intensifies traffic demands, incorporating pavement condition into noise modeling is essential. This study addresses this gap by analyzing the relationships among noise, speed, and pavement condition using ANCOVA, regression, and correlation. ANCOVA was selected because it allows the combined effect of continuous variables (traffic speed and flow) and categorical pavement-condition groups (PCI levels) on noise to be tested within a single framework. This approach enables us to control for covariates, to examine interaction effects between speed and pavement condition, and to obtain adjusted mean noise levels for each PCI category, which cannot be achieved by simple correlation or regression alone.

Findings from other regions confirm that deteriorated pavements reduce traffic speed and flow by up to 20% [11] and that road roughness can significantly lower vehicle speed and road capacity [12, 13]. For example, [12] found that a 1,000 mm/km increase in roughness reduces road capacity by 300 passenger cars per hour (PCU/h). [14] developed an empirical model showing that surface roughness has a greater influence on average speed than pavement type or speed limits; however, their model lacked differentiation by vehicle type, limiting its reliability. Local studies, such as those by Kamil and Al-Jameel [9], found a drop in noise level from 83 dB (PCI 77) to 80.4 dB (PCI 86), reinforcing the notion that smoother pavement results in lower noise. This study, therefore, builds on these insights to present a localized, statistically validated noise-prediction framework tailored to urban roads with rigid pavement. According to Khan [15], vehicle speed decreases by roughly 8.8% when pavement condition deteriorates from good to extremely poor. At the same time, in-car vibration increases by more than 30% and noise levels climb by about 3.3%. Sharwan [16] discovers that vehicle speed, road surface type, and roughness all have a significant impact on traffic noise, where noise levels climb with increasing speed and road roughness, with larger cars producing more noise than lighter ones. The novelty of this work lies in (i) focusing on rigid urban pavements that dominate major corridors in Iraqi cities, (ii) explicitly incorporating the Pavement Condition Index as an explanatory variable alongside traffic speed, flow and composition, and (iii) developing a localized statistical model for Najaf City that can be used to improve the accuracy of traffic-noise prediction and to support pavement-management and planning decisions under Iraqi conditions.

2. Methodology

The methodology adopted in this study consists of four main stages: (i) selection and characterization of road segments based on PCI; (ii) field data collection for traffic noise, vehicle speed, traffic volume and classification; (iii) data preparation and statistical analysis, including descriptive statistics, normality tests, ANCOVA, correlation and regression modelling; and (iv) interpretation of results and development of implications for pavement and noise management as illustrated in Fig. 1.

2.1 Study Area

In Najaf, Iraq, the analyzed sample comprises 5100 m of urban divided arterial road with rigid Portland cement concrete pavement distributed over the three PCI levels. This road links essential land uses, including the Najaf International Airport, business districts, and historic religious sites. The site provides a representative setting for examining traffic noise under various pavement conditions, owing to the city's unique urban context and significant traffic demand generated by tourists. Using the procedures in ASTM D6433 [16], Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys, three rigid-pavement segments were selected to represent different condition levels. For each segment, visible surface distresses were identified and quantified, deduct values were calculated, and the results were combined to obtain the PCI value according to the standard. This process yielded PCI scores of 86, 77, and 65, which correspond to ‘very good’, ‘good’, and ‘fair' conditions, respectively. Significant noise-reflecting obstacles, such as buildings, trees, and embankments, were absent from every section, reducing confounding acoustic effects and guaranteeing that the majority of the measured noise was produced by vehicles. ASTM D6433 applies to PCI surveys of both flexible and rigid pavements; in the present study, its procedures were used for rigid pavement segments.

