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Chinese Society of Pavement Engineering

ORIGINAL RESEARCH PAPER

Effect of Pavement Roughness on Arterial Noise Using Different Vehicle Types

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Abstract

For a healthy and sustainable environment, it is necessary to reduce the negative impact of noise on neighborhoods adjacent to arterials. The development of the automotive industry, the introduction of hybrid and electric vehicles, and improvements to vehicle bodies have made tire–pavement interaction the primary source of noise at regular traffic speeds. The objective of this study was to investigate the effect of pavement surface condition on noise levels for different vehicles, including gasoline, hybrid, electric vehicles, and a single-unit truck. Both interior and exterior noises were measured along rural and urban arterials. The exterior noise was measured using the controlled pass-by method. The results of the analysis indicated that pavement roughness and traffic speed had significantly influenced the interior noise level. It was found that the relationship between interior noise and vehicle speed, and pavement roughness is linear. Compared to gasoline car, hybrid and electric cars may reduce interior noise by 7 and 11 dB(A), respectively. For rural arterials and speeds of 80 km/h, exterior noise was strongly affected by pavement roughness. Analysis of exterior noise on urban arterials at 50 and 60 km/h speeds showed that pavement roughness has a significant impact on the noise level. In contrast, the noise analysis under two-speed levels, which are too close to each other, did not help in capturing the impact of speed on exterior noise. Therefore, further studies are recommended to highlight this issue. For a sustainable and healthy environment, it is vital to keep the pavement in good condition and increase the proportion of electric and hybrid cars in the vehicle fleet.

Keywords Traffic noise · Interior and exterior · Pavement roughness · Vehicle type · Modeling

1 Introduction

During the past decades, there has been a rapid increase in demand for transport, which led to growth in traffic volume and aggravation of some problems in society like a substantial increase in congestion, traffic accidents, and air and noise pollution. Noise is defined as unwanted sound. Today, many countries seek to improve their citizens' quality of life by reducing environmental noise. According to the World Health Organization (WHO), noise is considered the second largest environmental cause of health problems [1, 2]. Several countries have issued policy regulations to limit noise to certain levels [3]. However, most policies focus on exterior

vehicle noise, affecting adjacent neighborhood populations and pedestrians. The interior noise, which affects driver and vehicle passengers, is regulated by market requirements [4].

It is well acknowledged that highway traffic noise is the major dominant source of environmental noise [5, 6]. For example, Li [7] reported that traffic noise contributes to more than 90% of environmental noise in Europe. Highway traffic noise is generated by three significant sources of highway vehicles: propulsion system noise, aerodynamic noise, and tire–pavement interaction noise [8]. Today, the improvement of vehicle engine design, the introduction of hybrid and electric motors, as well as optimizing the vehicle's body to reduce the noise generated by the propulsion system and aerodynamic effect [9–12]. Thus, at average traffic speed, tire–pavement interaction noise is the primary source for passenger vehicles with a speed above 40 km/h and for trucks with a speed of more than 70 km/h [7, 13].

The tire–pavement interaction noise is affected by tire condition, vehicle speed, and pavement surface conditions [14]. However, studies indicated that pavement surface

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condition has a more significant potential for noise reduction [15, 16]. The objective of this study was to investigate the effect of pavement surface condition on noise levels for different vehicles, including gasoline, hybrid, electric vehicles, and a single-unit truck. The study took both interior and exterior noises into account. In Jordan, Irbid city's urban arterials and its governorate's rural arterials were used as case studies [17]. A smartphone application, using the Total-Pave app, was used in the study to estimate the International Roughness Index (IRI).

2 Background

Previous studies indicated that noise generated from tire–pavement interaction is the result of the interaction between tire and pavement. Studies should focus on this interaction rather than dealing with them independently [7, 18]. Traffic noise is classified into exterior and interior noises. The tire–pavement interaction mainly causes exterior noise, including structure-borne and air-borne noises. The structure-borne noise is generated from the radial vibration of tire tread blocks, while the air-borne noise is generated directly due to air displacement in the tire tread grooves as air pumping [19–21]. However, interior noise sources are engine, tire, and wind [22]. Chang et al. [23] indicated that the tire tread is the dominant source of interior noise under high vehicle speed levels, and the interior noise is also considerably related to vehicle speed [24].

