Transportation Research Part D 100 (2021) 103056

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Relationship between temperature and road traffic noise under actual conditions of continuous vehicle flow

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A R T I C L E I N F O

Keywords:
Road traffic noise
Temperature correction
Noise generation
In situ measurements
Normalisation
Noise mapping

A B S T R A C T

This paper focuses on studying the influence of temperature on the sound pressure level of tire-road noise emission using continuous environmental noise measurements. *In situ* noise measurements were performed next to a primary road under free flowing traffic where tire-road noise emission dominates, while simultaneously monitoring the air and pavement temperature. The broadband results showed a variation in noise level with temperature, with a ratio of -0.058 ± 0.007 dBA/°C for the pavement temperature and -0.161 ± 0.020 dBA/°C for the air temperature. A 1/3 octave band analysis revealed a decrease in sound level with increasing temperature in the fundamental bands of road traffic noise emission, and similar behaviour and values to that observed in the broadband analysis. The physical media in which temperature is measured appears to be important. Several implications may arise from this work in regard to reference standards for noise evaluation, calculation and measurement.

1. Introduction

This paper presents an experimental study of the relationships between temperature and environmental noise level generated by road traffic on a primary road. The tire-road noise emission is analysed for a mixed traffic under road operating conditions and for a dense asphalt. *In situ* noise measurements were performed in both broadband and frequency bands, while simultaneously monitoring the temperature of both the air and the pavement. This approach allows an approximation to this question by considering a mixed traffic flow including both light and heavy vehicles simultaneously, unlike research under controlled conditions.

The noise generated by road traffic is a source of environmental pollution that has adverse effects on the general population (Cai et al., 2020; Lan et al., 2020; Ma et al., 2021; Thacher et al., 2020) and on wildlife (Connelly et al., 2020; Finch et al., 2020; Iglesias-Merchán et al., 2016). Road traffic noise is also closely related to air pollution and its impacts on people's health (Andersson et al., 2020; Franklin and Fruin, 2017; Puyana-Romero et al., 2020). In this context, the European Environmental Noise Directive (European Directive, 2002) considers this type of infrastructure the main source of noise pollution, and requires the use of strategic noise maps (Barrigón Morillas et al., 2021; Khan et al., 2021; Lan and Cai, 2021; Wosniacki and Zannin, 2021) to provide a basis for assessing the environmental impact and for the design of measures for noise mitigation (Fredianelli et al., 2019; Montes-González et al., 2019; Paschalidou et al., 2019).

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https://doi.org/10.1016/j.trd.2021.103056

Available online 30 September 2021

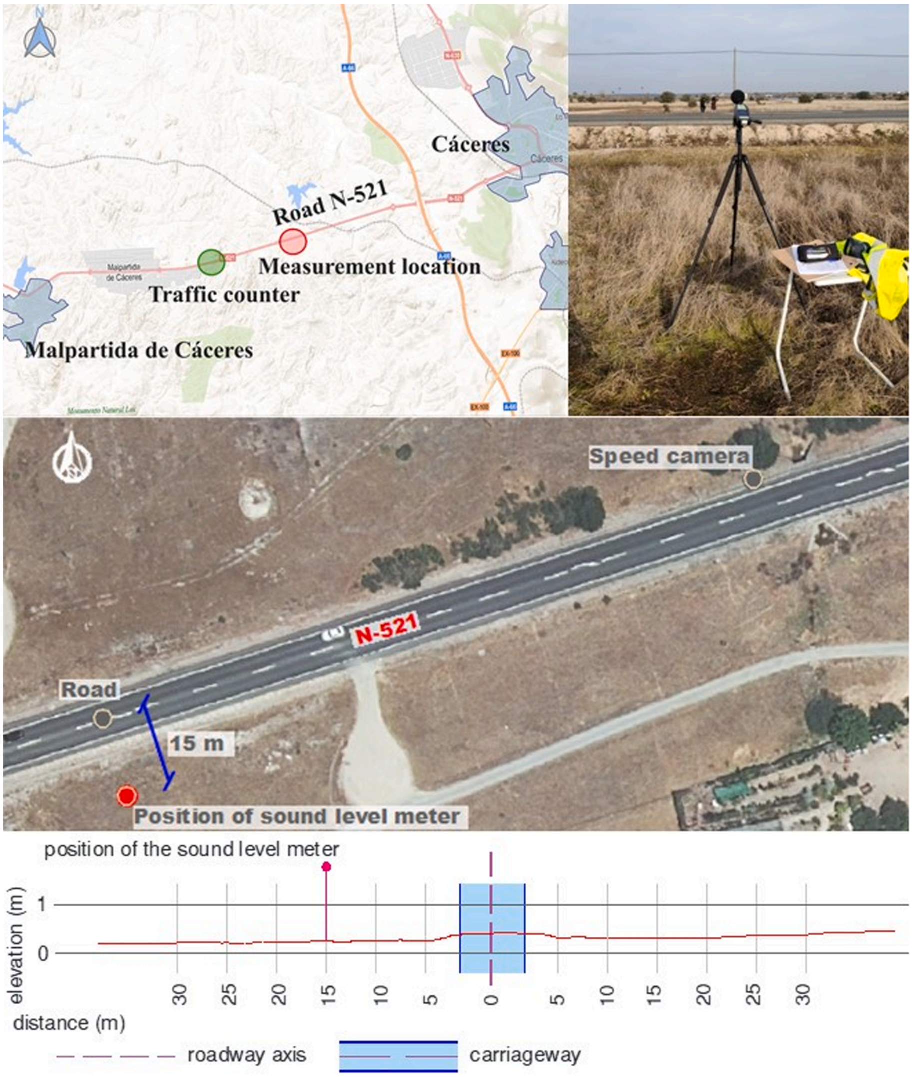

Fig. 1. Location, plan view and cross-sectional profile of the measurement site.

Factors influencing the noise levels from roads can be classified into three groups: infrastructure characteristics, traffic characteristics and environmental conditions. Infrastructure characteristics are variables that can be controlled during the process of designing, modifying or maintaining roads, and these include the type of pavement, the state of conservation, and the geometric design. Vázquez et al. (Vázquez et al., 2018a) found that the dynamic stiffness and the macrotexture of cold in-place recycled pavement are more important conditioning factors in the generation of tyre/road noise at medium frequencies than for other conventional hot bituminous mixtures. They also evaluated the medium-term evolution of the surface features of urban pavements, such as the rolling noise and mean profile depth (MPD), and concluded that the MPD may be related to pavement ageing and hence to the evolution of the tyre/pavement noise (Vázquez et al., 2018b). Del Pizzo et al. (Del Pizzo et al., 2020) identified a positively correlated zone for low frequency emission and a negatively correlated region at higher frequencies, by analysing 10 road surfaces in terms of their CPX noise and texture levels. Licitra et al. carried out a study that demonstrated the importance of the type of tyre on the sound pressure level generated on low-noise road surfaces (Licitra et al., 2017).

