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Case study

Influence of temperature on tire-pavement noise in hot climates: Qatar case

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ABSTRACT

The ambient air temperature greatly influences tire-pavement noise measurements. Therefore, various international standards recommended a temperature correction factor to compensate for noise measurements at varying temperatures. This temperature correction factor is developed based on the local environment (temperature varying from 5 °C to 35 °C) and generally varies with different pavements. Pavements in the Gulf region experienced harsh weather conditions, with temperatures often crossing 40 °C during summer. This study investigates the effect of air temperature on noise measurements in hot climatic conditions of Gulf regions. The On-Board Sound Intensity (OBSI) noise measurements technique was used to collect the noise data at different temperatures ranging from 25 °C to 43 °C. A linear regression analysis was performed to verify the relationship between noise and temperature. Three statistical criteria were selected to avoid parasitic phenomena and contamination of noise data during measurement. Statistical analysis demonstrated a strong relationship between noise intensity and temperature, especially at a frequency above 1250 Hz. Spectra analysis of the noise measurements also showed that the temperature coefficient is frequency-dependent, and generally, a frequency above 1250 Hz has a higher temperature coefficient. OBSI test results at various pavements with different mean texture depths of dense-graded pavement showed that the temperature coefficient varied from 0.052 dB/°C to 0.142 dB/°C. There is an apparent trend of decreasing temperature coefficient with increasing mean texture depth of dense graded asphalt pavements. However, no clear dependence on the temperature coefficient on the vehicle's speed is observed in this study.

1. Background

In the last few decades, traffic volume increased significantly on the road transportation network to meet the demand. Thus, more people are exposed to traffic noise in the modern days than in the past. Reducing traffic noise is a growing and pressing need for the people, mostly from urban dwellers, where the primary transportation corridors pass near their houses. To reduce noise to an acceptable limit, 'quieter pavement' is becoming an alternative option to a commonly used noise barrier wall. Noise barrier walls are solid obstructions placed between the highway and receivers to reduce the noise level between 7 and 10 dB at the receivers closest to

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the highway [1]. The noise barrier walls are expensive, i.e., 2.1 million dollars per mile [2,3], and sometimes ineffective due to intersection and side road merging to highways [4–6]. Quieter pavement is a concept for constructing or rehabilitating roadway surfaces intended to reduce tire/pavement noise impacts on the highway environment. Some researchers in Europe and the US showed that modifying the surface texture or mix design of the pavements can be an alternative and cost-effective solution to reduce noise without compromising of safety and sustainability of pavement [4,6,7]. However, a reliable and accurate noise measurement is a must for efficiently implement quieter pavement as a noise abatement procedure to identify the difference in noise level among various pavements [4].

Currently, noise measurement in the field is conducted in two ways: i) wayside noise measurement and ii) noise measurement near tire-pavement interaction. Noise measurement at near tire-pavement interaction is more accurate when the goal is to identify the small variation of noise over time or compare noise levels for various pavements [6]. Recent literature reviews by Li [8] and Praticò [9] demonstrated that there are several methods for measuring noise at source used by worldwide transportation authorities/personnel. However, most of the transportation personnel either use: a) close proximity trailer method (CPX), in which the sound level is measured, or b) onboard sound intensity (OBSI) measurement method based on the sound intensity measurement technique for measuring noise at the source. CPX trailer method is a quick noise measurement method and can be used to test large roads and provide a true reflection of tire-pavement generated noise [10]. Although CPX trailer is an efficient method to measure the pavement noise at source, this method underestimates pavement absorption due to errors owing to low-frequency noise from highly directive sources [8,9,11]. OBSI noise measurement provides more stable correlation both in overall and spectrum level with pass-by methods [8,9]. The OBSI method for noise measurement allows pavement engineers to investigate and compare tire-pavement noise in great detail [7]. The OBSI method also directly measures sound intensity in close proximity to the tire-pavement interface and allows various influencing factors affecting pavement noise directly compared [6,7,12].

In recent years, an increased effort has been put in place to improve the reproducibility and repeatedly of OBSI data as environmental conditions significantly influence the noise measurements. Temperature is found to be one of the primary sources of variation, as observed by the number of relevant research studies [4,6,7,12–22]. Therefore, to accurately assess the noise performance of the pavement surface, it is essential to compensate for any bias due to uncontrolled influences such as variation of temperature in the measurement site. In most international standards, the bias due to temperature variation during measurement time is compensated using temperature correction. AASHTO T360−16 [23] recommended correction factor for the tire-pavement noise level to a reference air temperature of 20 °C using Eq. 1:

$$\text{IL Normalized}\left(20^{0}\text{C}\right)(\text{dBA}) = \text{IL Measured}(\text{dBA}) + \alpha\left(\text{T} - 20^{0}\text{C}\right) \tag{1}$$

where, IL is the sound intensity level, T is the air temperature in degrees Celsius, and α is called the “temperature coefficient’’. In theory, α is specific to the tire, and the pavement surface is considered.

In the CPX trailer method, typically, two microphones are located near the tire (100–450 mm, one at the leading edge, the other at the trailing edge of the contact patch) to measure the average pressure level for a period (4–60 s).CPX trailer method is standardized in ISO 13471−1 [24] and followed a similar procedure to AASHTO T360−16 [23] for temperature correction. ISO 11819−2 [25] recommended temperature coefficient for different pavement types. Furthermore, ISO 11819−3 [26] also provides a correction procedure for two reference tires, i) one for Standard Reference Test Tire (SRTT) and ii) one for heavy vehicles, whereas AASHTO T360−16 [23] recommended temperature correction only for SRTT. Several research studies examined the effect of temperature on tire-pavement noise, including various noise measurement methods. The summary of the temperature coefficient of noise measurement for dense graded asphalt (DGA) pavements is presented in Table 1.

These studies demonstrated that the temperature coefficient values vary for different pavement surfaces even though the noise measurement methods and other parameters are the same. However, most of the studies conducted noise measurement in a different

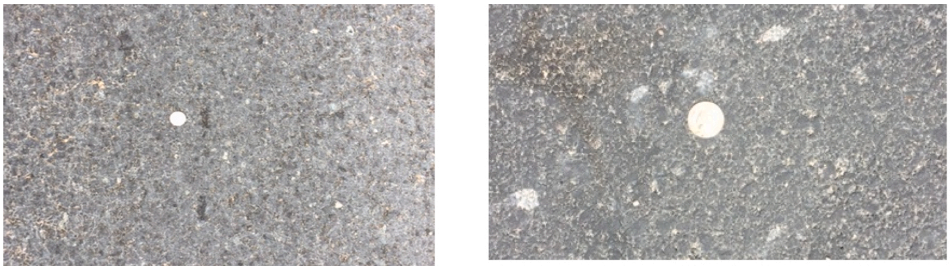
Table 1
Summary of temperature coefficients observed in various studies for DGA Pavement.

