Environmental Pollution

A comprehensive experimental study of the influence of temperature on urban road traffic noise under real-world conditions

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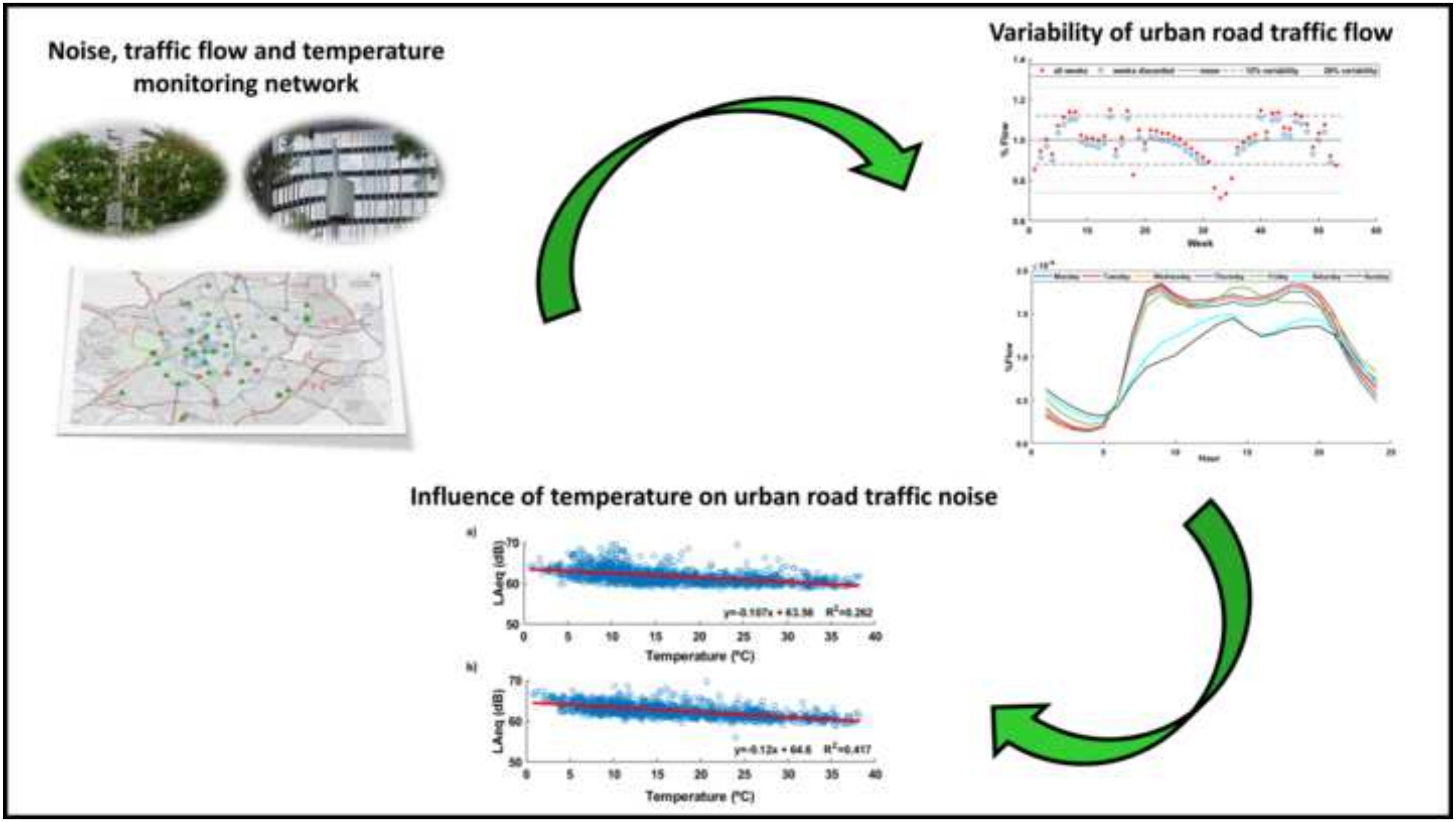
Corresponding Author:	David Montes González SPAIN
First Author:	Juan Miguel Barrigón Morillas
Order of Authors:	Juan Miguel Barrigón Morillas
	Guillermo Rey Gozalo
	David Montes González
	Manuel Sánchez-Fernández
	Alicia Bachiller León
Abstract:	The effect of road traffic noise in urban environments is an issue of social and scientific interest, due to its public health and economic impacts. Scientific literature showed a decrease in the level of tyre/road noise generated as temperature increases, but usually under standardised traffic conditions in non-urban environments. Based on a wide network for the hourly monitoring of road traffic flow, air temperature and noise levels across the city of Madrid (Spain), this work proposes and applies a new experimental methodology for studying the dependence of urban road traffic noise on temperature. This study was conducted under real-world traffic conditions involving a wide variability in urban configurations and in the type and state of preservation of vehicles, tires and pavements. From the analysis of data for a whole year, a time interval was identified (from Tuesday to Thursday and between 8 a.m. and 8 p.m.) in which the variability in road traffic flow for the whole city of Madrid was stable enough to allow for a linear regression study between temperature and noise levels from urban road traffic. The relationships found were highly significant ($p \leq 0.001$) for data from all the noise monitoring stations, with values of higher than 20% and up to 42% for the explanation of the variability in the measured noise levels by temperature at most of the measurement points. The values of the slope coefficients at the noise monitoring stations ranged from −0.036 to −0.125 dB/ºC, with an average value of −0.090 ± 0.011 dB/°C. These results are within the range of values reported in the scientific literature for experimental tests conducted under conditions of controlled or free-flowing traffic.
Suggested Reviewers:	Ulf Sandberg Swedish National Road and Transport Research Institute: Statens Vag och Transportforkningsinstitut ulf.sandberg@vti.se Researcher involved in environmental acoustics and cited in the manuscript
	Paulo Henrique Trombetta Zannin Federal University of Parana: Universidade Federal do Parana zannin@ufpr.br Researcher involved in environmental acoustics and cited in the manuscript
	Erik Bühlmann Grolimund + Partner AG erik.buehlmann@grolimund-partner.ch Researcher involved in environmental acoustics and cited in the manuscript
	Mario Mateus