Compared to factors associated with the infrastructure itself, the characteristics of the traffic (such as the flow, speed, vehicle typology, intrinsic characteristics or tyres) are more difficult to control. Rey Gozalo et al. (Rey Gozalo et al., 2019) observed a clear influence from the number and percentage of heavy vehicles on the uncertainty in noise maps, and found it hard to estimate the traffic speed in connection with noise mapping. The speed and vehicle typology are widely studied parameters that also condition the sound pressure level generated in tyre-road noise (Cho and Mun, 2008; Institute for Vehicle Technology, 2005).

Meteorological factors also affect both the propagation and the generation of sound energy. Standards for the assessment of environmental noise generally consider propagation in a broad way, but often do not clearly address issues related to noise generation (ISO 1996-1, 2016; ISO 1996-2, 2017; ISO 9613-1, 1993; ISO 9613-2, 1996). In this regard, ISO 11819-1, ISO 11819-2 and ISO/PAS

Fig. 2. Details of the road surface.

11819-4 (ISO/PAS 11819-4, 2013; ISO 11819-1, 1997; ISO 11819-2, 2017) cover the assessment of tyre/road noise and do not cover environmental noise emissions from road traffic. ISO 11819-1 standard (ISO 11819-1, 1997) indicates that sound levels should be corrected to a reference air temperature of 20 °C, but does not go so far as to propose a specific way to make this correction. ISO 11819-2 (ISO 11819-2, 2017) also establishes a reference air temperature of 20 °C and proposes a temperature correction of the sound level based on a coefficient given in ISO/TS 13471-1:2017 (ISO/TS 13471-1, 2017) that is only valid for two specific tires and not for a general circulation fleet. The value of this coefficient varies between −0.04 and −0.11 dBA/°C according to the type of surface and the speed of the vehicles. Values of between −0.05 and −0.10 were also proposed as standard for three different types of road surfaces, but these were independent of speed. The influence of air and pavement temperature on the generation of sound pressure levels has been explored by several researchers (Anfosso-LédéE and Pichaud, 2007; Bueno et al., 2011; Bühlmann et al., 2015; Bühlmann and Ziegler, 2011; Jabben, 2013; Kneib et al., 2016; Liao et al., 2015; Sandberg, 2015; Yuan et al., 2019) who based their studies on reference standards for the acoustic characterisation of pavements under controlled traffic conditions (ISO/PAS 11819-4, 2013; ISO 11819-2, 2017). Bühlmann and Van Blokland carried out a review where a great variety of results were shown for the relationship between tyre-road noise and temperature (Bühlmann and Van Blokland, 2014). To the best of the present authors' knowledge, there have been no studies in which the effect of temperature on the sound level of a road transport infrastructure has been measured under actual conditions of continuous vehicle flow. Jabben (Jabben, 2013) conducted a study in which the maximum sound pressure level, (LAmax), recorded for individual vehicles in a free flowing traffic was analysed. Prior analyses carried out under these standards have examined the effect of temperature on the sound pressure level generated as a function of variables such as pavement porosity and the types of tyres, vehicles and pavement. In these studies, the relationship between sound pressure level and air or pavement temperature has generally been determined by means of linear relationships, and the values found for the coefficients ranged between −0.03 and −0.11 dBA/°C. In some of these works, an analysis of this effect in the 1/3 octave bands has also been carried out, and the results have shown different behaviours depending on the frequency (Anfosso-LédéE and Pichaud, 2007; Bueno et al., 2011; Bühlmann and Ziegler, 2011). As a general rule, a higher linear relationship between temperature and sound level has been observed in frequency ranges of 31.5–630 Hz and 1.6–5 kHz, where the coefficients are mostly negative. However, the ISO/TS 13471-1:2017 standard (ISO/TS 13471-1, 2017) points out that the data collected in this way are not sufficiently consistent to allow for a frequency-dependent temperature correction, and therefore suggests that the same correction should be applied for all frequencies. In this regard, the recently proposed Common Noise Assessment Methods in Europe (CNOSSOS-EU) (European Directive, 2015) for strategic noise mapping uses a correction to the sound power emitted by road traffic to reflect the decrease with increasing air temperature. Based on a broadband analysis, CNOSSOS-EU proposes the application of a generic coefficient of −0.08 dB/°C for light vehicles (category 1) and −0.04 dB/°C for heavy vehicles (categories 2 and 3) for all asphalts, while for octave band analyses, these same correction coefficients are applied to all octave bands from 63 Hz to 8 kHz, without distinguishing between low, medium and high frequencies.

2. Methodology

2.1. Study area

On-site measurements were carried out on the N-521 road in Extremadura, Spain, in the section between the towns of Cáceres and Malpartida de Cáceres (Fig. 1). As discussed below, the point of measurement was chosen based on the characteristics of the road geometry, good pavement conditions, the proximity of an official speed camera and the average daily traffic (ADT). It was located 5 km from Malpartida de Cáceres, on a straight section of 3.4 km (plan view) with a horizontal cross section in the measurement area. There were no obstacles between the microphone and the road that could cause acoustic shielding effects (Montes González et al., 2020b; Van Blokland et al., 2014) and no reflective surfaces behind it that could produce sound reflections (Memoli et al., 2008; Montes González et al., 2020a) (Fig. 1).

The traffic flow in this section is monitored by the Ministry of Transport (Spanish National Government) using a traffic counter.

Based on the data recorded over the last ten years, the ADT on this stretch of road is 7658 vehicles, of which 7256 are light vehicles (95.1%) and 378 are heavy vehicles (4.9%). It can therefore be estimated that it has an annual flow that is close to the limit of three million vehicle passages established by the European Environmental Noise Directive (European Directive, 2002) at which it would be considered a major road. An estimated value of 600 vehicles per hour during the day could be expected based on the ADT.