Author	Measurement Method	Type of surface	Coefficient Range (dBA)/ ^{0}C)	Temperature range	Measurement taken
Rasmussen [5]	OBSI	DGA	0.007 to -0.09	N/A	N/A
Anfosso-Leede and Picard [13]	Pass-by	DGA	−0.1	0 °C to 30 °C	Various times of the season
Bendtsen et al. [14]	OBSI	DGA	−0.029 to -0.043	2 °C to 22 °C	Several consecutive days in a season
Rochat [15]	Pass-by	DGA	+0.08 to -0.19	14 °C to 34 °C	N/A
Bühlmann and Zeigler [16, 17]	CPX	DGA, Porous	−0.018 to -0.16	10 °C to 30 °C	Same day
Mogrovejo et al. [18]	OBSI	DGA	−0.07 to -0.12	4 °C to 32 °C	Various days of a season
Bühlmann and Blokland [19]	CPX, OBSI Pass-by	DGA	−0.1	N/A	Varies
Lodico and Donavan [21]	OBSI	, DGA(3/8″), DGA (3/4″)	−0.018 to -0.126	4 °C to 24 °C	Various times of the season
Smitt and Waller [27]	CPX	DGA	Negligible	10 °C to 30 °C	Same day
Jaben and Potma [28]	CPX	DGA	−0.03 to -0.12	−6 °C to 24 °C	Years
Mioduszewski et al. [29]	CPX	DGA	−0.06 to -0.14	5 °C to 30 °C	Years

season, which is a significant parasitic phenomenon that may result in an erroneous conclusion [16]. Suppose noise measurement is conducted at a different season. In that case, the effect of temperature on noise level could be contaminated with the effect of surface aging on noise due to the combination of traffic-induced stress and physio-chemical changes resulting from environmental conditions. This may result in a misleading outcome as the temperature coefficient value is small, as suggested in the literature.

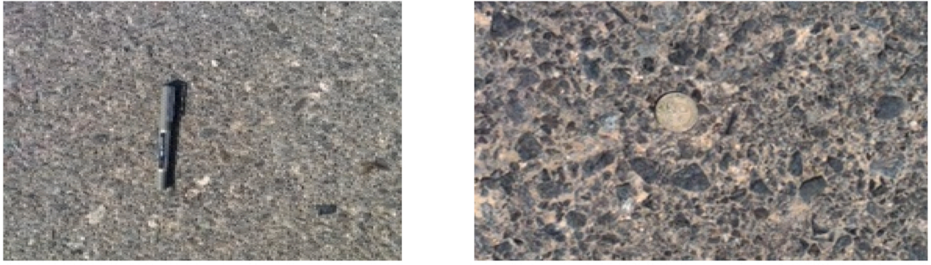
Furthermore, in the case of CPX and OBSI measurement, the age of SRTT could further contribute to noise variation as the tire's properties, such as hardness, may change due to time lag between noise testing [14]. The reason for researchers conducting noise tests at a different season or few days in a season is to cover a reasonable range of temperatures to identify the temperature effect on tire-pavement noise. However, some researchers [25] collected noise data by using the CPX technique on the same day to investigate the influence of temperature on tire-pavement noise level, although ranges of temperature for the studied pavement surface are small.

The literature review shows that very few studies [7,14,18,21] evaluated the temperature effect on tire-pavement noise using the OBSI method. However, these studies conducted the OBSI noise testing on different days or consecutive days in a season. Also, there is a lack of studies in the Gulf region where pavement surfaces experienced high ambient temperature. Air temperature in the Gulf region often reaches or exceeds 40 °C in the summer, whereas pavement temperature reaches or exceeds 60 °C. However, the effect of temperature on tire-pavement noise at such high temperatures is not investigated in the literature. Thus, without proper quantification of temperature coefficient on tire pavement noise measurement in this hot climatic region could lead to erroneous noise data. Therefore, the objective of this paper was to evaluate the effects of air temperature on tire-pavement noise, considering the higher temperature in the Gulf region using the OBSI method. Meanwhile, very few researchers studied the influence of temperature on pavement noise at the frequency level, especially using the OBSI data. Therefore, the temperature effect on the frequency spectra was also studied in this study. Frequency analysis of measured noise data could help understand the mechanisms involved in the tire's interaction with the pavement surface. The impact of vehicle speed on the temperature coefficient of tire-pavement noise was also examined. Pavement surface texture plays an important role in the tire-pavement noise mechanism [11,22]. Bernhard et al. [11] showed that negative texture with a characteristic length less than 10.0 mm tends to reduce noise. However, the texture of other sizes and types tends to increase noise. Microtexture may affect high-frequency noise generation mechanisms such as stick-slip and stick-snap by changing the contact conditions between tire and pavement. However, macrotexture (wavelength between 0.5 mm and 50 mm) has been shown to affect OBSI levels in the 630–1000 Hz range [29]. Recent research by Del Pizzo et al. [30] and de Leon et al. [31] demonstrated that road texture is positively correlated at the low-frequency range (315–800 Hz) and negatively correlated at the high-frequency range (2000–5000 Hz). The addition of rubber in the asphalt mixture influences the relationship between texture and noise, especially at the high-frequency range. Macrotexture can change the volume of air cavities, thus affecting the air pumping and pipe resonance mechanisms. It can also affect the impact, friction, and adhesion mechanisms. Therefore, the effect of surface texture characterized as mean texture depth (MTD) on the temperature coefficient is also investigated in this study.



a) Al Jemailiya street (1 year with NMAS of 12.5 mm with MTD of 0.65)

b) Rawdat Al Rashed road (1 year with NMAS of 19 mm with MTD of 0.95)



c) Dukhan highway (6 years with NMAS of 19 mm with MTD of 0.88)

d) Salwa road (8 years with NMAS of 19 mm with MTD of 2.92)

Fig. 1. Photographic view of typical pavement sections for this study.