In general, only a few empirical researches have looked at the connection between the state of the pavement's surface and either internal or external noise. Chen et al. [25] proposed that asphalt pavement roughness affects radial vibration noise between the tire block and pavement surface. Based on a limited number of field samples, they found a significant linear relationship between interior noise and pavement roughness. For exterior noise, they found a relationship between noise level and the product of pavement roughness and texture depth. However, they recommended that further studies should be carried out to confirm and complement their conclusions. It is worth mentioning that IRI and pavement condition index (PCI) are pavement performance indicators. Additionally, the value of each indicator is influenced by the severity of the distress patterns and slope variances on the pavement surface. For the same highway type and regional area, Piryonesi and El-Diraby [26] concluded that IRI and PCI are strongly related. They found that some distress, such as bleeding and polished aggregate, reduces the PCI drastically but does not affect the IRI. It is believed that these two types of distresses may provide a smooth surface and probably reduce the noise generated from tire–pavement interaction.

Literature has also provided information regarding noise level measurement methodologies. Tire–pavement interaction noise measurement has been extensively investigated since the 1970s. These include far-field, on-board, and in-vehicle noise measurements [7]. The far-field measurements category includes statistical pass-by, controlled pass-by, and statistical pass-by and time-averaged wayside, among other methods. Each method has its own intended purpose and specific instrumentation. For example, both statistical pass-by and controlled pass-by methods are used to measure exterior noise; however, the statistical pass-by method utilizes a random sample of typical vehicles measured one at a time, while the controlled pass-by method utilizes a few selected vehicles that are driven at a controlled speed past the measurement site. The statistical pass-by method is suitable for measuring the impact of traffic noise on citizens' neighborhood adjacent to highways [27]. However, the controlled pass-by method controls vehicle operating conditions to minimize noise sources other than tire–pavement interaction noise [28, 29]. To measure exterior noise level, a tripod-mounted microphone should be placed 7.5 m from the centreline of the lane of traffic to be tested and 1.2 m above the pavement level.

3 Methodology and Data Collection

Three passenger cars and one single-unit truck were selected as test vehicles to help the study reach its goals. The vehicles included a gasoline vehicle (Mitsubishi lancer, 1600 cc, Model 2013), an electric vehicle (Nissan leaf, Model 2013), and a hybrid vehicle (Ford c-max, 2000 cc, Model 2015). Moreover, the single-unit truck was Merced Actros, Model 2002. All field measurements were carried out in April, May, and June of 2020. The measurements were conducted during the COVID-19 quarantine period, which was applied from mid-March to mid-June in Jordan [17]. This condition facilitates the application of a controlled pass-by method.

All noise field measurements were performed under calm wind conditions, with temperatures varying from 20 to 25 °C. All vehicles and their tires were in good condition. The three test cars have the same type of tires (tire brand and pattern) and approximately the same tire tread depth. Also, the same single-unit truck was used in all field measurements. The selected flexible pavement sections, IRI measurements, and exterior and interior noise measurements are explained in the following subsections.

3.1 Selection of Pavement Sections

Three divided-multilane rural arterials in Irbid governorate and six divided-multilane urban arterials inside Irbid City were chosen for this study. The speed limit for urban

arterials varied from 50 to 60 km/h, while the speed limit for rural varied from 80 to 90 km/h. Sites selected for roughness and noise measurements were chosen to be straight, far from intersections or any traffic calming measures, and far from buildings structures or cross drainage structure as culverts and bridges. Furthermore, there should be no physical obstructions between the observer and the noise source at the location, such as parked cars or buildings [17, 30]. To increase the domain of the study, a wide range of pavement conditions, from poor to excellent conditions, were selected.

3.2 Pavement Roughness Measurements

In this study, pavement condition is evaluated using the IRI. The IRI is a measure that describes the pavement surface irregularities. Several researchers indicated that IRI is the best measure for determining pavement performance compared to others, such as PCI [31, 32]. Thus, different highway agencies worldwide adopted the IRI as a pavement performance measure and a quality assurance measure for ride quality. In Jordan, automated high laser profiler equipment is not available to measure the IRI. On the other hand, using rod-level to evaluate pavement roughness is time-consuming, in addition to the uncertainty of the measured roughness data. To save time and intensive labor, a smartphone application was adopted in this study to measure pavement IRI [33–35]. The TotalPave IRI application is a modern, easy, and cost-efficient way for road roughness data collection. Compared with traditional IRI measurements, this application provides an accuracy of greater than 85% in the IRI measurements [34]. The TotalPave app uses the smartphone's built-in accelerometer to examine the road vibrations and its GPS to position the data. TotalPave also have a separate road inventory application to be used for ocular inspections. The authorization to use the TotalPave application as a tool to measure the IRI in this study was obtained by communicating with the TotalPave Company in New Brunswick, Canada.