	University of Coimbra: Universidade de Coimbra mario.mateus@adai.pt Researcher involved in environmental acoustics and cited in the manuscript
	Jan Jabben National Institute of Public Health and the Environment: Rijksinstituut voor Volksgezondheid en Milieu jan.jabben@rivm.nl Researcher involved in environmental acoustics and cited in the manuscript
	Julien Cesbron Gustave Eiffel University: Universite Gustave Eiffel julien.cesbron@ifsttar.fr Researcher involved in the field of road traffic noise
Response to Reviewers:	

HIGHLIGHTS

- A nominal range of ±1.0 dB was found for 95% of the chosen hours at 54 gauge stations
- A method was found to study the link of urban road traffic noise with temperature
- The relationships were highly significant in the 21 noise monitoring stations used
- An average coefficient of −0.09 ± 0.01 dB/ºC was obtained in the city of Madrid
- Advances were made in understanding the population's exposure to road traffic noise


Noise, traffic flow and temperature monitoring network
Variability of urban road traffic flow
Week
Hour
Influence of temperature on urban road traffic noise
LAeq (dB)
Temperature (ºC)
LAeq (dB)
Temperature (ºC)

A comprehensive experimental study of the influence of temperature on urban road traffic noise under real-world conditions

Juan Miguel Barrigón Morillas[a], Guillermo Rey Gozalo[a], David Montes González[a*], Manuel Sánchez-Fernández[a,b], Alicia Bachiller León[a]

[a] Laboratorio de Acústica (Lambda), Departamento de Física Aplicada, Instituto Universitario de Investigación para el Desarrollo Territorial Sostenible (INTERRA), Escuela Politécnica, Universidad de Extremadura, Avda. de la Universidad, s/n, 10003 Cáceres, España.

[b] INTERRA, NEXUS, Universidad de Extremadura, Avda. de la Universidad s/n, 10003 Cáceres, Spain.

*Corresponding author. E-mail address: davidmg@unex.es

ABSTRACT

The effect of road traffic noise in urban environments is an issue of social and scientific interest, due to its public health and economic impacts. Scientific literature showed a decrease in the level of tyre/road noise generated as temperature increases, but usually under standardised traffic conditions in non-urban environments. Based on a wide network for the hourly monitoring of road traffic flow, air temperature and noise levels across the city of Madrid (Spain), this work proposes and applies a new experimental methodology for studying the dependence of urban road traffic noise on temperature. This study was conducted under real-world traffic conditions involving a wide variability in urban configurations and in the type and state of preservation of vehicles, tires and pavements. From the analysis of data for a whole year, a time interval was identified (from Tuesday to Thursday and between 8 a.m. and 8 p.m.) in which the variability in road traffic flow for the whole city of Madrid was stable enough to allow for a linear regression study between temperature and noise levels from urban road traffic. The relationships found were highly significant ($p \leq 0.001$) for data from all the noise monitoring stations, with values of higher than 20% and up to 42% for the explanation of the variability in the measured noise levels by temperature at most of the measurement points. The values of the slope coefficients at the noise monitoring stations ranged from −0.036 to −0.125 dB/ºC, with an average value of −0.090 ± 0.011 dB/°C. These results are within the range of values reported in the scientific literature for experimental tests conducted under conditions of controlled or free-flowing traffic.

Keywords: road traffic noise; temperature correction; urban environments, long-term measurements; noise mapping.

1. INTRODUCTION

Most of the world's population is nowadays concentrated in urban areas, so studies have therefore been carried out to analyse the dependence of urban noise on the size of these cities and their transport infrastructures (Zhao et al., 2022) (Barrigón Morillas et al., 2021a). Relationships between different types of human health disorders or diseases and noise pollution have been reported in the scientific literature (Andersson et al., 2020) (Cantuaria et al., 2018) (Blume et al., 2022) (Hao et al., 2021). There are also associated economic impacts of environmental noise in cities due to an increase in demand for health care (Díaz et al., 2020) (Carmona et al., 2017) and the devaluation of housing located in affected areas (Beimer and Maennig, 2017) (Szczepańska et al., 2015).

In general terms, the predominant source of environmental noise in urban contexts is road traffic (EEA, 2020). Studies addressing the impacts of urban road traffic noise and other associated problems are frequent in the scientific literature (Khan et al., 2020) (Barrigón Morillas et al., 2021b) (Roswall et al., 2017) (Montes-González et al., 2019). The contributions of tyre/road, engine and aerodynamic noise to the overall level of road traffic noise can vary depending on several factors, such as the speed and type of the vehicles, the characteristics of the tyres and road surfaces, and other conditions (IVT, 2005) (Vázquez et al., 2018) (Sandberg, U, 2003). And since temperature variations may induce some changes in tyre stiffness and road surface porosity (Ling et al., 2021) (Heutschi et al., 2016), the mechanisms of rolling noise generation can be influenced by this variable. According to the Nord2000 method, rolling noise is predominant for light and heavy vehicles driving at speeds above 40 km/h and 70 km/h, respectively (Kragh, J., 2011). While the Swiss sonROAD18 model suggests an increased relevance of rolling noise already from 30 km/h for passenger cars (Heutschi et al., 2018).