This is a seven-year-old road surface that can be assumed to be a dense asphalt. Its wearing course is composed of 8 cm of bituminous concrete AC22S in the lower layer, and 3 cm of discontinuous bituminous mix BBTM 11B in the upper part (Ministry of Transport of Spain, 2015). The discontinuous bituminous mix BBTM 11B has a void content greater than 12% and a surface macrotexture greater than 1.5 mm (see Fig. 2). The parameters of percentage of voids and MPD were measured when the pavement was laid. These data were provided by the Ministry of Transport, Mobility and Urban Agenda. This surface corresponds to the NL01 class, in accordance with CNOSSOS-EU (European Directive, 2015). The area adjacent to the road was mainly grass, and could be considered acoustically absorbent (Fig. 1).

2.2. Measurement procedure

In order to analyse the effect of temperature on the noise generated under actual conditions of continuous vehicle flow, the study needed to be designed in such a way that the variables or conditions that could influence the measured sound level were taken into account throughout the experimental procedure.

The obvious first step was to consider the variability in the characteristics of the passing vehicles, their typology and the numbers of vehicles driving past the microphone within a given unit of time.

There is a wide range of types of vehicle, and the maintenance conditions for both the vehicles and the tyres also vary. In order to obtain a suitable average of their effects on the noise level, the measurement time was selected to ensure that at least 100 vehicles passed in front of the measurement point. Based on the official ADT, a measurement time of 10 min was selected.

The speed limit on the stretch of road under study was 100 km/h, and an official speed camera was located close to the measuring point (Fig. 1). Measurements at this point showed that the average speed of the vehicles was slightly lower than the speed limit, and that the majority of the vehicles were travelling at within ±5 km/h of the average speed. Maximum variations of about 1 dBA were estimated for light and heavy vehicles for variations in speed of ±5 km/h (Institute for Vehicle Technology, 2005). The variability in sound level associated with vehicle speed was averaged over a total number of passing vehicles that was equal to or greater than 100, in the same way as for the vehicle characteristics (ISO 11819-1, 1997).

The noise level generated by traffic will also depend on the category of the vehicle. The category and flow of vehicles were visually monitored for each lane of traffic, and four categories of vehicle were identified based on CNOSSOS-EU (European Directive, 2015), as follows: Category 1: light motor vehicles; Category 2: medium heavy vehicles; Category 3: heavy vehicles; Category 4: powered two-wheelers. The last of these had two subcategories: Category 4A: mopeds; Category 4A: motorcycles.

As indicated above, only about 5% of the traffic did not fall into the category of light vehicles, meaning that its effect on the variability in the different measurements of the equivalent continuous sound level may not be significant. However, its possible effect was evaluated in this study by using an equivalence factor between the different vehicle typologies and light vehicles, following approaches previously used in the scientific literature (Sandberg, 2003; U.S. Department of Transportation, 2015).

A microphone with a windshield was located 15 m from the centre of the road (Sandberg, 2003) and at a height of 1.5 m from the ground, in order to make *in situ* measurements, as shown in Fig. 1 (ISO 1996-2, 2017; Montes González et al., 2020c; RSG, 2018). The equivalent sound pressure level was recorded in the broadband ($L_{eq,A}$) and 1/3 octave bands (L_{Xeq}) using a class 1 sound level meter/analyser. Thirty-six 10-minute measurements were carried out in two campaigns on different days. The calibration of the sound level meter was verified before and after each series of measurements.

The relative humidity, air temperature, wind speed and pavement temperature were recorded at the beginning and end of each measurement. The relative humidity and air temperature were measured at a height of 1.5 m above the ground (Anfosso-LédéE and Pichaud, 2007; Bueno et al., 2011; Bühlmann and Ziegler, 2011; ISO 11819-2, 2017) using a thermo-hygrometer sensor with an accuracy of ±1%; this was placed in the shade to ensure that direct sunlight did not affect the measurement. The pavement temperature was measured using a thermal camera with a sensitivity of <0.045 °C (reading temperature range −20 to +120 °C) at a single position on the side of the road and across the nearest lane from the location of the sound level meter. The camera was placed at a height of 1.5 m with an angle of 45° with respect to the horizontal. Before and after each measurement, a thermal image of the traffic lane was taken on the tread. The roadway temperatures were extracted from the thermal images, and the average was calculated (Bueno et al., 2011).

2.3. Data processing

As explained previously, the deviations in sound level that are associated with differences in speed and vehicle characteristics could be counterbalanced through the use of an average sound pressure level recorded over a 10-minute period, during which the number of vehicles registered was at least 100 (ISO 11819-1, 1997; ISO 1996-2, 2017). A similar average value of the sound power generated per vehicle unit is expected for all of the measurements taken. However, the number of vehicles that pass by is not expected to be the same in each 10-minute period. This means that the equivalent continuous sound level recorded in each measurement period will be influenced by the total number of vehicles that have passed in front of the microphone during that period. To take this fact into account, it is necessary to normalise the results against a reference flow. An average value of 780 vehicles/hour was recorded on site, and the normalised sound pressure level L_N was obtained from Eq. (1):