In this study, a smartphone, Samsung Galaxy A20 was used as a data logger device. Compared with IRI values obtained using the inertial profiler, Cameron [35] indicated that the use of Samsung Galaxy smartphone, with a 100 m pavement section, provided comparable IRI values, with a correlation of about 89%. The smartphone was securely fastened to the windscreen of the test car by a firm holder. Before the start of field measurements, the X, Y, and Z adjustments should be zeroes. The test car was driven at the arterial speed limit (50 or 60 km/h for urban arterials and at 80 km/h for rural arterials). The vehicle was centered along its centreline and driven in the outside traffic lane. As the vehicle attained the required uniform speed, the button of the TotalPave app was activated. Once the section is surveyed, the data are uploaded to the TotalPave web service,

and ultimately the IRI for every 100 m section length was obtained. Furthermore, the web service can deliver an Excel sheet file with data for IRI for a length of flexible pavement spaced 100 m apart. To improve the accuracy of the roughness data, each section was surveyed three times, and the average of the obtained IRI values was considered. However, it was found that the discrepancy between the maximum and the minimum IRI values was negligible and less than 2%.

3.3 Interior Noise Measurements

All test vehicles, including gasoline, hybrid, electric and single-unit truck, had their interior noise levels assessed. For measuring interior noise level, the Sound Level Meter (SLM) was fixed to a set-up such that the SLM is very close to the driver's ear with the mic head to the forward direction and according to the ISO 5128 specifications [36]. Figure 1 illustrates the set-up and the mic position. Additionally, a video recorder was mounted inside the car to capture noise level readings that were displayed on the SLM screen continuously throughout the pavement section. As stated earlier, each pavement section had a 100 m length. The test vehicle was driven into the pavement section along the centreline of the outer lane at a uniform speed corresponding to the speed limit (50 or 60 km/h in urban areas and 80 km/h for rural). To avoid acceleration or deceleration to maintain the same uniform speed level throughout the section, the test vehicle speed must be within the range of speed limit + 1.5% of the speed limit, otherwise the trail must be repeated. However, the actual vehicle speed was used in the statistical analysis. During measurements, the "LOW" option must be activated in the sound meter device and the A-weighing. The mean value was computed and considered as the value of the noise

Fig. 1 Set-up and mic position for interior noise measurement [17]

level for the pavement section. The test vehicle was clean from any sound sources, i.e., radio and air-conditioner were off, all windows were closed, and the pavement surface was dry [36]. Table 1 illustrates the statistical characteristics of the interior noise for each vehicle type.

3.4 Exterior Noise Measurements

The same vehicles that were used to measure the interior noise were individually used to measure the exterior noise. According to the ISO 361-1 [37], the cars are of category M1 and the truck of category N2. The noise was measured using the controlled pass-by method. The SLM was installed on a tripod of 1.2 m high and at 7.5 m away from the centreline of the outer traffic lane. The SLM is located at the middle of the pavement section, i.e., 50 m from the start of the pavement section. In urban areas, however, the SLM was placed at 5.0 m instead of 7.5 m due to the existence of side properties. During measurements, the test vehicle was driven at a uniform speed corresponding to the speed limit (50 or 60 km/h in urban, and 80 km/h in rural), and the maximum noise value was recorded with the measuring gear in "QUICK" option, and the A-weighting. In the field, it was checked that the background noise level was at least 10 dB less than the measured vehicle noise. Tables 2 and 3 present

the statistical characteristics of the exterior noise for rural and urban areas, respectively.

It is worth mentioning that the ISO 10844 [38] stipulated that the test section length is 20 m on each side of the mic line, including the propagation and drive lane extension lengths. Given that outside noise is heavily influenced by the IRI value close to the microphone, we chose a section of 100 m to measure the IRI. Irrespective of the IRI measuring techniques; it is well known that IRI is computed for a pavement section of 100 m [39].