The influence of temperature on the generation of tyre/road noise has been investigated in the scientific literature, mainly following the procedures established in standards such as ISO 11819-1, ISO 11819-2 and ISO 11819-4 (ISO 11819-1, 1997) (ISO 11819-2, 2017) (ISO/PAS 11819-4, 2013), under controlled traffic conditions on roads far from urban environments or in areas designated for this specific type of research. These studies have shown a decrease in noise level as the environmental temperature increases, with coefficients ranging between −0.03 and −0.11 dBA/ºC (Yuan et al., 2019) (Kneib et al., 2016) (Bueno et al., 2011) (Bühlmann et al., 2015) (Sandberg, U., 2015) (Bühlmann and Ziegler, 2011) (Anfosso-LédéE and Pichaud, 2007). A correction for temperature when testing with the CPX method (ISO 11819-2, 2017) is proposed in the ISO/TS 13471-1:2017 standard (ISO/TS 13471-1, 2017) that varies between −0.04 and −0.11 dBA/ºC, but this is only valid for two specific types of tyre, and is not applicable to a general circulation fleet. A recent study based on the CPX method proposed to combine the variables of air and road temperature in the correction approaches for temperature to ensure that important influences on tyre/road noise such as solar radiation and ambient air are taken into account (Bühlmann et al., 2021). There has also been research on the relationship between road traffic noise level and temperature under conditions of uncontrolled traffic flow (the type of vehicles and tyres used in the measurements is not decided, as neither is controlled their state of preservation). Jabben (Jabben, J., 2013) conducted a study under free-flowing traffic conditions in which the maximum sound pressure level (L_{Amax}) of each individual vehicle was recorded, as indicated in the ISO 11819-1 standard (ISO 11819-1, 1997). A negative increase in the coefficient of between −0.03 and −0.12 dBA/ºC was obtained for passenger vehicles and speeds of between 50 and 140 km/h, while a value of −0.04 dB/ºC was found for middleweight trucks in the range 70–100 km/h. Another study conducted under free flowing road traffic conditions was recently published by Sanchez-Fernández et al. (Sánchez-Fernández et al., 2021). Broadband results showed a variation in the road traffic noise level with a coefficient of −0.161 ± 0.020 dBA/◦C for air temperature and −0.058 ± 0.007 dBA/°C for pavement temperature, considering the equivalent sound level (L_{Aeq}) obtained from measurements with a minimum of 100 vehicles passing. In connection with this issue, the European Directive 996/2015 (COM, 2015) introduced the Common Noise Assessment Methods in Europe (CNOSSOS-EU) for the standardisation of strategic noise mapping calculations in European countries. The CNOSSOS-EU method makes a correction to the sound power emitted by road traffic to take into account the reduction in noise as air temperature rises, with coefficients of −0.08 dB/°C for light vehicles (category 1) and −0.04 dB/°C for heavy vehicles (categories 2 and 3). Kragh et al. (Kragh, J. et al., 2006) have also proposed a correction to the predicted noise level as a function of air temperature for the Nord2000 method (Nord2000, 2006), with a negative slope varying according to the type of road surface (dense asphalt concrete or stone mastic asphalt).

Studies of road traffic noise in urban environments have focused on methodological aspects such as spatial sampling (Quintero et al., 2021) (Barrigón Morillas et al., 2011) (Romeu et al., 2011), temporal sampling (Huang et al., 2021) (Montes González et al., 2020a) (Prieto Gajardo et al., 2016), the urban and architectural characteristics of the streets (Forssén et al., 2022) (Montes González et al., 2020b), the positions of the microphones (Zagubień and Wolniewicz, 2021) (Montes González et al., 2020c) (Mateus et al., 2015) and noise modelling (Aumond et al., 2021) (Rey Gozalo et al., 2019) (Nascimento et al., 2021). Also, the study of traffic noise can be improved with more details about traffic flow detection (Fredianelli et al., 2022). However, studies analysing the relationship between noise level from road traffic and air temperature under real traffic conditions in urban environments are rare. Only a previous study, estimating long-term noise level by short-term measurements, has found that average annual temperature was significantly related with road traffic noise at 31.5 Hz and 63 Hz, but not with $L_{Aeq,24h}$ (Wang et al., 2016). Conducting this type of research in real traffic conditions and in different urban scenarios would greatly expand the framework of study of this dependency. In contrast to previous research, situations with a wide variability in the range of aspects such as the vehicle brands and models and their state of maintenance, the tire types and their state of conservation, the urban settings and the types and age of road surfaces are considered simultaneously for the first time. Some urban traffic conditions may differ from those of non-urban transport infrastructures, as well as the speed range or the percentage of heavy vehicles, which are generally lower in cities. This work proposes and applies a methodology for studying the dependence of the noise level generated by urban road traffic on temperature, under real-world traffic conditions in a large city (Madrid, Spain). For achieve this objective, long-term measurements with an integration period of one hour were carried out at different points in the city to monitor the equivalent sound level (L_{Aeq}), traffic flow and temperature. To the best of the authors' knowledge, this is the first time that an experimental methodology has been proposed to achieve this objective.

2. MATERIALS AND METHODS

2.1. Study area and data collection

The study was carried out in the city of Madrid (Spain), that covers an area of 605.77 km² and an it has an official population of 3,334,730 people (INE, 2020), although the extended metropolitan area has 6,779,888 inhabitants. In addition to the main avenues and streets, the road transport infrastructure of Madrid consists of a series of ring roads for the redistribution of traffic flow, and the city is located at the centre of a radial transport system that connects it with the rest of Spain through six main highways and other secondary highways and roads (Fig. 1a). In terms of weather conditions, there is usually a large variation in both temperature (with average temperature oscillations ranging between 3 and 25ºC) and humidity, depending on the season (AEMET, 2021). Annual rainfall is around 400 mm, and the average annual wind speed is between 7 and 10 km/h (AEMET, 2021).