2. Testing methodology

2.1. Description of testing sections

Asphalt pavements in Qatar are constructed mainly by following DGA mix design. In this study, the OBSI noise testing was performed on four selected DGA pavements sections with varying ages to investigate the influence of temperature on tire-pavement noise measurements. The four different aged DGA surfaces were chosen as MTD changes with pavement aging, which may affect the temperature coefficient of tire-pavement noise. The as-built pavement data also showed that the nominal maximum aggregate sizes (NMAS) are varied for the top surfaces of selected pavement sections. A photographic view of the selected pavement sections is shown in Fig. 1.

2.2. Correlation between air and pavement temperature

This study is a part of ongoing research efforts to design and construct quieter pavements in Qatar. During this research project, the surface temperature of various pavement sections in the State of Qatar was measured along with air temperature. A Pocket Weather Meter was used to measure air temperature, whereas A Class II Infrared Laser temperature gun was used for surface temperature measurements of pavement. In general, the pavement temperatures followed the air temperature, as shown in Fig. 2, for the entire testing program in all four months. It was observed that in the early morning (until 9 AM), the pavement surface temperature increased fairly uniformly with air temperature. As the day progresses (after 9 AM), pavement surface temperatures increase at a higher rate than the air temperature due to sun heat. In the afternoon (after 4 PM), the pavement temperatures decreased faster than the air temperature as the sun was less directly overhead. In the nighttime (after 10 PM), the pavement temperatures often dropped below the air temperature. The highest variation (15–20 °C) of temperature between the pavement surface and the air was observed during mid-day (11 AM to 3 PM) due to the solar effects. From Fig. 2, it can be observed that there is a good correlation ($R^2 = 0.85$) between air temperature and pavement surface temperatures for pavements in Qatar. However, most of the international standards recommended using air temperature to analyze pavement noise. Hence, only the effect of air temperature on tire-pavement noise was investigated for this study.

2.3. Onboard sound intensity (OBSI) testing

Tire-pavement noise for this study was measured by the OBSI method following the AASHTO T360−16 standard [23]. The Acoustical and Vibrations Engineering Consultants (AVEC), Inc. OBSI system (Fig. 3) was used for all the noise measurements. In this equipment, the sound intensity probes consist of a pair of microphones connected with a preamplifier. The microphones and preamps were supplied by G.R.A.S. For calibration of microphone, a microphone Calibrator, Model: G.R.A.S type 42AB, was used. Other major components of this testing system include a 4-channel analyzer manufactured by National Instrument, AVEC OBSI software, and a semi-rugged laptop computer. An SRTT (P225 60R16 97S) in accordance with ASTM F2493−08 [32] was used for all the OBSI noise measurements. The selected Pocket Weather Meter was also used to measure wind speed/direction, barometric pressure, and humidity for all OBSI measurements. The weather data was collected before and after noise testing for data quality following AASHTO T360−16 [23]. All the OBSI test runs for individual pavement sections were conducted in similar environmental conditions (within an acceptable 1 °C range of variability). Most of the OBSI testing was conducted at ASSHTO T360−16 [23] specified speed 97 km/h unless mentioned for any particular purposes. The length of all the test sections is about 134 m. These sections were chosen according to AASHTO T360−16 [23], and noise measurement for each section was conducted for about 5.0 s. Details of the testing system and repeatability of noise test data can be found in Sirin et al. [33] and Ohiduzzaman et al. [34].

It should be noted that conducting OSBI testing at a temperature approaching 38 °C or higher could overload or invalidate signals

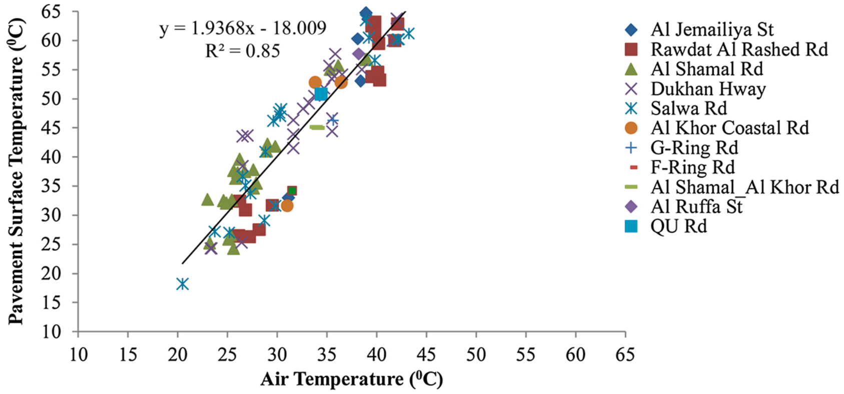


Fig. 2. Variation of pavement surface temperature (^{0}C) with ambient air temperature (^{0}C) for various dense graded asphalt pavements in the State of Qatar.

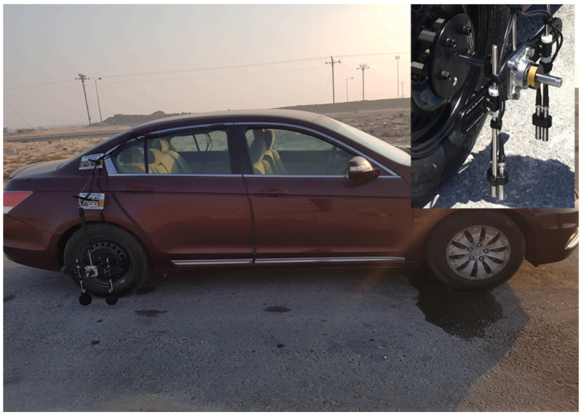


Fig. 3. OBSI noise testing setup.

recorded by preamplifiers [23]. Although most of the test runs above 38 °C temperatures did not provide any overload or invalid signals to the recording system, however, few tests showed invalid signals. If any invalid or overload signals occurred during noise data collection, the preamplifier with a microphone was disconnected from the testing setup and placed inside the car for a few minutes to be cooled down. When the preamplifier's temperature comes to a reasonable temperature, it was reconnected again with the testing system and performed a calibration before resuming the noise testing. Any run with invalid or overload signals was discarded from the data during the post-processing of data analysis.