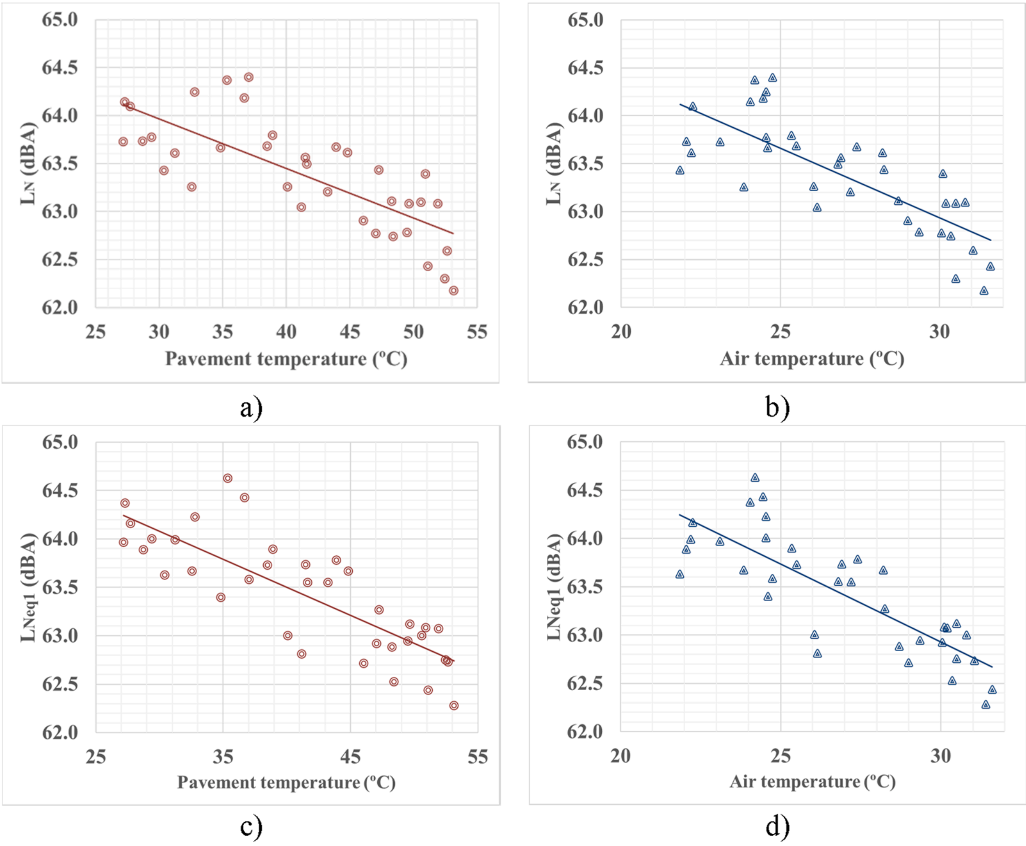

Fig. 3. Scatter diagrams and linear regression between the normalised sound levels (L_N and L_{Neq1}) and temperature.

$$L_N = L_0 - 10*log_{10}\left(\frac{V_m}{780}\right) + 10*log_{10}\left(\frac{t_m}{60}\right) \tag{1}$$

whereL_0 is the recorded sound pressure level; V_m is the total number of vehicles recorded in 10 min; and t_m is the measurement time in minutes.

Although the proportion of non-light vehicles recorded is less than 10% overall, the sound power emitted by these categories of vehicles can be considered different from that of category 1 vehicles (Cho and Mun, 2008; Institute for Vehicle Technology, 2005). To examine the possible influence of these vehicles on the results, a second normalisation was performed by considering the equivalence between the noise level emitted by category 1 vehicles and the rest of the vehicle categories, as shown in Eq. (2). The coefficients for vehicle categories 2, 3 and 4 in Eq. (2) were obtained by (Sandberg, 2003) based on a speed of 95 km/h for categories 1 and 4, and 90 km/h for categories 2 and 3.

$$V_{eq1} = V_{m1} + V_{m2}*3.83 + V_{m3}*6.31 + V_{m4} \tag{2}$$

where V_{eq1} is the equivalent total number of vehicles in category 1, and V_{mi} is the number of vehicles in category i (European Directive, 2015).

Again, the total equivalent number of vehicles in category 1 is not likely to be the same in each measurement, and another normalisation was therefore applied in order to analyse the relationship between the measured noise level and the temperature. The equivalent vehicle value V_{eq1} obtained from Eq. (2) was normalised based on the average total equivalent category 1 vehicle flow in the measurements (a total equivalent of 930 category 1 vehicles per hour). In a similar way as above, the category 1 equivalent normalised sound pressure level L_{Neq1} was derived from Eq. (3):

$$L_{Neq1} = L_0 - 10*log_{10}\left(\frac{V_{eq1}}{930}\right) + 10*log_{10}\left(\frac{t_m}{60}\right) \tag{3}$$

where L_0 is the recorded sound pressure level; V_{eq1} is the total number of equivalent vehicles in category 1; and t_m is the measurement time in minutes.

Table 1
Linear regression parameters between the sound pressure level and the air and pavement temperatures.

Independent variable	Dependent variable	β_i (dBA/°C)	*Standard error* β_i (dBA/°C)	Constant (dBA)	R^2	*Sig.*
T_P	L_N	−0.051	0.008	65.5	0.58	< 0.001
T_P	L_{Neq1}	−0.058	0.007	65.8	0.66	< 0.001
T_A	L_N	−0.146	0.020	67.3	0.60	< 0.001
T_A	L_{Neq1}	−0.161	0.020	67.8	0.66	< 0.001

Table 2
Regression and determination coefficients between the sound level and temperature reported in scientific literature.

Publication	$\beta_a \frac{dBA}{Â°C}$	$\beta_p dBA/Â°C$	R² *Air / pavement*	Method	Temperature range *Air / pavement*
Present researchL_N	−0.146	−0.051	0.58 / 0.60	Actual conditions of continuous vehicle flow	22–32 / 27–53
Present researchL_{Neq1}	−0.161	−0.058	0.66 / 0.66		
(Anfosso-LédéE and Pichaud, 2007)	−0.100	−0.060	0.92 / 0.86	CPB	0–30 / 0–50
(Bueno et al., 2011)	–	−0.060	- / n/d	CPX	- / 15–50
(Bühlmann and Ziegler, 2011)	−0.100 / −0.110[1]	–	0.8 / -	CPX	10–30 / -
(Liao et al., 2015)	−0.090	–	0.36 / -	OBSI	5–30 / -
(Yuan et al., 2019)	–	−0.086 / −0.081	- / n/d	SPB	- / 5–22

[1]Depending on the type of tyre used.

3. Results and discussion

3.1. Environmental and traffic variables

During the sound level measurements, the environmental variables of wind speed, relative humidity and air and pavement temperatures (T_A)and (T_P) were recorded. The wind speed was zero in most of the readings, and lower than 2 m/s even in the worst case. The relative humidity varied between 27% and 63%. The air temperature ranged from 22 °C to 32 °C, while the pavement temperature varied from 27 °C to 53 °C. A significant linear relationship between the air and pavement temperatures was found ($p < 0.001$), with a coefficient of determination R^2 of 0.93. This result is similar to values reported by other authors (Anfosso-LédéE and Pichaud, 2007; Rochat, 2009).

The average traffic flow recorded on site was 130 vehicles per measurement (780 vehicles/h). The distribution by vehicle category was as follows: category 1: 93.46%; category 2: 3.27%; category 3: 1.70%; and category 4: 1.57%.