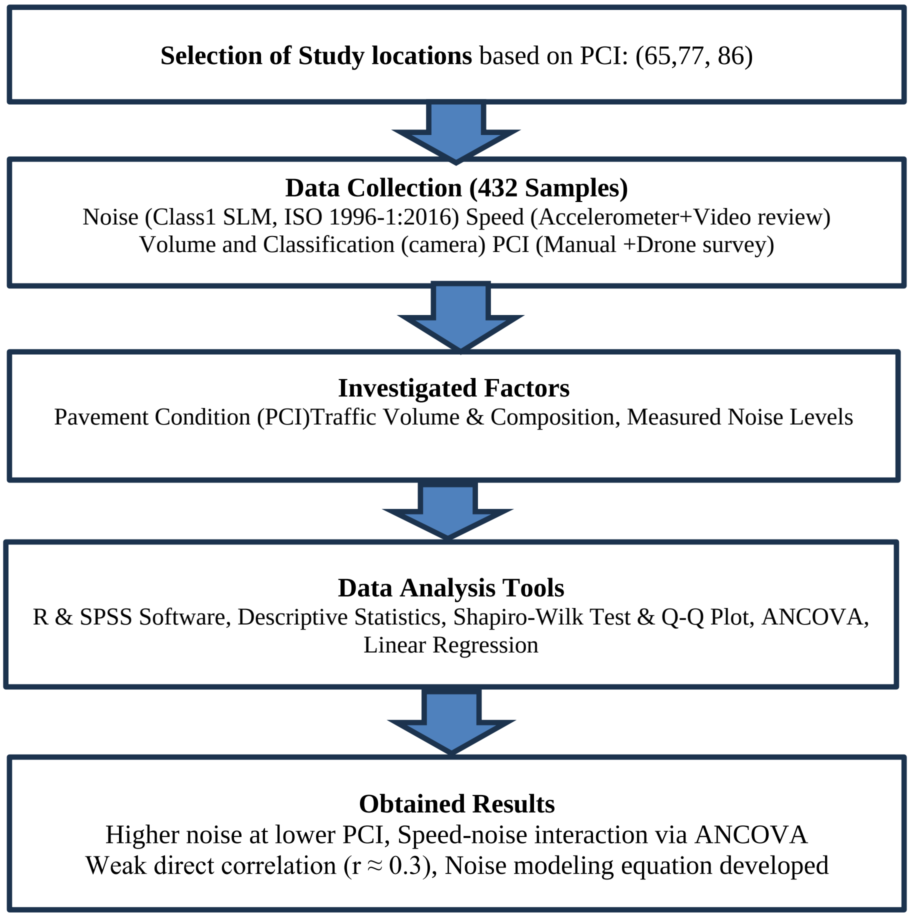

Fig. 1. Flow chart of this study

2.2 Data Collection

Field data were collected during daytime peak periods (06:00 AM – 06:00 PM) under dry weather conditions to ensure consistency. A total of 432 observations were recorded, equally distributed across the three PCI categories. The following parameters were measured:

- Traffic Noise (dB): measured at roadside using a calibrated Class 1 sound level meter (SLM), following ISO 1996-1:2016 guidelines for environmental noise measurement [17].
- Vehicle Speed (km/h): Captured using a high-precision accelerometer and verified via video footage.
- Traffic Volume and Classification: Acquired through video analysis using time-lapse cameras; classified into five vehicle types (light vehicles, motorcycles, buses, trucks, and heavy trucks).
- Pavement Condition Index (PCI): assessed primarily by manual field surveys according to ASTM D6433, where surface distresses on each slab were identified, measured, and converted into deduct values to compute the PCI. In addition, aerial verification was conducted using high-resolution nadir images acquired by a drone; these images were used to confirm the location and extent of significant distress visually and to assess the consistency of the manual ratings. Only the PCI values obtained from the manual ASTM D6433 procedure were used in the statistical analysis, while the aerial survey served as a validation tool.