The city of Madrid has a wide network of devices for the continuous monitoring of different variables related to the management of urban traffic and environmental conditions in the city (Ayuntamiento de Madrid, 2021). In particular, there are 60 fixed stations throughout the city to measure the flow of road traffic, 31 stations for monitoring noise levels, and 22 stations for taking readings of meteorological variables and air quality (see Fig. 1b). A knowledge of the traffic flows, noise levels, levels of particulate matter and chemical pollutants, and weather conditions allows for predictions of the possible effects on citizens. Fig. 1b shows the distribution of the noise (green), temperature (red) and traffic flow (blue) measurement points in Madrid.

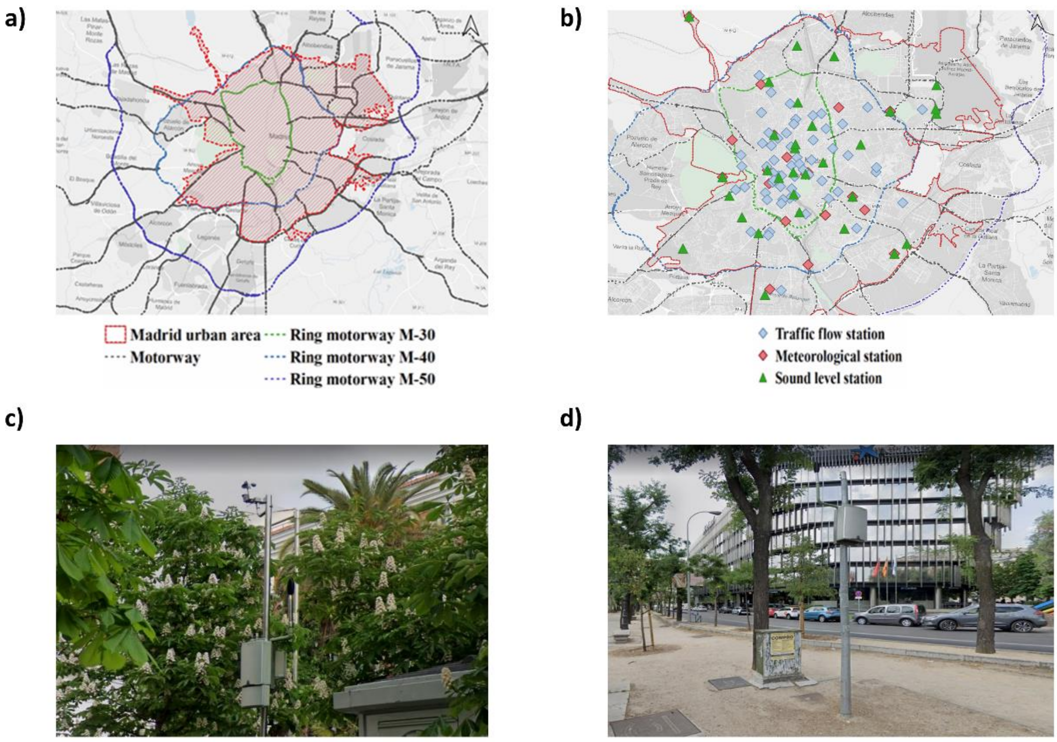


Fig. 1. (a) Overview of the road transport infrastructure of Madrid; (b) distributions of the noise, temperature and traffic flow measurement points in the study area; (c, d) locations of some microphones (from Google Street View)

When carrying out this study, all the data from the year 2019 collected from the networks for measuring vehicle flow, noise levels and meteorological variables were processed as described below.

2.2. Measurement procedure

The noise level measurement network consists of 31 stations located throughout the city (Fig. 1b). *In situ* measurements of the equivalent sound level (L_{Aeq}) were carried out using a logging period of 1 hour. Class 1 measuring stations (IEC 61672-1, 2013) were used, whose microphones were placed in the vicinity of traffic lanes and at heights of approximately 4 to 6 metres above the ground, trying to avoid reflections on nearby surfaces (ISO 1996-2, 2017) (Montes Gonzalez et al., 2018). Fig.1c and Fig.1d show the locations of microphones at some of the measurement points.

In view of the objective of this work, also hourly monitored data of vehicle flow (60 stations) and temperature (22 stations) were used (Fig. 1b). Vehicle flow data were used in order to determine the flow variability and to identify whether certain time intervals existed in which vehicle flow could be considered stable enough to obtain a theoretical maximum range of variability of noise associated to traffic variability. For this study a range of ±1.0 dB was considered. This theoretical range implies a variation of ±26% in traffic flow ($a = 1.26$ in Eq.(1)). Since the variability in the noise level is reduced if time periods of longer than one hour or the median value for the different stations are employed, a more restrictive range was estimated to be adequate in these cases. To this end, the range of ± 0.5 dB was considered. That implied a theoretical variation of ± 12 % in traffic flow ($a = 1.12$ in Eq.(1)).

$$Lw' = Lw + 10\log(a) \qquad \text{Eq. (1)}$$

where $w' = a \cdot w$

Some criteria were applied to discard measuring stations and anomalous data. When the main sound source in the noise monitoring station environment was not road traffic noise, it was not considered. It was discarded that a station should be discarded from the analysis if the data loss exceeded 10% of the hours. Concerning the presence of anomalies in the sound profiles, it was considered that, in cases where they occupied less than 10% of the measurement time, this time period would be eliminated from the analysis; if they exceeded 10%, the station would be discarded. Logically, also all sound events that varied by more than 10 dB from the average were excluded.