4 Analysis and Modeling

4.1 Interior Noise

As shown in Table 1, 624 flexible pavement sections were investigated, and each section has a 100 m length. The IRI for these sections varied from a minimum of 0.61 to a maximum of 11.44 m/km. It was found that 22.6, 50.16, and 11.86% of the pavement sections were in excellent, very good, and good roughness categories, respectively. While 11.54, 3.37, and 0.48% of the sections were found to be in fair, poor and bad roughness categories, respectively. All sections having poor or bad roughness categories were found to be in the urban areas.

Table 1 Descriptive statistics of the included variables for an interior noise study

Variables	Sample size	Minimum	Maximum	Mean	Std. deviation
IRI, m/km	624	0.61	11.44	3.34	1.73
Interior noise for gasoline car, dB(A)	624	54.33	116.69	78.01	9.12
Interior noise for electric car, dB(A)	624	46.56	90.1	66.68	7.66
Interior noise for hybrid car, dB(A)	624	47.87	106.63	70.78	9.25
Interior noise for truck, dB(A)	624	65.2	143.96	95.01	11.84

Table 2 Descriptive statistics of the included variables for exterior noise of rural arterials

Variables	Sample size	Minimum	Maximum	Mean	Std. deviation
IRI, m/km	37	1.37	4.08	2.15	0.67
Exterior noise for gasoline car, dB(A)	37	71.57	85.08	75.19	3.81
Exterior noise for electric car, dB(A)	37	56.61	73.83	63.25	4.18
Exterior noise for hybrid car, dB(A)	37	62.70	82.45	69.97	4.62
Exterior noise for truck, dB(A)	37	75.42	92.20	80.19	4.15

Table 3 Descriptive statistics of the included variables for exterior noise of urban arterials

Variables	Sample size	Minimum	Maximum	Mean	Std. deviation
IRI, m/km	41	2.20	5.30	3.79	0.79
Exterior noise for gasoline car, dB(A)	41	73.54	91.41	82.68	4.78
Exterior noise for electric car, dB	41	62.54	74.85	68.66	3.12
Exterior noise for hybrid car, dB(A)	41	70.60	85.20	77.97	4.12
Exterior noise for truck, dB(A)	41	82.19	98.56	89.14	4.80

Regardless of whether they were measured in rural or urban arterials, the resulting interior noise values for each car type were combined because they were all taken under the identical measurement conditions. The mean values of the interior noises generated by gasoline, hybrid, and electric car were 78.01, 70.78, and 66.68 dB(A), respectively. Furthermore, the value of the mean noise generated by the truck was 95.01 dB(A).

Based on multiple regression analysis, the following regression equations were developed for each type of the investigated cars:

$$INGV = 73.70 + 4.22IRI + 0.15S, \tag{1}$$

$$INHV = 67.51 + 4.19IRI + 0.17S, \tag{2}$$

$$INEV = 66.85 + 3.22IRI + 0.17S, \tag{3}$$

where INGV, INHV, and INEV are the interior noise for gasoline, hybrid, and electric car, dB(A). IRI: International Roughness Index, m/km, and S: Vehicle speed, km/h.

All the above model equations and their regression parameters were found to be statistically significant at 95% confidence level. Also, the coefficient of multiple determinations for Eqs. (1), (2), and (3) were 0.80, 0.83, and 0.80, respectively. Figures 2, 3 and 4 illustrate the relationship between interior noise and IRI for different car types at speeds of 50, 60, and 80 km/h, respectively. Table 1 and Fig. 2 show that the maximum measured values of the interior noises generated by the gasoline, hybrid, and electric cars were 116.69, 106.63, and 90.1 dB(A), respectively. Each noise value represents the mean over the whole pavement section. These maximum noise values
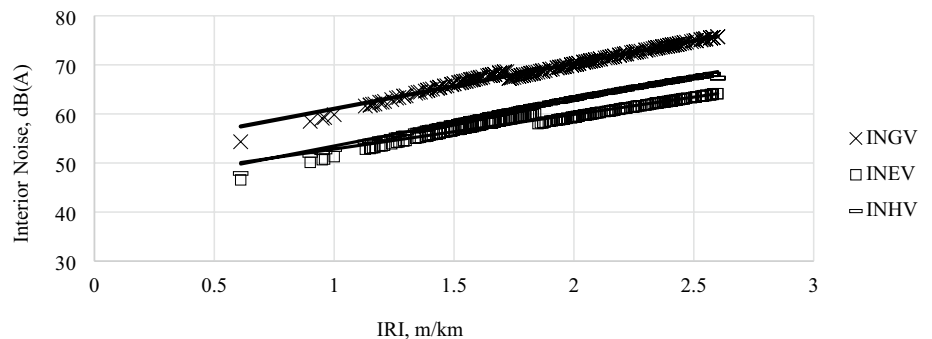