2.3 Data analysis and Statistical Analysis Framework

All collected data were cleaned and tested for outliers using R software. To assess the normality of the collected data, both Q-Q plots and the Shapiro–Wilk test were used in R software. The results showed that the collected data follow the normal distribution ($p > 0.05$). The reliability of PCI classification was further confirmed through inter-rater agreement ($\kappa > 0.80$). Different statistical models and methods were conducted using R software and SPSS to discover the relationships between noise levels and explanatory variables, such as:

- Descriptive Statistics: Means, standard deviations, and ranges were computed for all variables across PCI categories.
- Box Plot and Exploratory Data Analysis: Visual comparison of noise and speed across pavement conditions.
- ANCOVA (Analysis of Covariance): Used to assess the interaction between road condition (categorical factor) and noise level (continuous covariate), accounting for heterogeneous slopes.
- Simple Linear Regression: Modeled the relationship between speed and noise for baseline evaluation.
- Spearman's Rank Correlation: Non-parametric analysis to test monotonic relationships between speed and noise, supplementing linear model assumptions.

3. Results and Discussion

The 5.1 km arterial road segment in Najaf City, Iraq, was chosen due to its high traffic volume and key urban environment, as seen in Fig. 2. This section is perfect for researching traffic noise since it passes through commercial, industrial, and religious zones and links important locations like Al -Najaf Al-Ashraf International Airport and Al-Zahra Bridge.

The road was divided into three sections based on PCI values of 65, 77, and 86, enabling a comparative analysis of noise and speed under varying surface conditions. The absence of significant noise-reflecting barriers such as buildings or trees ensures that measured noise levels primarily reflect vehicular sources. The location's functional diversity and heavy traffic flows provide a representative, controlled setting for evaluating the relationships among pavement quality, traffic behavior, and environmental noise. The following parameters were measured from the mentioned location:

- Using a noise meter to measure noise.
- Since installing traffic meters on the highways was difficult, a digital camera was employed to measure traffic volumes using an accelerometer and calculate the average speed.
- The PCI was calculated using each of the following methods: The manual process and the drone.

Fig. 2. Location of the chosen data collection sites

In this study, a high-resolution drone equipped with a stabilized camera was used to support manual PCI assessments by capturing georeferenced aerial imagery along selected road segments. The drone flew at a low altitude (15–25 meters), capturing detailed images that revealed surface distresses such as cracking, spalling, and patching on rigid pavements. These images were overlaid on GIS base maps and analyzed to verify the presence, type, and extent of distresses identified during the manual survey. For the drone-assisted method, a multi copter equipped with a high-resolution camera was flown at an altitude of 25–30 m along each road segment. The collected nadir images were processed into an orthomosaic, from which individual slabs and surface distresses (cracking, spalling, patching, etc.) were visually identified and mapped. Distress quantities estimated from the orthomosaic were then converted into PCI values following the same ASTM D6433 procedure. To assess accuracy, a 10% random sample of slabs was inspected both manually in the field and from drone imagery; the difference between the two PCI values was within ±5 points for all sampled slabs, indicating good agreement and confirming that drone-assisted verification is sufficiently accurate to support the manual PCI assessment.

While the PCI values were primarily derived from field surveys conducted in accordance with ASTM D6433, drone imagery served as a crucial verification tool, enhancing the reliability and spatial coverage of the pavement condition assessment. Due to the high traffic volume, noise levels were measured at the edge of the road. Subsequently, a statistical analysis was performed to develop a model based on the collected data. Descriptive statistics are summarized in Tables 1, 2, and 3.

Table 1. Description of statistics for data

Road Condition	Sample size	Mean (speed level)	Standard deviation (speed level)
PCI 65	432	60.72222	4.116941
PCI 77	432	66.50000	8.122280
PCI 86	432	64.55556	2.961124

This table presents the mean and standard deviation of vehicle speed measured on road sections with different Pavement Condition Index (PCI) values. Each PCI category (65, 77, 86) included 36 speed observations. The key insights are:

- PCI 65 (Fair Condition): Lower mean speed (60.7 km/h) with moderate variability.
- PCI 77 (Good Condition): Highest mean speed (66.5 km/h) but also the most significant standard deviation, indicating a wider range of speed behavior.
- PCI 86 (Very Good Condition): Intermediate speed (64.6 km/h) with the lowest variability, suggesting more consistent speeds.