2.3. Statistical Analyses

A linear regression analysis was performed to analyse the relationship between $L_{Aeq,1h}$ (dB) and temperature (ºC) at each measurement station. The coefficient of determination (R^2) and the standard error of the coefficients were also calculated. The *F*-test was used to determine the significance of the relationship between both variables. The overall average slope and its 95% confidence interval were determined from the slope values obtained for each monitoring station. The standard deviation and the *t* student distribution were used for the calculation of the confidence interval because the number of monitoring stations selected was 21. Matlab R2021b was used for the above analyses.

3. RESULTS AND DISCUSSION

3.1. Analysis of vehicle flow stability

The aim of this section is to identify whether there are time periods in which the flow of road traffic in the city has a high enough value and sufficient stability to allow the effect of traffic flow on the variability in sound levels to be delimited. To achieve the highest possible temporal accuracy, the same interval of integration of the recording devices (one hour) was used as the basis for the flow analysis, although the usefulness of other time intervals of longer duration could also be explored. Although the noise pollution monitoring network points were located at different points from those of the flow gauging network, it is logical to assume that if such a stable time period existed for all or most of the traffic flow gauging stations, it could be considered valid for the whole city. During this period, as long as the predominant source of noise was road traffic, the variability in the sound levels should be explained by the variation in temperature in a statistically significant way.

3.1.1. Preliminary analysis

First, graphical analyses of the annual evolution of the flow were carried out based on time intervals of hours and days, as can be seen in the example of a station shown in Fig. a of Supplementary Material. From these graphical analyses of all the stations, it was observed that the data from six stations had total or partial absences or anomalies in the measurements, and these were therefore discarded from the study. At the remaining 54 stations, the average hourly flow for all stations (54·8760 one-hour slots) over 2019 was 1655 veh/h, with a minimum value of 259 veh/h at one station. From an analysis of these stations, it was possible to observe the expected weekly variation in the road traffic, with daily variations, reductions at weekends, and a decrease in flow around the summer holiday period. This graphical analysis also allowed some temporary periods to be detected in which there was an unexpected drop in the flow values at most of the stations. This decrease seemed to be associated with weekly periods and therefore a detailed study of the weekly flow has been carried out in the following section.

3.1.2. Weekly flow analysis

When the preliminary analysis was complete, a study of the variability in the average weekly vehicle flow was carried out. For this, the data from the 54 correctly operating flow stations were used. Logically, each station had vehicle flow values that were not comparable between them, so it was necessary to normalise the flows. To this end, the ratio of the vehicle flow for each week with respect to the annual average value of the weeks was calculated for each flow gauging station. In this way, the data from all the stations could be compared and used together. These ratios were then averaged over 54 stations, giving a single ratio for each of week of the year and for the whole city of Madrid. A graphical representation of the results obtained for the averaged ratio of normalised road traffic flow from all the 54 stations for each week of the year is shown in Fig. b of Supplementary Material with red star markers.

Based on these values, a sequential analysis was carried out of the weeks in which the ratio of vehicle flow exceeded the 12% variability range with respect to the annual mean. In each phase, those weeks with flows exceeding this range of variability were eliminated and the mean was recalculated. As a result of this process, data for all the weeks corresponding to the month of August and all those which had two or more bank holidays in the city of Madrid in 2019 were finally discarded. All the remaining weeks (a total of 44) had a ratio of the vehicle flow within the range of 12% with respect to the average of those weeks. This implies that the expected variability associated with traffic at weekly levels is ±0.5 dB. The results are shown in Fig. b of Supplementary Material with blue circle markers.

3.1.3 Analysis of the stability period

For all flow gauging stations, using data from the weeks that met the stability criterion set out above, an analysis was made of the evolution of the hourly flow, for each day of the week. The aim was to see if there was any time period during the year in which the variability of the flow, using the minimum interval of the logging network (one hour), could meet the stability criterion of 26%. For this purpose, the flow for each hour of the year at each station (365·24 = 8760 hours) was normalised with respect to the annual flow, and these data were then averaged for each day of the week (Monday to Sunday), resulting in 168 values for each station. Finally, the hourly results for all 54 flow measurement stations were averaged. The results of this analysis are shown in Fig. 2.

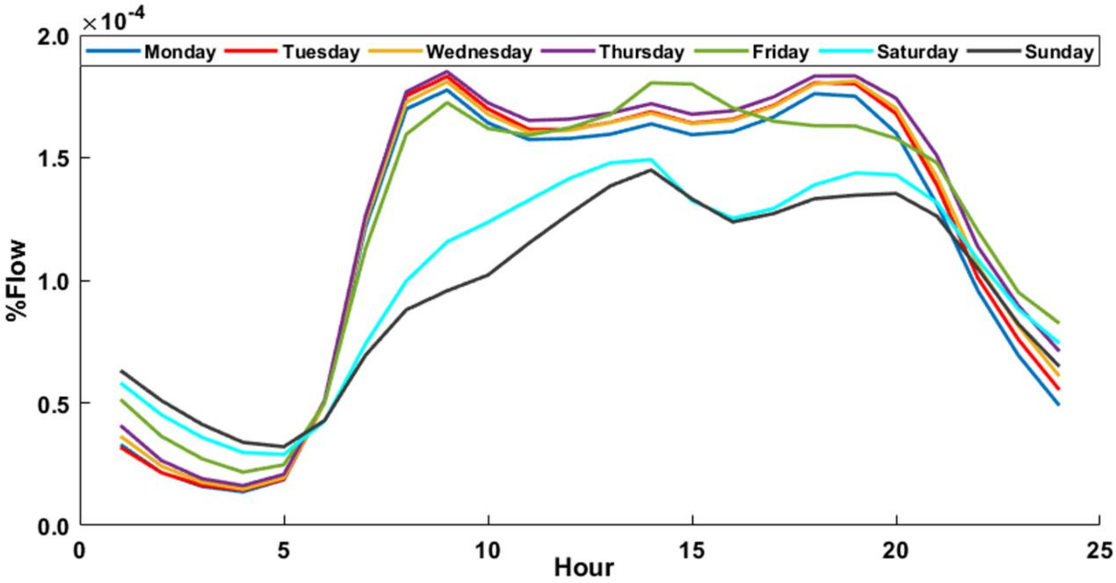


Fig. 2. Average ratio of normalised road traffic flow from all stations, for each day of the week