Fig. 2 The relationship between interior noise and IRI for different cars at a speed of 50 km/h
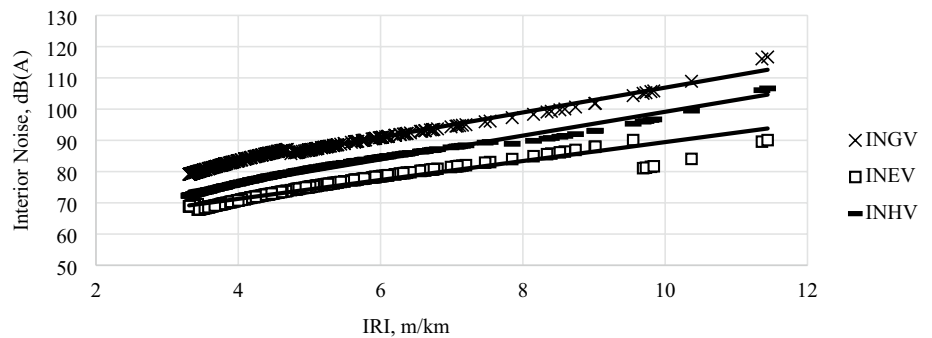
Fig. 3 The relationship between interior noise and IRI for different cars at a speed of 60 km/h
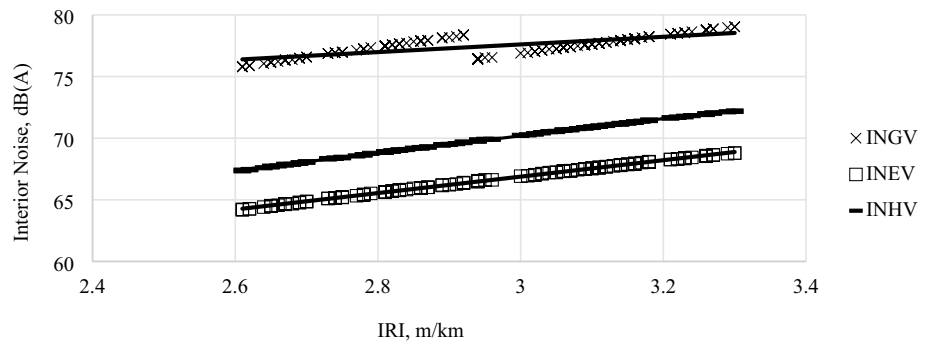
Fig. 4 The relationship between interior noise and IRI for different cars at a speed of 80 km/h

were observed on pavement section with bad roughness category of 11.44 m/km and along an urban arterial with speed limit of 50 km/h, as shown in Fig. 2. Also, the maximum value of noise generated by the single-unit truck on this section was 143.96 dB(A), as presented in Table 1.

Furthermore, a general model was developed for all cars, by introducing dummy variables to indicate the type of vehicle. Using regression analysis, the following model was obtained:

$$INV = 75.54 + 3.88 IRI + 0.16S - 7.23H - 11.32E, \quad (4)$$

where INV is the Interior noise level generated by a given car, dB(A), H is the dummy variable, 1 if the car is hybrid and 0 otherwise. E is the dummy variable, 1 if the car is electric and 0 otherwise.

Table 4 presents the statistical characteristic of the above equation. As shown in the table, the above regression equation and all its parameters were significant at the 95% confidence level (p value < 0.05). Moreover, the coefficient of multiple determination of the above equation is 0.97. In addition, an investigation of residuals revealed that they were randomly distributed and no outliers were detected [17]. Compared with the gasoline car, Eq. (4) indicates that the use of a hybrid car may reduce the interior noise by about 7 dB(A), and the use of electric car may reduce the interior noise by nearly 11 dB(A).

Based on regression analysis, interior noise generated by the single-unit truck was modeled and the following regression equation was obtained:

$$INT = 89.61 + 5.47 IRI + 0.20S, \quad (5)$$

where INT is the interior noise level generated by a single-unit truck, dB(A). The model equation and its statistical parameters were significant at the 95% confidence level. Also, the coefficient of determination is 0.84.