Table 2. Descriptive data for PCI with speed samples

Statistical Parameter	Actual Input Variables			Output = (noise level)
	I1	I2	I3	
	A sample that included (432) field readings taken in three sections on the road			
Range	83.00	36.00	2.00	12.50
Minimum	161.00	49.00	1.00	71.30
Maximum	244.00	85.00	3.00	83.80
Mean	181	63.01	2	78.63
Std. Deviation	17.08	5.73	0.82	2.75

The sample size was 432. The results show that all data are subjected to the normal distribution, and the resulting data from the statistical analysis were used to assess the noise levels in the study area precisely. Furthermore, using SPSS software, all data were examined for skewness and kurtosis. Table 2 summarizes the statistical properties of the variables used in the model that predicts noise levels. It includes 432 observations across the entire dataset and provides the following:

- I1: Traffic volume (range: 83–244 vehicles, mean: 181, SD: 17.08)
- I2: Speed level (range: 49–85 km/h, mean: 63.01, SD: 5.73)
- I3: Vehicle classification (1 to 3 categories, mean: 2, SD: 0.82)

- Noise level (Output): Ranges from 71.3 dB to 83.8 dB, with a mean of 78.63 dB and a standard deviation of 2.75.

Table 3. Descriptive data for PCI with noise samples.

PCI	Sample size	Mean (noise level)	Standard deviation (noise level)
PCI 65	432	81.17222	1.655745
PCI 77	432	77.84167	2.819258
PCI 86	432	76.81111	1.607621

Checking for data normality. A typical graphical technique for determining whether data is non-normal is a Q-Q plot, also known as a Quantile-Quantile plot. Another word for percentile is quantile. Plotting the quantiles of a data set versus the quantiles of a theoretical reference distribution is known as a Q-Q plot. The hypothesis that the data have a normal distribution is supported if the plot is a straight line. Data typically seems distributed, as seen in Fig. 3. However, the Shapiro-Wilk test, another R method for testing normality, was employed to verify this. A goodness-of-fit test is the Shapiro-Wilk test. It often looks at how closely the sample data resembles a normal distribution. By arranging and standardizing the sample, it investigates this. To put it another way, the test's null hypothesis is that the data are normally distributed. For both noise and speed levels, the test's P-values were 0.05 and 0.06, respectively, suggesting strong P-values. As a result, the null hypothesis should not be rejected, leading to the conclusion that the data are normally distributed.