3.2. Broadband analysis

As indicated in the methodology section, a study of the relationship between the sound level and temperature required a normalisation of the sound levels in order to take into account the differences in traffic flow during the measurement period. This normalisation was carried out in two phases. Firstly, given the low traffic flows measured for vehicle categories other than type 1, an average value for the sound power per vehicle using Eq. (1) was assumed. Then, despite the low proportions of vehicle categories 2, 3 and 4, the effect that their presence had on the relationship between noise level and temperature was considered of interest. Eqs. (2) and (3) were used to carry out this normalisation. The results for the relationships between the sound level and the pavement and air temperatures are shown in Fig. 3 and Table 1.

Fig. 3(a) shows the linear relationship between the equivalent normalised sound pressure level L_N and the pavement temperature T_P, which can explain 58% of the variability of the measured sound level with a probability of more than 99.9% (see Table 1). The coefficient of variation of the sound level with the temperature of the pavement ($\beta_P dBA/Â°C$) has a value of −0.051 ± 0.008 dBA/°C, representing a decrease in sound level with an increase in pavement temperature. The dependence of the sound level on the air temperature was then analysed, and Fig. 3(b) shows a linear relationship that explains 60% of the variability (p-value < 0.001). In this case, the coefficient of variation obtained for the air temperature ($\beta_A dBA/Â°C$) was $-0.146 \pm 0.020 dBA/Â°C$, which, in terms of its absolute value, is clearly higher than that obtained for the pavement temperature even considering its standard error. This increase in β is evidently related to the smaller range of variation in the air temperature with respect to the pavement temperature. Despite the close relationship between the two temperatures ($R^2 = 0.93$), these findings reflect the importance of the physical media in which the temperature is measured, in terms of determining the value of the coefficient of dependence of the sound level on this environmental variable.

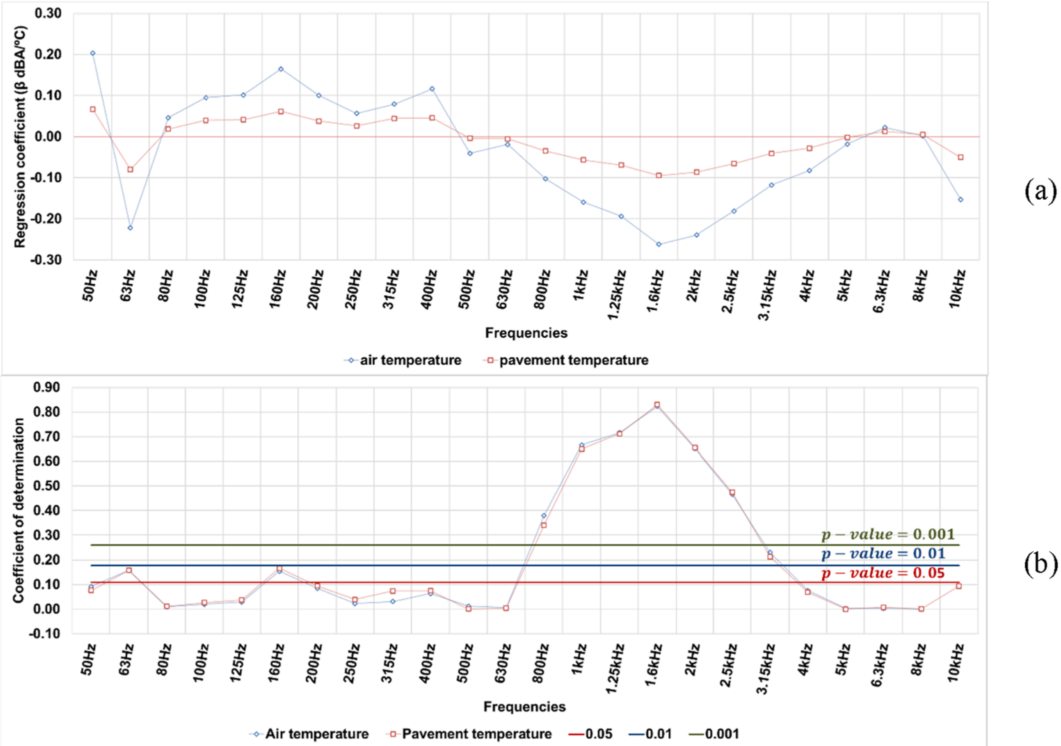

Fig. 4. Regression and determination coefficients for the linear relationship between the normalised sound pressure level (L_N) and the air and pavement temperatures in the 1/3 octave bands.

The effect of considering vehicles other than category 1 on the relationship between sound level and temperature was then analysed using Eqs. (2) and (3). The results for the relationship of the sound pressure level normalised to equivalent category 1 vehicles (L_{Neq1}) and the pavement temperature are shown in Fig. 3(c). The linear relationship between these variables explains 66% of the variability in the measured sound level as a function of pavement temperature, with a significance lower than 0.001; this represents an increase in the explanation of the variability of sound levels when all categories of vehicles were considered. The $\beta_P$coefficient is equal to $-0.058 \pm 0.007 dBA/\hat{A}°C$ in Fig. 3(c). A value of $\beta_A = -0.161 \pm 0.020 dBA/\hat{A}°C$ was found for the relationship between L_{Neq1} and T_A (Fig. 3(d)). This linear relationship can explain 66% of the variability in the sound level with air temperature, with a p-value < 0.001. Hence, when air temperature is considered, this second normalisation (Eqs. (2) and (3)) also provides an improvement in the explanation of the variability in the measured sound levels. Although the values of the slopes of the lines shown in Fig. 3 (c) and Fig. 3 (d) are slightly higher than those in Fig. 3 (a) and Fig. 3 (b) in absolute values, this increase is not significant considering the standard error of the slopes.

In summary, taking into consideration all of the vehicle categories improves the determination of noise emission levels as a function of either the pavement or the air temperature, even though the proportion of vehicles other than category 1 is low.

These results were then compared with those obtained in previous studies of pavements of the same type (Table 2) (Anfosso-LédéE and Pichaud, 2007; Bueno et al., 2011; Bühlmann and Ziegler, 2011; Liao et al., 2015; Yuan et al., 2019). In this respect, it must be taken into consideration that this is a seven-year-old dense mixture. Some studies used the air temperature to obtain the coefficient of variation in the sound pressure level with temperature (Bühlmann and Ziegler, 2011; Liao et al., 2015), while others derived the coefficient from the pavement temperature (Bueno et al., 2011; Yuan et al., 2019). Anfosso-Lédée and Pichaud (Anfosso-LédéE and Pichaud, 2007) determined the coefficients for both temperatures, in this case using the CPB method. They obtained a coefficient of variation in the sound level for a dense pavement of $-0.100 dBA/^{\circ}$C using the air temperature, and $-0.060 dBA/^{\circ}$C from the pavement temperature.