4.2 Exterior Noise

Exterior noise generated from the test vehicles was measured for rural and urban arterials at 7.5 and 5.0 m, respectively, from the centreline of the outer lane. Thus, it was not possible to pool rural and urban measurements, and the analysis was carried out for each area type separately. Table 2 illustrates the characteristics of the collected data for rural arterials. Roughness values for the investigated rural arterials varied from 1.37 to 4.08. Thus, the pavement roughness category is classified as good or superior. However, the mean values of the exterior noises generated from gasoline, hybrid, and electric cars were 75.19, 69.97, 63.25 dB(A), respectively. The mean value of the exterior noise generated by the truck on rural arterials was 80.19 dB(A).

For rural arterials, the following equations were developed to estimate exterior noise for each car type:

$$ENGV = 66.28 IRI^{0.172}, \quad (6)$$

$$ENHV = 59.22 IRI^{0.227}, \quad (7)$$

$$ENEV = 53.66 IRI^{0.223}, \quad (8)$$

where ENGV, ENHV, and ENEV are the exterior noise generated by gasoline, hybrid, and electric car, respectively. The above models and their parameters were found to be significant at 95% confidence level. The coefficient of determinations for Eqs. (6), (7), and (8) were 0.88, 0.90, and 0.86, respectively. Figure 4 shows the scatter of the actual noise data and the fitted lines for different cars and IRI values. Table 2 and Fig. 5 indicate that the maximum values

Table 4 Statistical characteristics of the general model in Eq. (4)

Analysis of variance					
Variable	Sum of squares	DF	Mean square	F value	p value
Regression	177,601.104	4	44,400.276	15,714.175	0.000
Residual	5275.193	1867	2.825		
Total	182,876.298	1871			
$R^2 = 0.971$			Adj. $R^2 = 0.970$		

Regression parameters estimates				
Variable	Parameter estimate	Standard error	t value	p value
Constant	75.544	0.391	193.137	0.000
IRI	3.880	0.035	110.162	0.000
E	− 11.326	0.095	− 119.020	0.000
H	− 7.230	0.095	− 75.976	0.000
S	0.164	0.004	36.529	0.000

Fig. 5 The relationship between exterior noise and IRI for different cars at speed 80 km/h
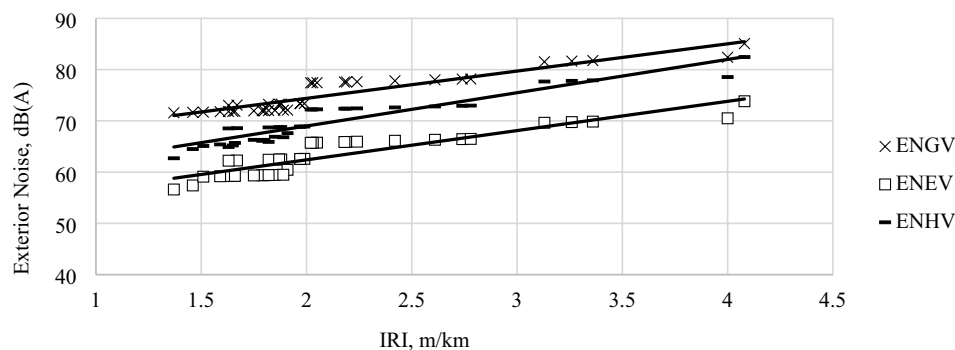
of the exterior noises on rural roads generated from the gasoline, hybrid, and electric cars were 85.08, 82.45, and 73.83 dB(A), respectively. These noise values were observed on pavement section with IRI of 4.08 m/km. While the minimum measured exterior noises on rural roads generated from the gasoline, hybrid, and electric cars were 71.57, 62.70, and 56.61 dB(A), respectively, as shown in Table 2 and Fig. 5. Clearly, the minimum noise values were measured on pavement section having IRI of 1.37 m/km.

Also, the data were pooled and the following general model for rural arterials was developed to estimate the exterior noise generated from cars:

$$\text{EXVR} = 62.63 + 5.84\text{IRI} - 5.22H - 11.94E, \tag{9}$$

where EXVR is the exterior noise generated by a given car type for rural arterials. The model equation and its parameters were significant at 95% confidence level, and the obtained coefficient of determination was 0.94. Compared with gasoline car, Eq. (9) indicates that the use of hybrid car may reduce the exterior noise by 5.22 dB(A), and the use of electric car may reduce the exterior noise by 11.94 dB(A).