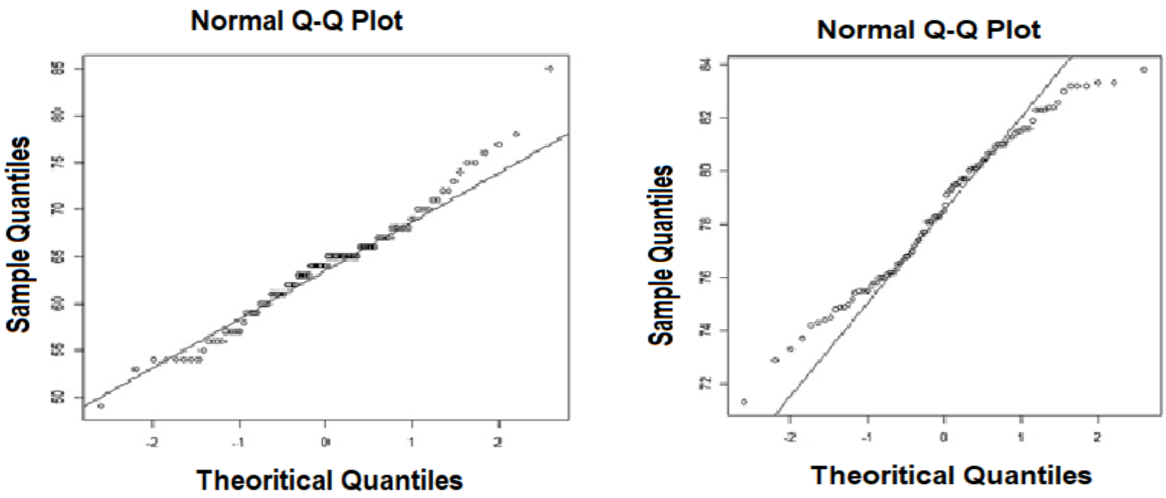

Fig. 3. Q-Q plot for noise level on the left and speed level on the right

3.1 Speed Level Analysis

The box plot of speed levels categorized by road condition is shown in Fig. 4. According to the plot, PCI77 road conditions tend to have higher speed levels, as they enable cars to travel faster. Additionally, it shows that the PCI 77 condition has a higher standard deviation in vehicle speed than the other PCI conditions, which explains why it is the most manageable for large groups of drivers with varying speed ranges.

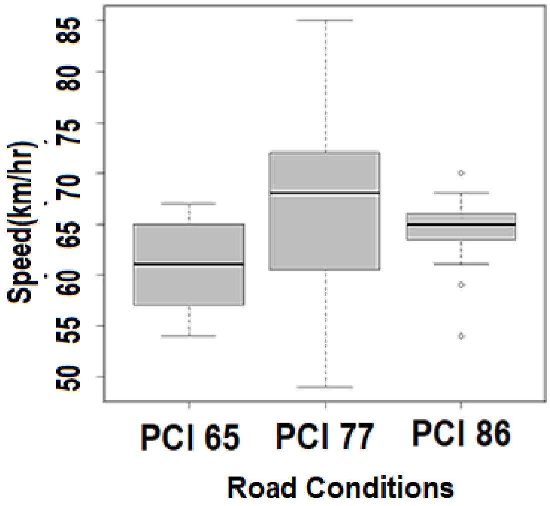

Fig. 4. Box plot of speed data divided by road condition categories

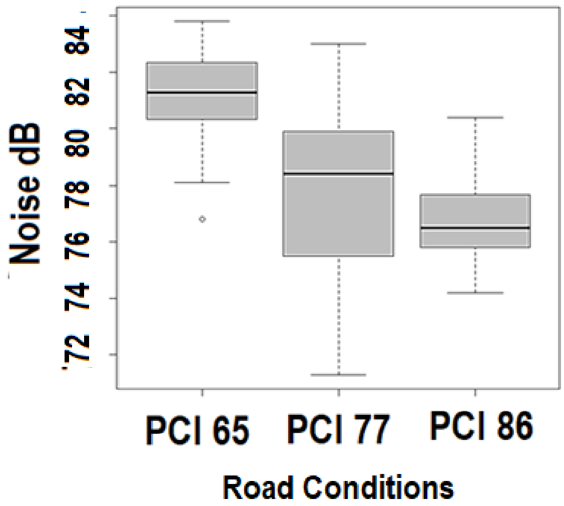

Fig. 5. Box plot of noise data divided by road condition categories

3.2 Noise Level Analysis

A pavement's overall structural and surface condition can be measured using the Pavement Condition Index (PCI), a numerical rating ranging from 0 to 100. This study examined three pavement condition types: PCI 86, representing Very Good to Excellent conditions; PCI 77, indicating good conditions; and PCI 65, indicating fair conditions. Surface defects like cracking, raveling, and patching alter how tires interact with the road as pavement gets worse, which has an impact on noise level. Engine, exhaust, aerodynamics, and tire pavement interaction are some of the components that contribute to the up-traffic noise.

The tirepavement interaction, which is dependent on the pavement surface, becomes the primary source at speeds greater than around 25–30 miles per hour. Although tire type, pavement composition, and vehicle speed all affect noise levels, the box plots in Figure 5 reveal a distinct pattern. Because there is less vibration and air pumping, PCI 86, which has a smooth surface, produces the least noise. The box plot for PCI 77 indicates a moderate increase in noise due to minor surface roughness caused by pavement flaws, little cracking, and mild wear. Finally, the boxplot shows higher noise (impact noise caused by vibration) in PCI66, where the surface is in poor condition, with noticeable cracking, patching, and raveling.