The magnitude of temperature effect on tire-pavement noise is small; hence reproducibility and repeatability of the noise data possess significant challenges. They may lead to a weak correlation between temperature and noise measurements. Additional precautions regarding measurement setup and procedure are required to minimize parasitic phenomena and reduce standard uncertainties when investigating temperature effects on tire-pavement noise [19]. Unfortunately, such details were often missing or incompletely reported in the literature. Bühlmann and Zeigler [16] demonstrated that data with weak correlation results from parasitic phenomena rather than noise-generation mechanisms being insensitive to temperature.

In this study, the repeatability of noise data was first examined. The difference of overall A-weighted sound intensity level among three valid runs was set to 1 dB under the same testing temperature by AASHTO T360−16 [23] standard. This resulted in a standard deviation below 0.5 dB, which is reasonably good repeatability of the OBSI measurements. However, it is the same order of magnitude as the temperature influence of noise, as evidenced in the literature. Hence, the difference between three valid runs is restricted to 0.5 dB instead of 1 dB, which brings the standard deviation below 0.3 dB. However, it proved to be a major challenge. Even with the same driver, the same testing system attached to the same car, and the same environmental condition, there is always a variation of the sound intensity level of successive runs on the same surface. When driving the car manually, it is impossible to drive the vehicle at the same wheel track every time. The presence of localized distresses in pavement surfaces provides further challenges in reducing variability among noise data. The slight variation of testing speed further contributed to the variability of noise data. Although various vehicle speeds were eliminated in this study by driving the vehicle using automated cruise control mode, it was still required more than seven, even in some cases 10 repeated valid runs to obtain 0.5 dB different among valid runs. However, it was required much time to acquire that many valid runs, which resulted in temperature variation than the acceptable limit recommended by AASHTO T360−16 [23], highlighting the general problem of investigating the small difference in noise intensity. It was decided that the difference among A-weighted overall noise intensity levels was set at 1 dB, but four repeated valid runs were used for averaging in the studied section instead of the AASHTO T360−16 [23] recommended three valid runs. This additional run brings down the standard deviation below 0.4 dB, which is not perfect for analyzing temperature effect on noise generation but still provides good repeatability of noise tests.

It can be seen from Fig. 2 that there is a significant variation in temperature between day and night during summer times. Therefore, in this study, noise testing was performed various times over a day to identify the influences of temperature on tire-pavement noise measurement. Noise testing on the same days eliminates the parasitic phenomenon due to other factors such as aging of the tire, aging of pavement, traffic-induced distress, which may affect noise data.

3. Discussion of test results

At first, nine test sections on Salwa road were selected to examine the correlation between noise level and air temperature. These test sections were located in both traffic directions. Tests were conducted at four different times on a summer day, with temperatures varying 25 °C to 43 °C.

3.1. *Effect of temperature on overall A-weighted noise level*

The sound intensity level measured at different temperatures for various Salwa road sections is shown in Fig. 4. In general, the sound intensity level followed a downward trend with increasing air temperature. It is observed in the literature that the coefficient of determination (R^2) is usually used to describe the relationship between generated noise and temperature. However, the use of R^2 only could lead to an erroneous relationship because of slope uncertainties. This is because reviewed literature data (see Table 1) and measured data (see Table 2) in this study showed that the slope values of the tendency equations as a function of temperature are small (magnitude usually less than 0.1). Therefore, statistical analysis was performed to identify the slope uncertainty. Parameter P-value of linear regression analysis was chosen to quantify the slope's uncertainty recommended by other studies [13]. The P-value is used to determine the slope's uncertainty by calculating the percent chance in which the true slope does not equal the zero-slope line that lies within a specified confidence region of the regression line through the measured data. If the percent certain (calculated from P-value) is above a threshold, there is a statistically significant temperature effect on pavement noise. However, parasitic phenomena on noise levels can still easily offset the temperature influence leading to wrong conclusions if only R^2 and P-value are used to understand the noise-temperature relationship [16]. The use of standard error (SE) of slope could be candidate criteria that prevent parasitic phenomena inclusion in true noise-temperature by extracting cases with small or no temperature effects. Therefore, in this study, three statistical measures were selected to examine the noise-temperature relationship: i) R^2 value above or equal to 80 %; ii) % of slope uncertainty above or equal to 80 %, which is calculated from 100*(1-P-value) [any value equal or above 80 % indicates that a genuine relationship exists between sound level and temperature for each data set]; and iii) standard error of slope $\leq$0.1 dB/°C [16]. It can be seen from Table 2 that all test sections except Section 6 ($R^2 = 0.78$) in Salwa road met the aforementioned three selected data criteria. This demonstrated that a strong relationship exists between noise intensity and temperature for studied testing sections. The slope value obtained as a function of temperature (per °C) for the tested sections ranges from -0.03 to -0.082. Therefore, the average slope value was calculated, and the average decrease in noise level for all the measurements reflected a gradient of -0.05 dB/°C. The average slope gradient and the ranges of slope for noise temperature equation obtained for various Salwa road sections align with the previous research studies on DGA pavements.

3.2. Effect of temperature on 1/3rd octave band frequency level

As discussed, the overall A-weighted noise level decreases with increasing temperature. However, the effect of air temperature on noise was analyzed at frequency level to understand the mechanism involved in tire-pavement noise. The sound emission during vehicle moving at reference speed (~97 km/h) was evaluated at 1/3rd Octave band frequency spectra between 400 Hz and 5000 Hz. Fig. 5 shows the sound level spectra associated with the reference test section of the studied DGA pavement surface at different temperatures. Below 1250 Hz, the frequency spectra showed very little or no trend with temperature. However, for frequencies at or above 1250 Hz, there is a clear decreasing noise level with increasing temperature observed. This is in line with the previous study by Anfosso-Leede and Pichaud [13]. At frequencies above 2000 Hz, noise levels at warmest temperatures (39.8 °C and 43.3 °C) are identical, and the two coldest temperatures (25.2 °C and 28.5 °C 5) are similar. The noise level at the warmest temperature is approximately 1–2 dB lower than the coldest temperature.

A linear regression analysis was performed for all studied test sections on Salwa road to identify the correlation between temperature and noise level at 1/3rd Octave band frequency. The results are presented in Table 3. The same three statistical criteria are used for the noise-temperature relationship, as was the case for the overall A-weighted noise level and shown in Table 4. It can be seen from Tables 3 and 4 that a weak correlation exists between the noise-temperature relationship for the frequency below 1250 Hz. This may be due to the measurement uncertainties at these low frequencies [13]. However, in frequency ranges between 1600 Hz and 4000 Hz, a good correlation exists between noise level and temperature. Fig. 6 shows the percentages of passing for the test section for correlation criteria at various frequencies. At frequencies below 1000 Hz, less than 20 % of sections passed the correlation criteria, while for frequencies in between 1600 Hz and 4000 Hz, about 80 % of the test sections passed the correlation criteria. This

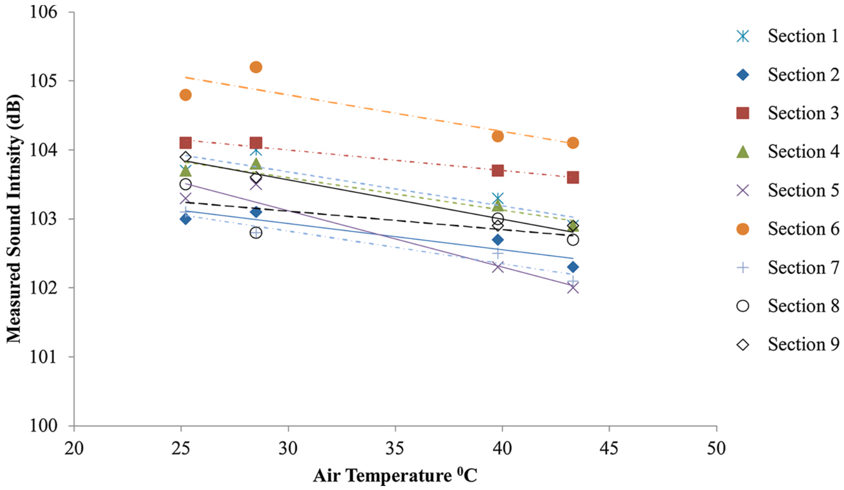


Fig. 4. Variation of sound intensity level with air temperature for various sections on Salwa road.

Table 2
Regression line statistics parameter for tested sections on Salwa road.

Section	Sound intensity-air temperature slope (dB/ ^{0}C)	R^{2}	% Certainty of slope= 100*(1-P-value)	Standard Error of slope (dB/ ^{0}C)
Section 1	−0.049	0.81	89.8	0.017
Section 2	−0.038	0.84	91.8	0.012
Section 3	−0.030	0.98	98.8	0.003
Section 4	−0.047	0.92	96.1	0.010
Section 5	−0.082	0.93	96.5	0.016
Section 6	−0.053	0.78	88.6	0.020
Section 7	−0.047	0.93	96.3	0.009
Section 8	−0.057	0.97	98.3	0.008
Section 9	−0.049	0.97	98.5	0.006

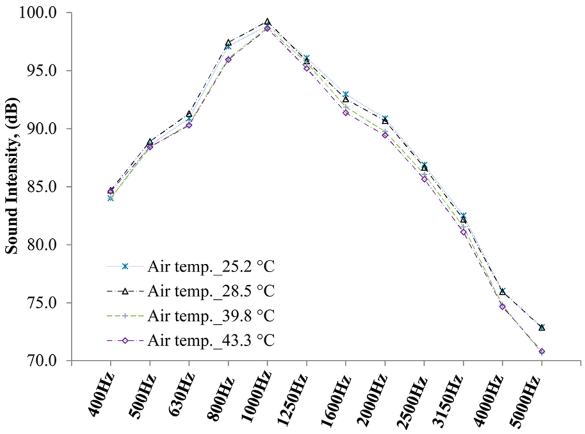


Fig. 5. OBSI level at 1/3rd Octave band frequency level at different temperature for Section-1 on Salwa road.

demonstrated that a strong correlation exists between noise and temperature at these frequencies range.

It can be seen from Table 3 that significant differences were observed between temperature coefficients over noise spectra. The temperature influence is lower at a frequency below 1250 Hz and generally is higher at a frequency above 1600 Hz. The highest temperature coefficient was observed at a high frequency of 5000 Hz. At low frequency, tire-pavement noise is dominated by the vibration induced by surface roughness and tire thread block hence less influenced by temperature effect. Also, wind turbulence-induced noise in the microphones may mask the effect of temperature at lower frequencies. The air pumping mechanism is mainly responsible for noise at higher frequencies (above 1250 Hz). Adhesion and friction mechanism due to flow in and out of the air from tire thread also contributed to the noise generation. However, a mechanism involving temperature effect on pavement noise at high frequencies has not been clearly identified. Some researchers [13,35] demonstrated that the stick-slip mechanism is responsible for the temperature effect as the friction coefficient decreases with increasing temperature. This is because the stick-slip mechanism is influenced by compression and expansion of tire-thread cavities.

3.3. *Effect of pavement surface texture on temperature coefficient of noise*

Once the correlation between noise- temperature relationship was established based on the statistical criteria, OBSI noise testing was performed on multiple sections of other DGA sections in Rawdat Al Rashed road, Dukhan highway, and Al Jemailiya street. The same statistical data criteria were used in these pavement test sections also. The temperate coefficient was determined from the slope of the noise-temperature relationship of multiple sections of the individual highway and averaged and shown in Fig. 7. Test results demonstrated that the range of temperature coefficient for tire-pavement noise for a hot climatic condition like the State of Qatar is comparable to studies conducted for DGA surfaces in other countries, as shown in Table 1. This is in line with ISO 13471−1 [24] recommended temperature coefficient correction factor for DGA pavements. However, these test results are based on only SRTT as opposed to ISO 13471−1 [24] standard, which recommended two tires for light and heavy vehicles. It can be seen from Fig. 7 that the temperature coefficient varied for different roads, even though all four are DGA surfaces. However, the maximum aggregate size of pavement and age are different; therefore, they have different temperature coefficients. This indicates surface texture could play an important role in the temperature effect of tire-pavement noise. Therefore, the mean texture depth (MTD) of all those four surfaces was measured using the sand patch test method [36]. In order to inspect any traceable relationship between the temperature coefficient and surface texture, they are plotted against each other and shown in Fig. 8. The relationship between temperature coefficient and MTD of pavement surface can be described by the logarithmic equation, as observed in Fig. 8. Although the R^{2} value is relatively low

Table 3
Regression analysis data at frequency spectra for various sections on Salwa road.

Section	Statistical Parameter	Frequency (Hz)											
		400	***500***	***630***	***800***	***1000***	***1250***	***1600***	***2000***	***2500***	***3150***	***4000***	***5000***
Section-1	*Slope*	−0.005	−0.008	−0.035	−0.076	−0.002	−0.007	−0.060	−0.080	−0.044	−0.057	−0.071	−0.140
	R2	0.000	0.120	0.750	0.880	0.180	0.160	0.970	0.990	0.990	0.940	0.910	0.920
	SE of Slope (per ^{0}C)	0.058	0.015	0.014	0.019	0.003	0.011	0.007	0.035	0.002	0.010	0.014	0.029
	% certainty of slope	6.730	35.290	86.800	94.100	42.800	40.400	98.620	99.750	99.680	96.750	95.600	95.660
Section-2	*Slope*	−0.008	−0.057	−0.086	−0.106	−0.055	−0.047	−0.081	−0.093	−0.067	−0.063	−0.084	−0.147
	R2	0.000	0.190	0.400	0.580	0.250	0.410	0.710	0.880	0.780	0.880	0.920	0.920
	SE of Slope per ^{0}C)	0.061	0.084	0.074	0.063	0.066	0.039	0.035	0.023	0.025	0.016	0.016	0.030
	% certainty of slope	8.120	43.700	63.500	46.600	50.800	64.900	84.050	94.100	88.110	93.600	96.050	95.750
Section-3	*Slope*	−0.032	−0.042	−0.051	−0.095	−0.020	−0.031	−0.081	−0.072	−0.048	−0.053	−0.074	−0.138
	R2	0.700	0.720	0.680	0.890	0.450	0.700	0.980	0.970	0.930	0.960	0.960	0.930
	SE of Slope (per ^{0}C)	0.014	0.018	0.024	0.022	0.015	0.015	0.008	0.008	0.009	0.008	0.010	0.025
	% certainty of slope	83.161	84.767	82.231	94.591	66.807	83.856	98.951	98.515	96.220	97.770	98.095	96.650
Section-4	*Slope*	0.020	−0.008	−0.024	−0.064	−0.055	−0.069	−0.066	−0.071	−0.069	−0.090	−0.079	−0.125
	R2	0.320	0.120	0.280	0.720	0.770	0.990	0.980	0.940	0.940	0.940	0.860	0.860
	SE of Slope (per ^{0}C)	0.021	0.016	0.026	0.027	0.020	0.005	0.006	0.012	0.011	0.015	0.021	0.035
	% certainty of slope	56.692	34.600	53.000	84.800	87.743	99.343	99.084	96.810	97.200	96.970	93.069	92.717
Section-5	*Slope*	0.000	−0.032	−0.029	−0.081	−0.053	−0.061	−0.083	−0.076	−0.069	−0.090	−0.080	−0.132
	R2	0.000	0.130	0.100	0.630	0.770	0.840	0.980	0.970	0.960	0.950	0.910	0.890
	SE of Slope (per ^{0}C)	0.055	0.057	0.058	0.043	0.019	0.019	0.007	0.008	0.010	0.015	0.016	0.032
	% certainty of slope	2.150	36.810	32.120	79.470	87.976	91.780	99.300	98.566	97.980	97.305	95.502	94.475
Section-6	*Slope*	0.022	0.022	−0.017	−0.036	−0.007	−0.039	−0.091	−0.071	−0.065	−0.071	−0.092	−0.148
	R2	0.140	0.880	0.270	0.650	0.260	0.950	0.970	0.970	0.920	0.870	0.990	0.980
	SE of Slope (per ^{0}C)	0.039	0.005	0.019	0.018	0.008	0.006	0.010	0.008	0.014	0.019	0.003	0.014
	% certainty of slope	38.400	93.840	51.990	80.810	50.800	97.800	98.910	98.480	95.830	93.350	99.940	99.040
Section-7	*Slope*	−0.005	−0.038	−0.080	−0.101	−0.024	−0.030	−0.071	−0.084	−0.058	−0.085	−0.075	−0.144
	R2	0.000	0.550	0.770	0.860	0.510	0.620	0.850	0.960	0.920	0.860	0.880	0.850
	SE of Slope (per ^{0}C)	0.047	0.024	0.029	0.028	0.016	0.017	0.020	0.011	0.011	0.016	0.018	0.042
	% certainty of slope	6.410	74.430	87.923	92.655	71.460	78.470	92.130	92.200	96.000	92.720	93.793	91.846
Section-8	*Slope*	0.020	−0.003	−0.061	−0.088	−0.018	−0.006	−0.062	−0.088	−0.060	−0.061	−0.078	−0.138
	R2	0.260	0.000	0.610	0.800	0.510	0.850	0.910	0.980	0.950	0.930	0.990	0.930
	SE of Slope (per ^{0}C)	0.020	0.037	0.034	0.030	0.012	0.020	0.013	0.008	0.009	0.011	0.002	0.025
	% certainty of slope	50.661	4.743	78.030	89.346	71.510	20.634	95.213	98.825	97.431	96.691	99.868	96.665
Section-9	*Slope*	0.015	0.012	−0.046	−0.080	−0.049	−0.052	−0.107	−0.135	−0.090	−0.080	−0.113	−0.158
	R2	0.020	0.000	0.120	0.390	0.570	0.890	0.950	0.890	0.890	0.970	0.960	0.950
	SE of Slope (per ^{0}C)	0.084	0.089	0.085	0.069	0.029	0.011	0.018	0.035	0.023	0.011	0.017	0.027
	% certainty of slope	14.211	11.070	34.414	62.387	75.612	94.853	97.321	94.223	94.272	98.381	98.010	97.244
Average	*Slope*	0.003	−0.017	−0.048	−0.081	−0.031	−0.038	−0.078	−0.086	−0.063	−0.072	−0.083	−0.141
	R2	0.16	0.30	0.44	0.71	0.47	0.71	0.92	0.95	0.92	0.92	0.93	0.91
	SE of Slope (per ^{0}C)	0.0443	0.0383	0.0404	0.0354	0.0209	0.0209	0.0138	0.0164	0.0126	0.0134	0.0130	0.0287
	% certainty of slope	29.615	46.58	63.33	80.53	67.28	74.67	95.95	96.83	95.86	95.95	96.66	95.56

Table 4
Effect of temperature on noise frequency for data criteria, i) $R^2 \geq 0.80$, ii) % of certainty ≥ 0.80, and iii) Standard error (SE) of slope $\leq$ 0.1 dB per °C.

Freq. (Hz)	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
Section 1	x	x	x	√	x	x	√	√	√	√	√	x
Section 2	x	x	x	x	x	x	x	x	x	√	√	x
Section 3	x	x	x	x	x	x	√	√	√	√	√	x
Section 4	x	x	x	x	x	√	√	√	√	√	x	x
Section 5	x	x	x	x	x	√	√	√	√	√	√	x
Section 6	x	√	x	x	x	√	√	√	√	√	√	√
Section 7	x	x	x	x	x	x	x	√	√	√	√	x
Section 8	x	x	x	x	x	x	√	√	√	√	√	x
Section 9	x	x	x	x	x	√	√	x	x	√	√	x

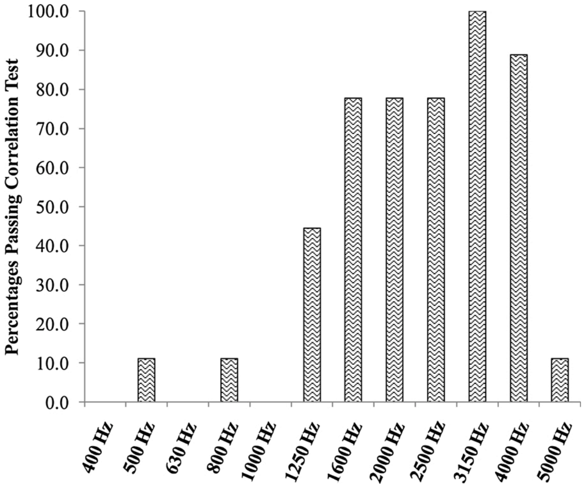


Fig. 6. Percentages of passing correlation for test sections at 1/3rd octave band frequencies spectra.

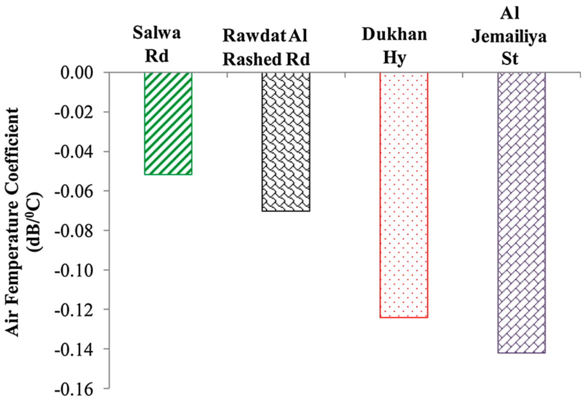


Fig. 7. Air temperature coefficient for various pavement sections in the State of Qatar.

($R^2 = 0.728$), it still showed an apparent decreasing temperature coefficient with increasing MTD of the pavement surface. With increasing MTD of pavement surface, tire-pavement noise is dominated by the vibration induced by surface roughness and tire thread block hence less influenced by temperature effect. Furthermore, the Stick-slip mechanism is influenced by compression and expansion of tire-thread cavities, which are generally less affected with increasing MTD. It is to be noticed that only four DGA surfaces are investigated; hence more tests on other DGA surfaces could improve the R^2 value of the relationship between temperature coefficient and MTD of the pavement surface.

Fig. 9 showed the temperature effect on noise frequency spectra for all pavement surfaces. It is noticeable from Fig. 9 that the temperature coefficient is lower in the frequency below 1250 Hz and is higher for frequencies above 1250 Hz for all the pavement surfaces. This is in line with the earlier studies [16,37]. Furthermore, at a frequency above or at 1250 Hz, the temperature coefficient

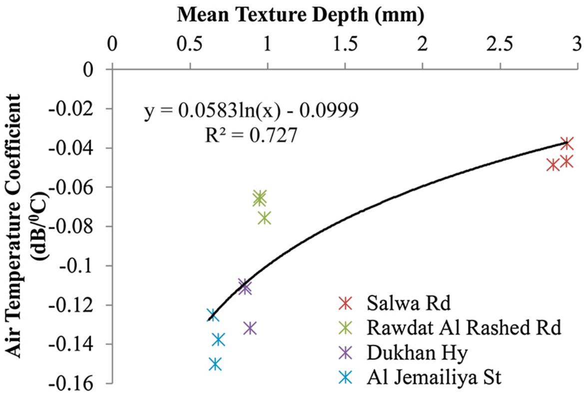


Fig. 8. Effect of mean texture depth (MTD) of pavement on air temperature coefficient.

followed the same order of mean texture depth (Al Jemailiya st, Dukhan Hy, Rawdat Al Rashed rd, and Salwa rd). This indicated a relationship between the temperature coefficient and MTD of pavement at a frequency above 1250 Hz. However, at frequencies below 1250 Hz, there is no clear trend between temperature coefficient with MTD of the pavement surface.

3.4. *Effect of speed on the noise-temperature relationship*

It is well established in the literature that sound noise increases with increasing vehicle speed irrespective of tire and pavement type [4,7,12]. However, limited studies were conducted on vehicle speed's influence on the temperature coefficient of tire-pavement noise, especially with the OBSI measurement method [38]. Therefore, two pavement surfaces were selected to verify the effect of driving speed on the temperature coefficient of tire-pavement noise. OBSI tests were conducted at three specified speeds (57, 72, and 97 km/h) at varying temperatures following the AASHTO T360−16 [23]. Experiments were conducted at multiple sections of both pavement surfaces, and the average temperature coefficient for overall A-weighted noise for each speed is calculated and shown in Fig. 10. It can be seen from Fig. 10 that the temperature coefficient does not follow any specific trend for this range of speed. This demonstrated that the noise-temperature relationship is independent of speed. These findings are not in line with the previous study by Bühlmann et al. [38], which summarized an increase of temperature coefficient with increasing vehicle speed. The same is correct at the frequency response of the 1/3rd Octave band, as shown in Figs. 11 and 12for Al Jemailiya and Rawdat Al Rashed road, respectively. Although this noise temperature relationship was validated only at three-speed limits, it applied for most of the road's driving speeds. However, extrapolation is not recommended beyond this speed range since tire/pavement interaction is not the primary source of noise at lower speeds (e.g., below crossover speeds). In contrast, at higher speeds, the aerodynamic noise becomes predominant. The effect of temperature on noise is minimal (around 0.1 dB); therefore, noise measurement at very low and high speeds could result in the wrong conclusion as noise from other sources can affect the noise measurements.

4. Conclusions

Changes in ambient air temperature can affect the tire-pavement noise measurements. The harsh weather conditions in the State of Qatar could influence the noise measurements. The researchers conducted OBSI noise measurements on various sections of four DGA surfaces of varying ages and with different nominal maximum aggregate sizes for the top pavement layers. To avoid the parasitic phenomenon, noise measurements at different temperatures were performed on the same day during the summer, where there is a significant variation in temperature in the day and night-time in the Gulf region. The following conclusions can be drawn from this study:

i) The air temperature significantly influences the tire-pavement noise generation; therefore, it should be considered when conducting noise testing. A linear relationship could approximately describe the dependence of tire-pavement noise on temperature. The average air temperature coefficients for all four DGA surfaces in Qatar ranged between -0.052 dB/^{0}C and -0.142 dB/^{0}C. The range of temperature coefficient for tire-pavement noise for dense-graded pavement in hot climatic conditions like the State of Qatar is within the range compared to other studies conducted in other countries.
ii) The temperature coefficients are frequency-dependent. At low frequencies, the temperature coefficient is small. However, the temperature coefficient is higher at frequencies above 1250 Hz.
iii) The temperature coefficient is greatly influenced by various pavement factors such as the age of pavement, nominal maximum aggregate size, and traffic density.
iv) The temperature coefficient could be approximately correlated with the mean texture depth of the DGA pavement surface. Tire-pavement noise is dominated by the vibration induced by surface roughness and tire thread block for higher mean texture depth of pavement hence less influenced by temperature effect.

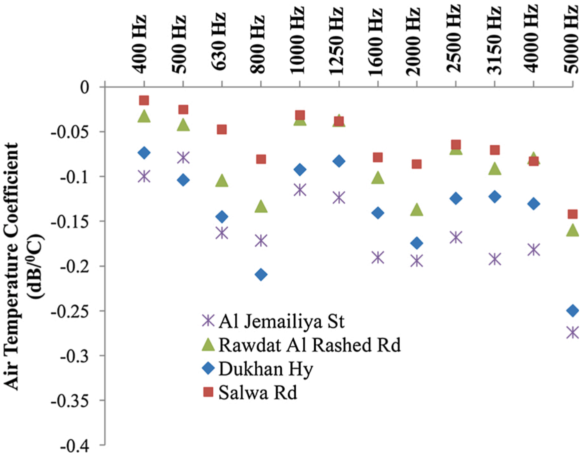


Fig. 9. Air temperature coefficient for various pavements at 1/3rd Octave frequency.

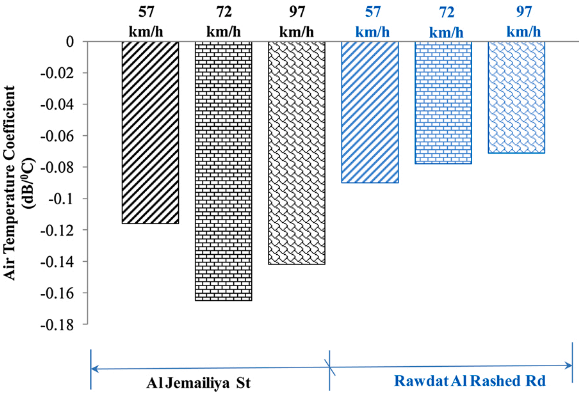


Fig. 10. Effect of speed on air temperature coefficient at overall A-weighted noise level.

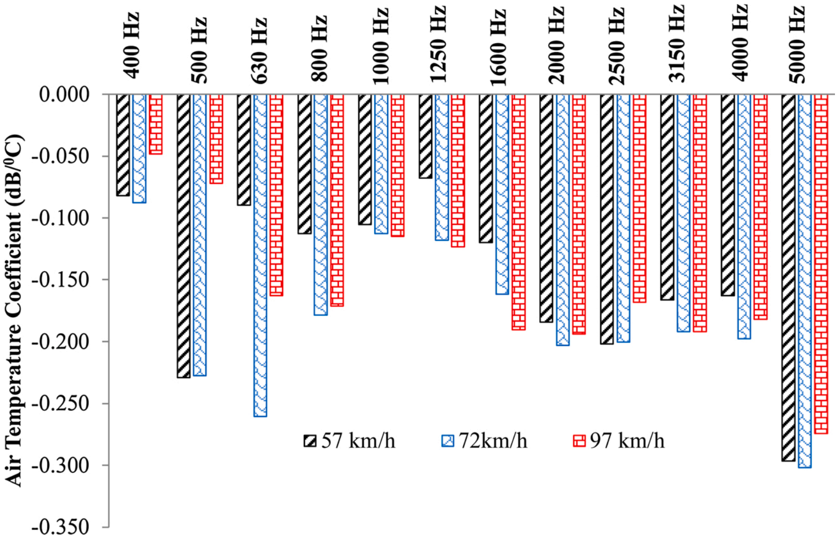


Fig. 11. Effect of speed on air temperature coefficient at 1/3rd Octave frequency for Al Jemailiya street.

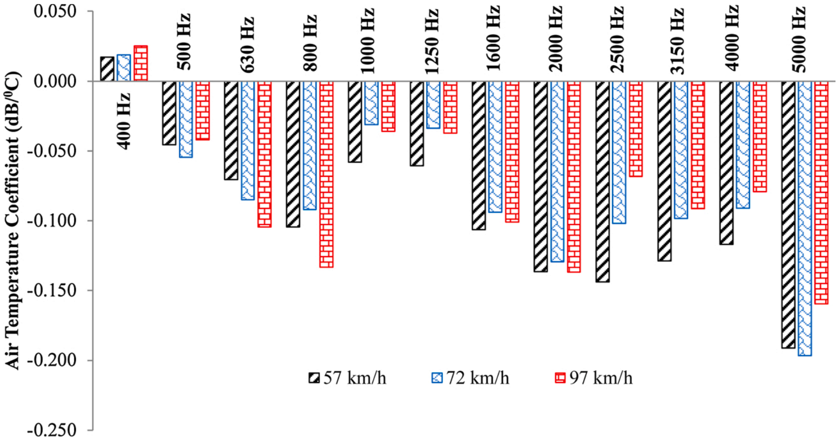


Fig. 12. Effect of speed on air temperature coefficient at 1/3rd Octave frequency for Rawdat Al Rashed road.

v) This temperature effect on the tire-pavement noise is found to be independent of the studied vehicle speed (from 56 to 100 km/h).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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