Also, the following model equation was developed to estimate the exterior noise generated from the single-unit truck on rural arterial:

$$\text{ENTR} = 70.40\text{IRI}^{0.178}. \tag{10}$$

Equation (10) and its parameter were found to be significant and 95% confidence level, and the obtained coefficient of determination was 0.91.

For the investigated urban arterials sections, roughness values varied from 2.2 to 5.3 with mean value of 3.79 m/km, as shown in Table 3. The mean values of exterior noise generated from gasoline, hybrid, and electric car were 82.68, 77.97, and 68.66 dB(A), respectively. The mean value of the exterior noise generated by the truck was 89.14 dB(A). According to the speed limit of the investigated arterials, noise level was measured at 50 or 60 km/h. The exterior noise generated from gasoline, hybrid, and electric cars were pooled and a general model equation was developed to estimate noise for urban arterials. The developed equation was as follows:

$$\text{ENVU} = 65.00 + 4.67\text{IRI} - 4.72H - 14.02E, \tag{11}$$

where ENVU is the exterior noise generated from a given car type on urban arterials, dB(A). The above equation and its parameters were significant at the 95% confidence level. Besides, the coefficient of determination was 0.94. It is worth mentioning that the analysis indicated that vehicle speed had no effect on the generated exterior noise, therefore; the speed was discarded in the final model development. Figure 6 shows the relationship between exterior noise and the IRI for different vehicle types and at speeds of 50 and 60 km/h. Table 3 and Fig. 6 illustrate that the maximum

Fig. 6 The relationship between the external noise and IRI for different vehicles at speed 50 and 60 km/h
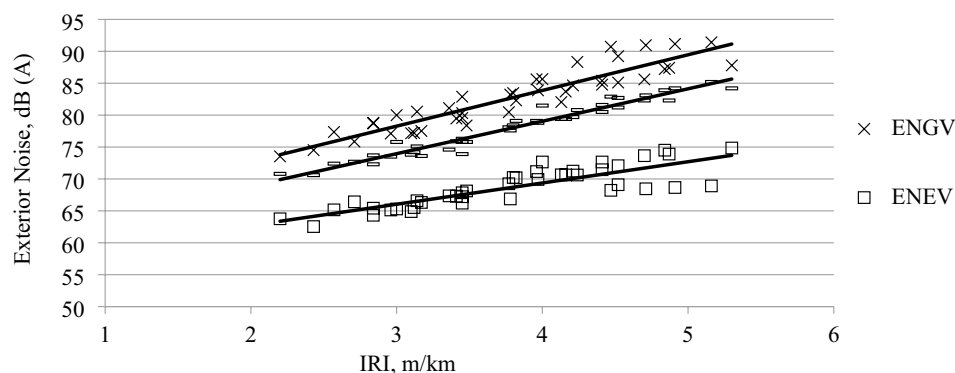
values of noises generated from the gasoline, hybrid, and electric cars were 91.41, 85.20, and 74.85 dB(A), respectively. These noise values were observed on pavement section with IRI of 5.30 m/km. On the other hand, the measured minimum values of exterior noises generated from the gasoline, hybrid, and electric cars were 73.54, 70.20, and 62.54 dB(A), respectively. And, these minimum values were observed on pavement section having IRI of 2.2 m/km, as shown in Table 3 and Fig. 6.

Finally, the following equation was developed to estimate the exterior noise generated from truck on urban arterials:

$$\text{ENTU} = 70.33e^{0.062\text{IRI}}, \tag{12}$$

where ENTU is the exterior noise generated from the truck on urban arterials, dB(A). The above equation and its parameters were significant at the 95% confidence level, and the coefficient of determination was 0.85.

5 Discussion

The findings of this study showed that traffic speed and the flexible pavement surface roughness had a substantial impact on interior noise. Equation (4) indicates that an increase in pavement roughness by 1 m/km would increase the interior noise by about 3.9 dB(A). Also, the same equation indicates that an increase of traffic speed by 10 km/h would increase the interior noise by 1.6 dB(A). Based on a large sample of field data (624 observations/car * 3 car types), this study confirmed the impact of pavement roughness and traffic speed on interior noise level. Although the same result is obtained for the single-unit truck model in Eq. (5), the impact of roughness and truck speed had greater effect on the interior noise level. These results are comparable to the findings of previous studies. For instance, Chen et al. [25] concluded that interior noise is linearly and highly related to the IRI. Furthermore, He et al. [40] found that interior noise is greatly influenced by the vehicle speed, specifically at speeds more than 80 km/h.