3.3 Statistical Model

A statistical processing of data was conducted as follows:

3.3.1 ANCOVA Analysis

ANCOVA is just another example of the general linear model. A box plot would not provide sufficient information, so an Interaction plot would offer more detail on the observed data, as shown in Fig. 6 and Table 4. The lines of the three road condition levels are not parallel at some noise levels, so that one might expect a statistically significant interaction. A model with interaction allows the slopes to differ across groups. In other words, the interaction provides for non-parallel lines. Therefore, the question that could be answered here is whether the effect of noise depends on the road conditions levels. Examining the figure and the table results, including p-values, one can conclude that there is no evidence of difference between slopes for most cases where p-value > 0.05 which explain that not only the pavement conditions that explain noise level for different speed limits although there was a significant relationship between speed limit and noise level for that study area.

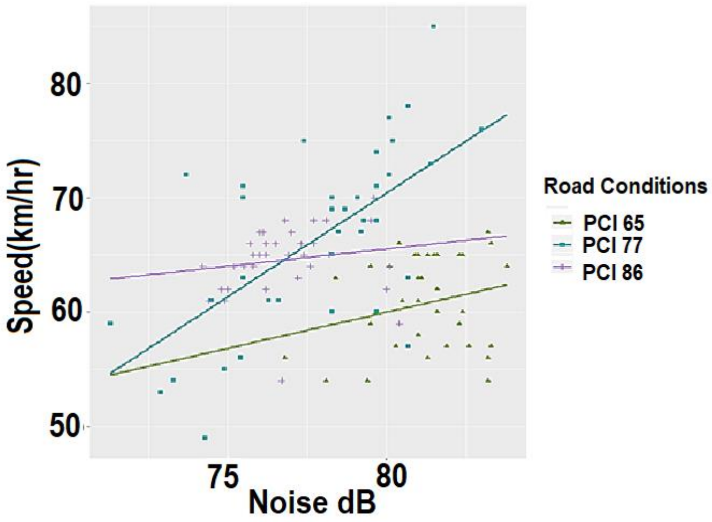

Fig. 6. Interaction plot of observed data

Table 4. The results of the ANCOVA analysis

Case	Intercept	Estimated Std error	T value	P-value
	9.5225	38.9196	0.245	0.8072
Road.ConditionPCI 77	-84.0924	44.6723	-1.8	0.0626
Road.ConditionPCI 86	31.8699	54.3463	0.586	0.5589
Noise	0.6308	0.4794	1.316	0.1912
Road.Condition PCI 77: noise	1.1815	0.5559	2.125	0.0360
Road. ConditionPCI 86:noise	-0.3292	0.6882	-0.478	0.6334

3.3.2 Correlation

The correlation between traffic speed and noise was studied. Traffic speed and noise measurements are conducted simultaneously from 6:00 AM to 6:00 PM, with 5-minute measurement intervals. traffic speed data (pcu/hour) and Noise level (dB) were analyzed using Spearman's correlation analysis. The correlation coefficient was only about 0.3, indicating a weak relationship between noise and speed levels. The simple linear regression model is also used to address the research questions mentioned above. The model of simple linear regression is:

$$E(Yi\ ) = \beta_o + \beta_1 \times X_i + \epsilon_i \quad (1)$$

Where Yi = the expected response variable, refers to the noise level, means the average value that would be seen if a considerable number of plots with that xi were used, x_i: level of speed for the ith observation, and ϵi: random error term for the i^{th} observation.

This linear model assumes that ϵi is independent, normally distributed with mean zero, and has a homogeneous variance σ^2. Using the R software, which includes code for a simple regression model, the results are shown in Table 5 below. It is essential to remember that:

- Intercept: Predicted noise level (y) with no effect of speed applied (x=0) is estimated to average 75.5 (must be taken with caution because zero is beyond the range of the data).
- Slope: A one km/hr. increase in speed (1 unit increase in x) is associated with a 0.048 predicted increase in noise (y).