Of the researchers who examined only the air temperature, (Bühlmann and Ziegler, 2011) reported a coefficient of variation of -0.100or $-0.110 dBA/^{\circ}$C, depending on the type of tyre, using the CPX method, while Liao et al. (Liao et al., 2015) found a value of $-0.090 dBA/^{\circ}$C using the OBSI method.

Of the researchers who investigated only the pavement temperature, Bueno et al. (Bueno et al., 2011) obtained a coefficient of variation of $-0.060 dBA/^{\circ}$C from the CPX method. Yuan et al. (Yuan et al., 2019) conducted a study using the CPB method in which they considered three driving speeds (40, 60 and 80 km/h) and two different vehicles, and calculated coefficients of variation of $-0.086 dBA/^{\circ}$C, $-0.083 dBA/^{\circ}$C and $-0.081 dBA/^{\circ}$C for these three speeds, respectively.

For the air temperature, the results presented in this paper were above the range of variation reported in previous studies, which

Table 3
Linear regression parameters (slope, standard error of slope, R^2 and p-value of R^2) between the sound pressure level L_N in the 1/3 octave bands and the air and pavement temperatures.

Fr.	**50 Hz**	**63 Hz**	**80 Hz**	**100 Hz**	**125 Hz**	**160 Hz**	**200 Hz**	**250 Hz**
Low frequencies	Pavement temperature							
m	0.07	−0.08	0.02	0.04	0.04	0.06	0.04	0.03
$\hat{\sigma}_m$	0.04	0.03	0.03	0.04	0.04	0.02	0.02	0.02
R^2	0.08	0.16	0.01	0.03	0.04	0.17	0.09	0.04
Sig.	n.s.	< 0.05	n.s.	n.s.	n.s.	< 0.05	n.s.	n.s.
	Air temperature							
m	0.20	−0.22	0.05	0.09	0.10	0.16	0.10	0.06
$\hat{\sigma}_m$	0.11	0.09	0.08	0.11	0.10	0.07	0.06	0.06
R^2	0.09	0.16	0.01	0.02	0.03	0.15	0.08	0.02
Sig.	n.s.	< 0.05	n.s.	n.s.	n.s.	< 0.05	n.s.	n.s.

Fr.	**315 Hz**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1 kHz**	**1.25 kHz**	**1.6 kHz**	**2 kHz**
Mid-frequencies	Pavement temperature								
m	0.04	0.05	0.00	−0.01	−0.04	−0.06	−0.07	−0.09	−0.09
$\hat{\sigma}_m$	0.03	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01
R^2	0.07	0.08	0.00	0.00	0.34	0.65	0.71	0.83	0.66
Sig.	n.s.	n.s.	n.s.	n.s.	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Air temperature								
m	0.08	0.12	−0.04	−0.02	−0.10	−0.16	−0.19	−0.26	−0.24
$\hat{\sigma}_m$	0.08	0.08	0.06	0.04	0.02	0.02	0.02	0.02	0.03
R^2	0.03	0.06	0.01	0.01	0.38	0.67	0.72	0.82	0.65
Sig.	n.s.	n.s.	n.s.	n.s.	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Fr.	**2.5 kHz**	**3.15 kHz**	**4 kHz**	**5 kHz**	**6.3 kHz**	**8 kHz**	**10 kHz**
High frequencies	Pavement temperature						
m	−0.07	−0.04	−0.03	0.00	0.01	0.01	−0.05
$\hat{\sigma}_m$	0.01	0.01	0.02	0.02	0.02	0.02	0.03
R^2	0.47	0.21	0.07	0.00	0.01	0.00	0.09
Sig.	< 0.001	< 0.01	n.s.	n.s.	n.s.	n.s.	n.s.
	Air temperature						
m	−0.18	−0.12	−0.08	−0.02	0.02	0.00	−0.15
$\hat{\sigma}_m$	0.03	0.04	0.05	0.05	0.07	0.07	0.07
R^2	0.47	0.23	0.08	0.00	0.00	0.00	0.11
Sig.	< 0.001	< 0.01	n.s.	n.s.	n.s.	n.s.	< 0.05

were conducted using standardised test methods and under controlled conditions in terms of the vehicles and tyre-road surface. The results obtained in this study for the dependence of sound level on pavement temperature were within the range of variation of previous investigations (Table 2).

When the coefficients of variation for the sound level with temperature (β_i) reported in the scientific literature are compared, higher values were obtained when the air temperature was considered rather than the pavement temperature; this broadly corresponds to the results of the present study, although the values of the coefficients found in this paper were greater than those in the literature.

3.3. *Spectral analysis*

To provide a detailed analysis of the dependence of sound level on temperature, the broadband analysis was complemented by a study in the 1/3 octave bands in the range 50 Hz to 10 kHz. In the same way as for the broadband analysis, the sound pressure levels were normalised to a reference flow L_N (Eq. (1)) and to the equivalent flow of category 1 vehicles L_{Neq1}(Eqs. (2) and (3)). These calculations were carried out for both the air and pavement temperatures.

Fig. 4 and Table 3 show the results for the relationship between L_N and the air and pavement temperatures. In the case of Fig. 4 (b), considering that the number of data used in the regression is the same for the different frequencies analysed, the value of the coefficient of determination for which it was significant with a probability of 95%, 99% and 99.9% was obtained. Thus, the horizontal lines in Fig. 4 (b) indicate the p-values of 0.05, 0.01 and 0.001. At low frequencies, significant relationships were observed in the 63 Hz and 160 Hz third octave bands for both temperatures (p-value < 0.05), although with a low explanation of variability of between 15% and 17%. The slope at 63 Hz implies a decrease in sound level with increasing temperature (-0.08 ± 0.03 dB/°C for T_P and -0.22 ± 0.09 dB/°C for T_A), with similar behaviour to the broadband results. In contrast, the slope found in the 160 Hz band is positive (0.06 ± 0.02 dB/°C for T_P and 0.16 ± 0.07 dB/°C for T_A), indicating an increase in sound level with increasing temperature.