Based on empirical field data, this study highlighted the impact of car type on the generated interior noise. Compared with gasoline car, Eq. (4) indicates that the use of hybrid and electric car would reduce the interior noise by nearly 7 and 11 dB(A), respectively. This reduction is very vital for the health and comfort of drivers and passengers who are traveling for long distances. Compared with cars, interior noise generated by the single-unit truck is strongly affected by the pavement roughness and the speed. For truck, Eq. (5) indicates that each 1 m/km increase in the IRI would increase the noise by about 5.5 dB(A), and the increase of speed by 10 km/h may raise the noise by 2 dB(A).

Similarly, exterior noise was investigated in the study. For rural arterials, it was found that the pavement roughness had strongly influenced the exterior noise. The identified relationship between pavement roughness and exterior noise had a power form for each type of cars. However, a general linear model equation for all cars was developed by pooling the data, as shown in Eq. (9). Compared with interior noise, exterior noise is highly sensitive to the roughness level. For example, an increase in roughness by 1 m/km would increase exterior noise by 5.84 dB(A). Compared to the gasoline car, this equation shows that the use of hybrid and electric cars would reduce the exterior noise by approximately 5 and 12 dB(A), respectively.

For urban arterials, Eq. (11) was developed as a general model to estimate exterior noise level for each car type. The analysis revealed that pavement roughness had a strong and significant effect on exterior noise. In contrast, the noise analysis under two-speed levels, which are too close to each other, did not help in capturing the impact of speed on exterior noise. Therefore, further studies are recommended to highlight this issue.

The results of this study indicate the effects of pavement roughness, traffic speed, and vehicle type on the level of interior noise. Also, the study indicates that exterior noise is strongly influenced by the pavement roughness and vehicle type. Compared with interior noise, exterior noise is highly sensitive to pavement roughness level. Therefore, this study explores the importance of pavement maintenance not only to improve riding quality, but also to reduce the generated noise for a healthy and sustainable environment. Furthermore, governments should adopt the necessary policies to increase proportions of hybrid and electric vehicles fleet.

Finally, it was mentioned that the accuracy of the used TotalPave app is greater than 85%. A question may be raised whether an error of 15% or less does affect the concluded results. Authors believed that this issue is not greatly affected the obtained results for two reasons. First, in all developed models, the impact of IRI on the generated noise is strongly significant and not marginally; as indicated by the small magnitude of p value (see Table 4). Second, the coefficients associated with the IRI in each noise model and for each noise type are approximately equal, especially for cars. Finally, this indicates that the generated noises due to tire–pavement interactions for all cars are nearly similar. Thus, authors expected that the error of the app was not great to influence the soundness of the results. Probably, repetitions of roughness measurement three times and the use of average value for each pavement section enhance the accuracy of the obtained IRI.

6 Conclusions

Based on the results of this study, the following points were concluded:

1. Interior noise measured along urban and rural arterials was found to be strongly affected by pavement roughness, vehicle speed, and vehicle type. Results indicated that an increase in roughness by 1 m/km would increase the noise by 3.9 dB(A), and an increase in car speed by 10 km/h may increase the noise by 1.6 dB(A).
2. Compared with gasoline car, the use of hybrid and electric cars may reduce interior noise by 7 and 11 dB(A), respectively.
3. For individual cars and the single-unit truck, the relationship between the estimated interior noise and each of pavement roughness and traffic speed had a linear form.
4. For rural and urban arterials, analysis of exterior noise indicated that both of pavement roughness and vehicle type had influenced the generated noise. Compared with interior noise, exterior noise is much more affected by the pavement roughness. In contrast, the external noise was unaffected by vehicle or truck speed. Thus, further studies are recommended to investigate a wide range of traffic speeds on the exterior noise.
5. For cars, two general linear models were developed to estimate exterior noise along urban and rural arterials. Likewise, two exponential models were created to calculate the amount of exterior noise a truck makes along rural and urban arterials.
6. This study indicates the importance of keeping pavement surface in a good condition and increasing the proportion of hybrid and electric vehicles in traffic fleet as vital measures to reduce traffic noise.

Data Availability Statement All data, models or code that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this research paper.

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