Fig. 2 shows that Saturdays and Sundays had notable differences in flow compared to working days. Although a certain stability can be observed for all weekdays, on closer inspection, Fridays show a different time structure. It can also be noted that the greatest stability and similarity in behaviour occurs from Monday to Thursday, in the period between 8 a.m. and 8 p.m., where Mondays have a slightly lower flow values than the other three days. Based on these preliminary results for weekly traffic flow, it can be concluded that there seems to be an enough stability of flows in the daily interval from Tuesday to Thursday and during the hourly period from 8 a.m. to 8 p.m (36 hours). This potential stability was then analysed further.

Therefore, in order to analyse this preliminary conclusion in detail, the ratio of hours between Tuesday and Thursday and during the period 8 a.m. to 8 p.m. with a flow variation of 26% with respect to the annual average (1560 hours) was calculated for each of the 54 gauging stations. The mean ratio of hours was then determined for all the stations. The results indicated that on average, more than 95% of the hourly time slots

(1482 of 1560 hours) met the 26% requirement considering all stations. And individually, more than 72% of the stations (39 stations) have more than 95% of the hours (1482 of 1560 hours) verifying the requirement for 26% flow variability. The gauging station with the lowest ratio in this range had 77% of the hours (1201 hours) verifying this requirement. In conclusion, taking into account the hour as the base time interval of calculation, the fact that there was a time interval (from Tuesday to Thursday and from 8 a.m. to 8 p.m.) in which the variability of the flow is less than 26% of the average flow for more than 95% of the hours, corresponding to 54 traffic gauging stations in a large city such as Madrid, can be considered an important result that allows for a linear regression study between environmental temperature and the noise levels measured in this time interval. The avenues and streets of Madrid where the monitoring stations were located belonged to urban roads where the speed limit in 2019 was 50 km/h.

3.2. Analysis of the annual variability in temperature

The temperature measurement network is composed of 22 stations, which are generally placed at different locations from those for measuring sound levels. Given this lack of coincidence between the measuring stations for both variables of interest, in order to carry out a study of the dependence of the sound level on temperature, a prior study of the temperature data measured at the different stations was carried out in order to verify their correct functioning and to check that similar trends were seen at all points. The average value for all stations could then be used for the linear regression analysis.

This preliminary graphical analysis of all stations showed some anomalies. In particular, one of the stations had a significant lack of data, and was therefore discarded from the analysis. It was also observed that there were occasional data losses at a relevant proportion of the stations (19 stations). An example is given in Fig. c of Supplementary

Material. These partial data were discarded, while the rest of the data at these stations were retained.

Once the data were verified, an analysis of the annual variability was carried out and similar trends were found for all stations. Fig. d of Supplementary Material shows the average temperature at the 21 monitoring stations for each day of the year, as well as the values of the maximum and minimum temperatures measured in the temperature network. Given the evolution of the mean, maximum and minimum temperature values throughout the year (Fig. d of Supplementary Material), it can be concluded that the structure of the annual variation is similar in the different measuring stations. Therefore, it was considered that the mean temperature, taken from the data from the 21 temperature measurement stations spread throughout the city, can be considered representative of the hourly variation at all of the sound measurement points.

3.3. Analysis of the dependence of road traffic noise level on temperature

As a result of the study of the temporal variability in road traffic flow over a large urban area, based on data from 54 traffic gauging stations, a time interval was found in which more than 95% of the hourly time slots deviated less than 26% from the average flow. If the main source of sound at these noise level measurement points is road traffic, this average variability in flow would be equivalent to an average variability in noise levels of 1 dBA. Consequently, an analysis of the noise pollution measurement network should be carried out to detect those stations where other noise sources may be predominant or where, for different reasons, there may be a lack of data or a significant presence of anomalous events. This was done by means of two simultaneous procedures: the location of each station was examined in order to estimate the foreseeable sources of noise in the area; and a graphical representation of the annual variability was created in order to determine the variability in noise levels at each station and to detect possible absences of data, alterations in their usual operation or the presence and importance of anomalous noise events (Fig. e of Supplementary Material). Since the distances between the nearest street (centre of the traffic lines) and the measurement microphone in range from 10 m to 35 m for the measurement stations used in this study, the variation of sound absorption as a function of weather conditions is not considered in the study (ISO 1996-2; IEC 61672-1:2013).

The previously described criteria were considered for discarding measurement stations and anomalous data. From the analysis of the locations of these stations, it was concluded that road traffic was not the main source of noise at three of them: stations 3, 18 and 26. Station 3 was located in a square with restricted traffic and significant commercial activity, whereas station 18 was situated in a large green area, and station 26 was near a set of suburban train tracks with a significant flow of rail traffic. From an examination of the annual sound profiles, anomalous events and data loss were found at all the 31 stations, randomly throughout the year, both in a punctual manner and in certain longer periods of time. As the data loss exceeded 10% of the 8760 hours (365·24) in the stations 11, 12, 16 and 28, they were discarded from the analysis. The stations 14, 15 and 17 were eliminated because the anomalous periods exceeded 10% of the measurement time. The anomalous periods in the sound profiles that occupied less than 10% were discarded from the analysis in stations 1, 4, 5, 20 and 24. As an example, Fig. f is included in the Supplementary Material that shows the annual sound profile for station 5, with an integration period of one hour. In this figure, it can be seen that around hours 4,000 and 6,800, there were continuous sound levels which exceed the base period (day (7:00-19:00), evening (19:00-23:00) and night (23:00-07:00)) value by more than 10 and 20 dB, respectively. Logically, also all sound events that varied by more than 10 dB from the average were excluded. Finally, 21 of the 31 stations that comprise the noise pollution measurement network were used for this study of the relationship between noise levels and environmental temperature (Fig. e of Supplementary Material).