The next bands in which significant relationships were found corresponded to the range 800 Hz to 3.15 kHz. The relationship between sound pressure level and temperature in this band range is negative, and has a greater absolute value for air temperature than for pavement temperature, for the same reasons as identified in the broadband analysis. It was also observed that except for the 3.15 kHz band, the frequency bands showed correlations with a significance lower than 0.001, low standard errors of slopes, and high

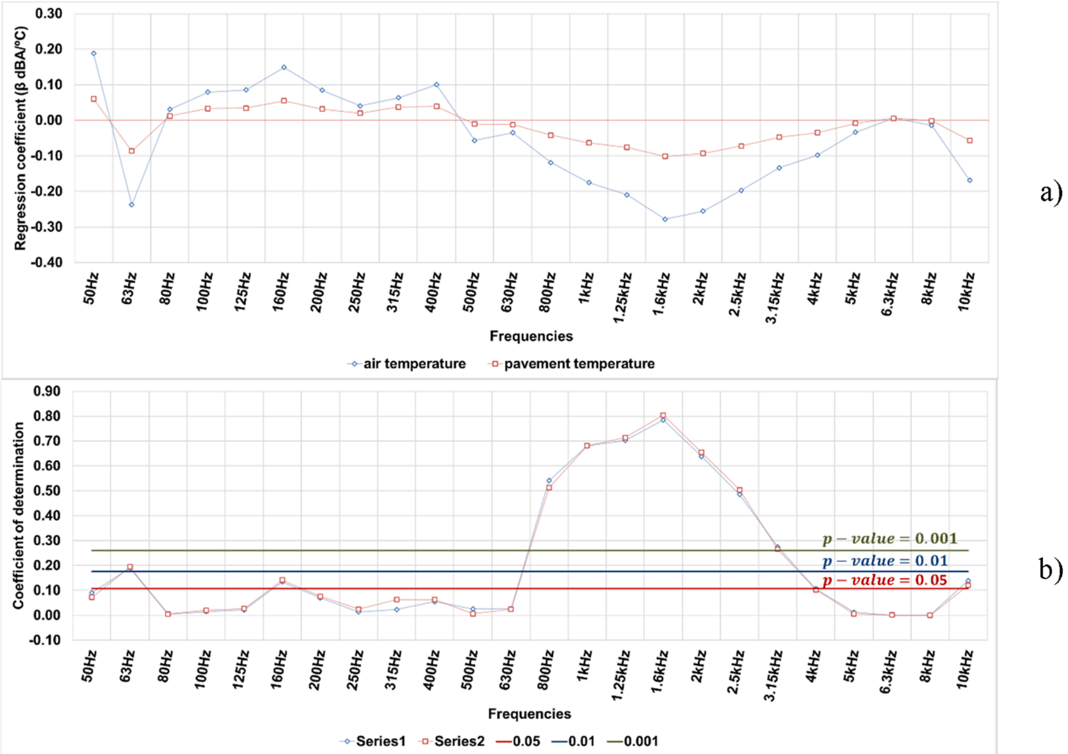

Fig. 5. Regression and determination coefficients for the linear relationship between the category 1 equivalent normalised sound pressure level (L_{Nequ1}) and the air and pavement temperatures in the 1/3 octave bands.

explanations of the variability in the sound level with temperature. The results in the third octave bands between 1 and 2 kHz are particularly remarkable, where the R^2 values varied between 0.65 and 0.83, indicating sound level variation coefficients ranging from -0.06 ± 0.01 to -0.09 ± 0.01 dB/°C for T_p and -0.16 ± 0.02 to -0.26 ± 0.02 dB/°C for T_A (Table 3). For the rest of the high frequency bands, significant relationships (p-value < 0.05) were only found in the 10 kHz band for T_p. The explanation of the variability in the sound level was also low (11%) and a standard error of about 50% of the slope value.

Fig. 5 and Table 4 present the results for the relationships between the L_{Neq1} values and the air and pavement temperatures. The horizontal lines in Fig. 5 (b) indicate the different levels of significance of the coefficient of determination, analogous to Fig. 4 (b). In general, these show similarities to those obtained for L_N (Fig. 4 and Table 3). At low frequencies, significant relationships with temperature were again found only for sound levels measured in the 63 and 160 Hz bands. The slope was negative in the first case ($\beta_P = -0.09 \pm 0.03 dB/\hat{A}°C$; $\beta_A = -0.24 \pm 0.08 dB/\hat{A}°C$), and positive in the second ($\beta_P = 0.06 \pm 0.02 dB/\hat{A}°C$; $\beta_A = 0.15 \pm 0.06 dB/\hat{A}°C$). However, while the significance in the 160 Hz band was still 95%, it improved to 99% in the 63 Hz band. The next frequency range in which a significant relationship with temperature was found appeared between 800 Hz and 3.15 kHz, with similar p-values to those found for the previous normalisation. However, the results for the 800 Hz band were noteworthy, as the variable L_{Neq1} could explain more than 50% of the variation in the sound level with temperature, while the figure for the variable L_N was lower than 40%. For the rest of the high-frequency bands, significant relationships (p-value < 0.05) were again only found in the 10 kHz band, although in this case they applied to both temperatures.

When the results are analysed and both normalisations are compared, it can be seen that the 1/3 octave bands of 63 and 800 Hz are the main ones at which the combined effects of the different vehicle categories are the strongest; that is, it can be said that the emission power in these bands behaves in a similar way to that indicated for the equivalences considered for category 1 (Sandberg, 2003).

From a comparison between the findings of this research and those in the literature, it can be observed that several authors (Anfosso-LédéE and Pichaud, 2007; Bueno et al., 2011; Bühlmann and Ziegler, 2011) have reported results with a similar trend for the range 800 to 3.15 kHz. The result for the 10 kHz band could not be compared with previous publications, as no analysis had been performed above 5 kHz (Anfosso-LédéE and Pichaud, 2007; Bueno et al., 2011; Bühlmann and Ziegler, 2011). Regarding the results in the low-frequency bands, it is worth highlighting one paper (Bühlmann and Ziegler, 2011) in which positive values were obtained for the coefficients of variation in the sound pressure level with temperature, although this result was discarded in the subsequent analysis. A. del Pizzo et al. (Del Pizzo et al., 2020), in their study of the dependence of pavement texture on road traffic noise using the CPX method, found a positive linear relationship between sound pressure level and megatexture at low frequencies and negative at high frequencies associated with macrotexture. This paper also indicated the relation between this behaviour and the different generation mechanisms that dominate the two regions: tyre vibrations for low frequency and aerodynamic mechanisms for high frequency. It

Table 4
Linear regression parameters (slope, standard error of slope, R^2 and p-value of R^2) between the category 1 equivalent normalised sound pressure level (L_{Nequ1}) in the 1/3 octave bands and the air and pavement temperatures.