Table 5. The results of the statistical analysis

Parameter	Intercept	Std. Error	t value	Pr(>|t)
Noise	75.53056	2.90208	26.026	<2e-16
Speed	-0.04815	0.04520	1.065	0.289

$$Expected\ (noise) = 75.53056 - 0.048154 \times speed + error \quad (2)$$

4. Discussion

Analysis of field data from urban roads in Najaf revealed statistically significant insights into the relationships among pavement surface condition, vehicle speed, and traffic noise. The observed variations in noise levels across different Pavement Condition Index (PCI) values underscore the pivotal role of road surface quality in influencing urban environmental noise.

- Pavement Condition and Noise Levels: The results demonstrated that noise levels decreased as PCI improved, consistent with previous findings by Kamil and Al-Jameel [9] and Khan et al. [8], who reported that surface roughness intensifies tire-pavement interaction, leading to increased acoustic energy emission. In the current study, road sections with a PCI of 65 (fair condition) exhibited an average noise level exceeding 81 dB, compared to approximately 76.8 dB on roads with a PCI of 86 (very good condition). This 4–5 dB difference is acoustically significant, as even small decibel increases can substantially change perceived loudness and influence public health outcomes [2].
- Pavement Condition and Vehicle Speed: A positive trend was also observed between PCI and average vehicle speed, with drivers traveling more cautiously on deteriorated surfaces. Roads with PCI 65 recorded a mean speed of approximately 60.7 km/h, while those with PCI 77 and 86 recorded 66.5 km/h and 64.6 km/h, respectively. Although the difference is moderate, it aligns with findings from Hashim et al. [11] and Pinatt et al. [10], which suggest that poor pavement quality disrupts traffic flow and induces speed variability, particularly in mixed traffic environments.
- Noise-Speed Relationship and Interaction Effects: While a weak positive correlation (Spearman's $\rho \approx 0.3$) was identified between speed and noise, the ANCOVA model revealed a significant interaction between PCI and noise levels, suggesting that pavement condition mediates the speed–noise relationship. This result highlights the non-linear nature of traffic noise generation, where the influence of speed on noise cannot be evaluated independently of surface quality. The interaction effect suggests that speed increases may result in greater noise under rough pavement, but to a lesser extent on smoother roads, a phenomenon supported by Torija et al. [6] in their acoustic modeling studies.
- Implications for Urban Noise Modeling: These findings highlight the limitations of applying universal or overly simplistic noise prediction models in local contexts without accounting for infrastructure-specific variables, such as PCI. The results support including pavement surface condition as a core input in future predictive modeling, particularly in urban areas with diverse vehicle types, heavy use, and sensitive land uses such as religious centers and hospitals. In addition, while linear regression models provided baseline interpretations, the modest explanatory power suggests the potential value of applying more advanced statistical or machine learning approaches (e.g., artificial neural networks) in future research to capture complex, non-linear interactions more effectively.

5. Conclusions

This study examined how pavement surface condition influences traffic noise and vehicle speed on a major urban arterial in Najaf, Iraq. PCI classified road sections, and field data on noise, speed, and flow were analyzed using ANCOVA, Spearman's correlation, and linear regression. The results show a clear inverse relationship between PCI and noise: segments with poorer condition (PCI 65) produced noise levels about 4–5 dB higher than those in very good condition (PCI 86), an environmentally meaningful difference. Pavement condition also affected operating speeds, with lower PCI values associated with reduced average speeds, indicating drivers' response to deteriorated surfaces. Although the simple correlation between speed and noise was modest ($r \approx 0.3$), ANCOVA revealed a significant interaction between speed and PCI, indicating that pavement condition moderates the speed–noise relationship. The data satisfied normality assumptions, supporting the robustness of the statistical models, and the resulting prediction equation provides a practical tool for estimating roadside noise from observed traffic and PCI. Overall, the findings show that improving pavement quality is not only a structural or safety measure but also an effective environmental strategy to reduce traffic noise in dense urban corridors.

5.1 Limitations of the Study

The study only looks at a few road segments or evaluates speed and noise over a brief period of time. Because road noise changes significantly between seasons, traffic numbers, weather, and ti me of day, this may lessen the data's representativeness.

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