Table 1 shows the values of the different parameters of the regression analysis between road traffic noise levels and temperature in the areas of Madrid where the noise monitoring stations were located. The values of the slope (with standard error), intercept coefficient, coefficient of determination (R^2), significance level and number of data (N) are given. As an example of the analysis performed to obtain the results shown in Table 1, Fig. 3 shows the measured values of the hourly equivalent sound level over one year with respect to temperature at two monitoring stations in Madrid.

Table 1. Parameters used in the regression analysis between road traffic noise levels ($L_{Aeq,1h}$) and temperature in the different areas of Madrid (from Tuesday to Thursday and from 8 a.m. to 8 p.m.)

Nº	**Station name**	**Slope (Std. Error)**	**Intercept coefficient**	R^2	**Sig.**	**N**
1	Paseo de Recoletos	−0.069 (0.004)	69.2	0.23	≤ 0.001	1246
2	Carlos V	−0.059 (0.004)	71.1	0.15	≤ 0.001	1515
4	Plaza de España	−0.104 (0.005)	66.4	0.24	≤ 0.001	1152
5	Barrio del Pilar	−0.055 (0.005)	62.4	0.08	≤ 0.001	1507
6	Gregorio Marañón	−0.080 (0.002)	73.6	0.42	≤ 0.001	1482
7	Escuelas Aguirres	−0.073 (0.003)	68.5	0.24	≤ 0.001	1478
8	Cuatro Caminos	−0.092 (0.004)	67.8	0.23	≤ 0.001	1452
9	Ramón y Cajal	−0.098 (0.004)	70.8	0.28	≤ 0.001	1499
10	Manuel Becerra	−0.036 (0.005)	65.1	0.04	≤ 0.001	1515
13	Arturo Soria	−0.125 (0.004)	64.4	0.36	≤ 0.001	1497
19	Santa Eugenia	−0.084 (0.004)	68.6	0.26	≤ 0.001	1520
20	Embajada	−0.107 (0.005)	63.6	0.26	≤ 0.001	1530
21	Barajas Pueblo	−0.120 (0.004)	64.6	0.42	≤ 0.001	1478
22	Cuatro vientos	−0.113 (0.004)	70.3	0.39	≤ 0.001	1486
23	El Pardo	−0.063 (0.005)	59.0	0.08	≤ 0.001	1505
24	Campo de las Naciones	−0.091 (0.005)	62.6	0.20	≤ 0.001	1473
25	Sanchinarro	−0.116 (0.005)	65.5	0.30	≤ 0.001	1451
27	Castellana	−0.096 (0.003)	65.3	0.37	≤ 0.001	1512

29	Ensanche de Vallecas	−0.123 (0.004)	63.4	0.38	≤ 0.001	1518
30	Urb. Emabajada II	−0.102 (0.005)	59.0	0.21	≤ 0.001	1529
31	Tres Olivos	−0.080 (0.005)	60.1	0.16	≤ 0.001	1519

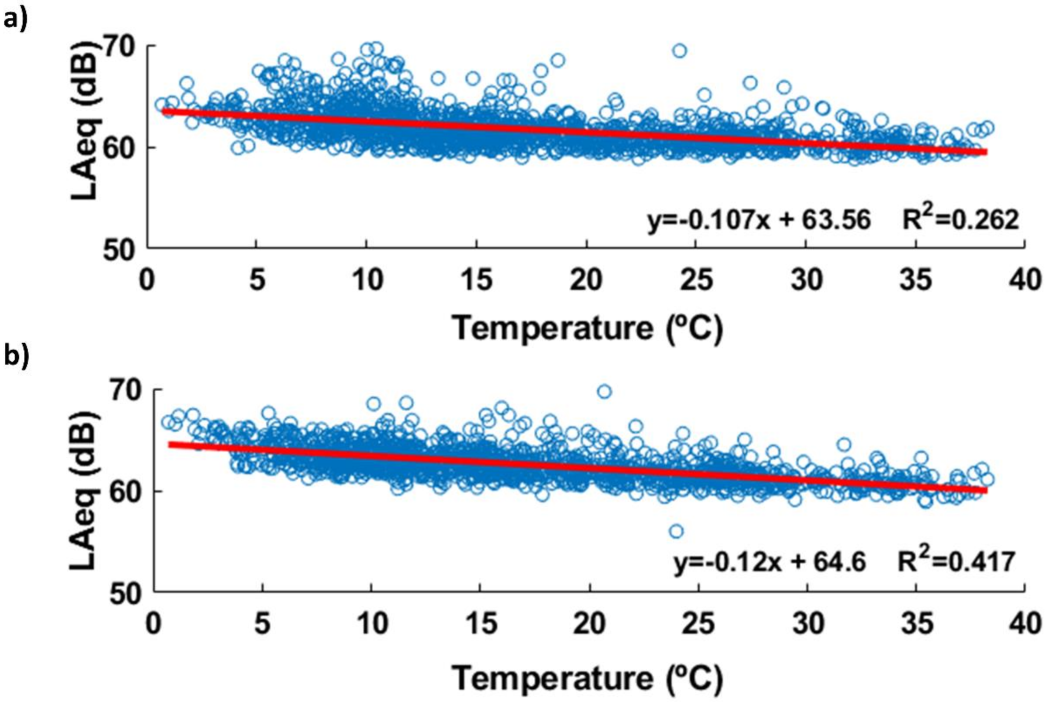


Fig. 3. Values of L_{Aeq} measured every hour over a period of one year with respect to temperature at (a) station 20; (b) station 21