Fr.	50 Hz	63 Hz	80 Hz	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz
Low frequencies	Pavement temperature							
m	0.06	−0.09	0.01	0.03	0.03	0.06	0.03	0.02
$\hat{\sigma}_m$	0.04	0.03	0.03	0.04	0.04	0.02	0.02	0.02
R^2	0.07	0.19	0.01	0.02	0.03	0.14	0.08	0.02
Sig.	n.s.	< 0.01	n.s.	n.s.	n.s.	< 0.05	n.s.	n.s.
	Air temperature							
m	0.19	−0.24	0.03	0.08	0.09	0.15	0.08	0.04
$\hat{\sigma}_m$	0.10	0.08	0.08	0.11	0.10	0.06	0.05	0.06
R^2	0.09	0.19	0.00	0.01	0.02	0.13	0.07	0.01
Sig.	n.s.	< 0.01	n.s.	n.s.	n.s.	< 0.05	n.s.	n.s.

Fr.	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1 kHz	1.25 kHz	1.6 kHz	2 kHz
Mid-frequencies	Pavement temperature								
m	0.04	0.04	−0.01	−0.01	−0.04	−0.06	−0.08	−0.10	−0.09
$\hat{\sigma}_m$	0.02	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01
R^2	0.06	0.06	0.01	0.02	0.51	0.68	0.71	0.80	0.65
Sig.	n.s.	n.s.	n.s.	n.s.	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Air temperature								
m	0.06	0.10	−0.06	−0.04	−0.12	−0.18	−0.21	−0.28	−0.26
$\hat{\sigma}_m$	0.07	0.07	0.06	0.04	0.02	0.02	0.02	0.02	0.03
R^2	0.02	0.05	0.03	0.03	0.54	0.68	0.70	0.78	0.64
Sig.	n.s.	n.s.	n.s.	n.s.	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Fr.	2.5 kHz	3.15 kHz	4 kHz	5 kHz	6.3 kHz	8 kHz	10 kHz
High frequencies	Pavement temperature						
m	−0.07	−0.05	−0.03	−0.01	0.01	0.00	−0.06
$\hat{\sigma}_m$	0.01	0.01	0.02	0.02	0.02	0.02	0.03
R^2	0.50	0.27	0.10	0.01	0.00	0.00	0.12
Sig.	< 0.001	< 0.01	n.s.	n.s.	n.s.	n.s.	< 0.05
	Air temperature						
m	−0.20	−0.13	−0.10	−0.03	0.01	−0.01	−0.17
$\hat{\sigma}_m$	0.03	0.04	0.05	0.05	0.07	0.07	0.07
R^2	0.49	0.27	0.11	0.01	0.00	0.00	0.14
Sig.	< 0.001	< 0.01	n.s.	n.s.	n.s.	n.s.	< 0.05

seems therefore that the low frequency emission range may require specific studies.

4. Conclusions

An experimental study of the relationship between the air and pavement temperatures and the road traffic noise levels on a primary road under actual conditions of continuous vehicle flow is presented in this manuscript. Several variables or circumstances that can influence the measured sound level were taken into account.

Some key findings can be drawn from the broadband results. When the temperature was taken at the road surface, the coefficients of variation in the sound level with temperature were similar to those published in the scientific literature under controlled conditions, following the reference standards. However, when the air temperature was considered, the coefficients of variation in sound level with temperature were higher than previously published results recorded under controlled conditions in dense pavements. Despite the high proportion of light vehicles in the mixed traffic on the road (over 92%), normalising to a flow of vehicles equivalent to category 1 was found to improve the explanation of the variability of sound level with temperature, regardless of the physical media in which the variable was measured.

Several conclusions could also be derived from the spectral analysis in the 1/3 octave bands. In the fundamental noise emission bands of road traffic, the trends in the dependence of sound level on temperature coincided with the published outcomes, resulting in a decrease of the sound level with increasing temperature. However, the values of the coefficients of variation depended on the physical media in which the temperature was measured. Thus, when the temperature of the pavement was measured, the slopes were similar to those published in the scientific literature, while when the air temperature was taken into account, the slopes were greater than those previously reported. Another finding of note is the positive value of the coefficient of variation in the sound level with temperature in the 160 Hz band, which implies an increase in the sound level with increasing environmental temperature; this effect has not previously been reported.

From a comparison of the spectral results with and without normalisation to category 1 equivalent vehicles, no appreciable effects relating to the type of normalisation were found in most frequency bands, in contrast to the results of the broadband analysis. However, noticeable improvements were observed in the 1/3 octave bands of 63 and 800 Hz and 3.15 kHz for the normalisation of vehicles equivalent to category 1.

The results found in this study for traffic noise, obtained on a road in actual conditions of use with dense asphalt and mixed and continuous flow of vehicles, are not necessarily transferable to other types of pavements or flows. The possibility of applying this type of study to the temperature corrections for strategic noise maps indicates the need for further research with methodologies that allow to measure the effect of temperature on the equivalent continuous sound level in other situations: other types of asphalt, other types of flows, other proportions of light and heavy vehicles, etc. In the other hand, the possible importance of the physical media in which the environmental temperature is measured in terms of assessing the correction factors for the effects of temperature on the sound level should be highlighted.

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.

Acknowledgements

This work was co-financed by Consejería de Educación y Empleo of Junta de Extremadura, the Extremadura Public Employment Service (SEXPE) and European Union (FSE) through grants to promote the hiring of research support personnel in the Autonomous Community of Extremadura (PAI20/40).

This project was co-financed by European Regional Development Fund (ERDF) and Junta de Extremadura (GR18107, IB18050 and GR18053).

This work was also supported by Consejería de Economía, Ciencia y Agenda Digital of Junta de Extremadura and European Regional Development Fund (ERDF) through grants for the financing of industrial research and experimental development projects (IDA-19-0022-3).

This work was also supported by Consejería de Economía, Ciencia y Agenda Digital of Junta de Extremadura, European Union and European Social Fund (ESF) through grants for the strengthening of R&D&I through the mobility of postdoctoral researchers (PO17014) and by Consejería de Economía, Ciencia y Agenda Digital of Junta de Extremadura through grants for attracting and returning research talent to R&D&I centres belonging to the Extremadura Science, Technology and Innovation System (TA18019), where University of Extremadura was the beneficiary entity in both cases.

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