The relationships shown in Table 1 between urban road traffic noise levels and temperature were highly significant ($p \leq 0.001$) for all the monitoring stations located in Madrid. The values for the explanation of the variability in the measured noise levels by temperature were higher than 20% at most measurement points, and values of 42% were reached at some of them. These results can be considered noteworthy because they indicate that a significant ratio of the variability in urban road traffic noise can be predicted based only on the average temperature when the traffic flow is stable. The relationships obtained are independent of the time period considered in the study and are valid for day-time period or a night-time period, for a working day or a public holiday, given the nature of the physical mechanisms involved. Values of between 4% and 8% for the explanation of variability were obtained at three of the monitoring stations, and these could be associated with the presence of noise sources other than urban road traffic in their environments. All the results were obtained by applying a relatively unrestrictive criterion of eliminating anomalous sound events when the sound level varied by more than 10 dB with respect to the annual average for each station. Since the equivalent sound level recorded over one hour at a given point does not show much variability when the main sound source is road traffic (for a stable vehicle flow), other more restrictive criteria for the elimination of anomalous sound events could be applied meaning that higher values for the explanation of the variability in the noise level with temperature would be obtained at all measurement stations, with the same sign for the slope. A previous study conducted in Taichung (Taiwan) did not find a significant relationship between average annual road traffic noise ($L_{Aeq,24h}$) and temperature, although a significant negative relationship between average annual temperature and traffic noise in the 31.5 Hz and 63 Hz octave bands was reported (Wang et al., 2016). These results are probably related to the use of a 24-hour noise indicator and the fact that road traffic flow in cities usually decreases considerably during the night and is not the main source of noise during this period.

It can also be noted from Table 1 that all slope coefficients are negative, indicating a negative dependence of the road traffic noise level on temperature. The slope coefficient values obtained at the 21 noise monitoring stations range from −0.036 to −0.125 dB/ºC. These results are within the range of values reported in the scientific literature (Yuan et al., 2019) (Kneib et al., 2016) (Bueno et al., 2011) (Bühlmann et al., 2015) (Sandberg, U., 2015) (Bühlmann and Ziegler, 2011) (Anfosso-LédéE and Pichaud, 2007) (Bühlmann et al., 2021) (Sánchez-Fernández et al., 2021) (Jabben, J., 2013). Different results have been reported for the speed dependency of temperature effects in the literature (Bühlmann et al., 2015). The results presented for tyre/road noise from tests undertaken only under controlled conditions differ in terms of whether the coefficient of variation of sound level with temperature decreases or increases as vehicle speed rises (Bühlmann et al., 2015). On the other hand, the results obtained for road traffic in free flowing traffic conditions show higher temperature effects at higher speeds (Jabben, J., 2013). Since the scientific literature shows highly significant relationships between air and pavement temperature with high values of the coefficient of determination (Anfosso-LédéE and Pichaud, 2007) (Sánchez-Fernández et al., 2021), similar results could probably be achieved in the case that pavement temperature could have been monitored. If it is considered that the general speed limit established for urban environments in Madrid was 50 km/h on the dates when the measurements were taken, the values obtained at many of the monitoring stations (see Table 1) in Madrid were higher than those previously reported in the scientific literature under free traffic flow conditions at this speed (Jabben, J., 2013), and are more similar to those reported for controlled traffic conditions (Bühlmann et al., 2015) (Bueno et al., 2011).

In the case of the calculation methods for strategic noise maps, the CNOSSOS-EU method (COM, 2015) proposes a correction of −0.08 dB/°C for light vehicles and −0.04 dB/°C for heavy vehicles, while the Nord2000 method (Kragh, J. et al., 2006) suggests coefficients of −0.1 dB/ºC and −0.062 dB/ºC for dense asphalt concrete and stone mastic asphalt, respectively. No dependence on vehicle speed was established. When the values of the slope coefficients shown in Table 1 for all noise monitoring stations in Madrid are averaged, a value of −0.090 ± 0.011 dB/ºC (95% confidence interval) is found, which would be within the range provided by both the CNOSSOS-EU method (COM, 2015) for light vehicles and the Nord2000 method (Kragh, J. et al., 2006).

4. CONCLUSIONS

This experimental research proposes a novel methodology for studying the dependence on temperature of the noise level generated by urban road traffic under real-world traffic conditions. Highly significant ($p \leq 0.001$) relationships were found between urban road traffic noise levels and temperature in the period of stable traffic flow (from Tuesday to Thursday and from 8 a.m. to 8 p.m.) for all the noise monitoring stations located in the city of Madrid. The explanation of the variability of measured noise levels by temperature was over 20% at most of the measurement points, and values of up to 42% were reached at some of them. The values of the slope coefficients obtained at the noise monitoring stations ranged from −0.04 to −0.13 dB/ºC. When the values of the slope coefficients were averaged for all noise monitoring stations in order to compare them with the corrections proposed for strategic noise mapping, it was found a value of −0.090 ± 0.011 dB/ºC (95% confidence interval).

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Declaration of interests

☒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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

CRediT author statement

Juan Miguel Barrigón Morillas: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Project administration, Funding acquisition. **Guillermo Rey-Gozalo**: Software, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Funding acquisition. **David Montes González**: Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Manuel Sánchez-Fernández**: Investigation, Writing - Review & Editing. **Alicia Bachiller León**: Software, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization.