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RESEARCH ARTICLE

Drastic mobility restrictions during SARS-CoV-2 pandemic: an opportunity to learn about constraints on the way to a pollution-free city

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Abstract

Road traffic is one of the main sources of pollution in modern cities. If there is a desire to move towards healthier cities, it may be necessary to modify the current model of mobility. The SARS-CoV-2 pandemic, together with the measures applied by most governments in the world to control the mobility of citizens, offered a unique opportunity to assess the changes in pollution levels after a drastic reduction in road traffic. In this study, air and noise pollution levels and road traffic flow were analyzed in the city of Cáceres, Spain, before and during the state of emergency imposed by the Spanish government. The values obtained were compared with the quality limits established by both the Spanish government and the World Health Organization (WHO). A traffic noise prediction model has been employed to evaluate the acoustic impact resulting from the reduction in traffic flow. As a result of this study, it was found that air pollution was indeed reduced due to the mobility restrictions imposed to control the pandemic, but that the WHO's recommendations for the values of the day-evening-night noise indicator (L_{den}) and the night-time noise indicator (L_n) for road traffic noise, which should not be exceeded, were not met. These findings highlight the need to review current urban mobility models if the WHO's recommendations are to be reached with regard to reducing the effects of exposure of the population to urban noise.

Keywords SARS-CoV-2 pandemic · Noise and air pollution · Traffic flow · Lockdown · Action plans

Introduction

There are many articles that have studied the problems associated with road traffic, in terms of both the noise and air pollution that this traffic generates (Adza et al. 2022; Fecht et al. 2016; Montes-González et al. 2018a). The World Health Organization (WHO) has published several reports over the years highlighting the health problems associated with both excessive noise pollution (e.g., WHO 2018) and the presence of high concentrations of certain substances such as NO_2, O_3, SO_2, $PM_{2.5}$, and PM_{10} (WHO 2021) and has set limits for these pollutants with the aim of achieving healthy environments. If these limits represent the ideal for a healthy life in a city, it is reasonable to ask whether they are achievable in the usual ways in which daily activities are carried out, whether economic or social.

At its 2015 General Assembly, the United Nations set out a series of goals for sustainable development (United Nations 2015). Of the 17 sustainable development goals (SDGs) that were proposed, Goal 3 (*Ensure healthy lives and promote well-being for all at all ages*) and Goal 11 (*Make cities more inclusive, safe, resilient and sustainable*) will be considered in the present work. In this context, an analysis will be conducted to determine whether it is possible to reduce existing noise and air pollution in cities to make them healthier. As the United Nations has stated, increasing numbers of people are now living in cities, and the rural–urban drift seems to be unstoppable (United Nations 2019). This is accompanied by an increase in the flow of road traffic in cities. All of the studies carried out by official organizations, such as the aforementioned reports published by the WHO or those of the European

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Environmental Agency (2020; 2022), to mention only the most recent, indicate that if the current model of development for cities continues, health problems will increase. Therefore, if the enhancement of the quality of life in cities is desired, among the various proposals available, one that must not be forgotten is the reduction of dependence on private vehicles (Mann and Singh 2022).

Given the effects of noise on people's health, traffic noise prediction models have been used in recent years to assess the acoustic impact of existing or future infrastructures. Several published studies are concerned with the problem of choosing the right traffic noise simulation method (Patel et al. 2022; Wolniewicz and Zagubień 2015; Quartieri el al. 2009). The fine-tuning of these models is essential for an accurate evaluation of the acoustic footprint of new facilities.

The question to be answered by city managers is how far the reliance on personal automobiles would need to be reduced to achieve a healthy city. Several studies have proposed different city models with the aim of rectifying this situation (Nieuwenhuijsen 2020; Mouratidis 2021; Yildirim et al. 2023). Amidst the different suggestions, one of the key proposals involves managing traffic flow, though the primary challenge lies in determining the extent to which this traffic flow should be adjusted, without noticeably affecting the economic activity carried out in the city, given the current interdependence between this economic activity and urban mobility (Dadashova et al. 2021; Patatoukas & Skabardonis 2016). However, a recent global event in the form of the pandemic associated with the SARS-CoV-2 virus allows us to find a possible answer. In an attempt to control its spread, governments in a large number of countries took measures to reduce the clustering of people in workplaces, meeting places, and even outdoors. These measures led to a drastic reduction in the mobility of people and thus the economic activity in cities. As a result of this reduced mobility, road traffic fell dramatically. Studies carried out on all continents have reported variations in noise or air pollution levels (e.g., Asensio et al. 2020; Rodríguez et al. 2022; Mishra et al. 2021; Muhammad et al. 2020; Sharma et al. 2020). These papers have analyzed variations in pollution levels in cities or in the soundscape. Although some studies have been published on the effect of a reduction in traffic flow on noise levels in a city (Hemker et al. 2023), in our opinion, it remains to be seen whether this extreme situation led to a sufficient reduction in pollution levels (air or noise) to reach the limits established by the WHO for living in a healthy environment. Moreover, when creating noise maps through computational techniques, sound measurements are crucial. They are needed not only for calibrating or validating the model but also for confirming the accuracy of its predictions (WG-AEN 2007). Under normal conditions, it is not possible to obtain a genuine reduction in traffic flow like that caused by the COVID-19 pandemic required for validation.

This paper analyzes the levels of noise and air pollution in the city of Cáceres during a temporal period surrounding the lockdown imposed by the Spanish government (before, during, and after) and, therefore, throughout the different stages it went through, in terms of the limits established by both the WHO and the Spanish government itself. To observe the variations that occurred during the lockdown, the measured values of noise level and air pollution during almost one and a half months prior to the declaration of the state of emergency (from the 1st of February to the 13th of March) have been taken as a reference for what could be considered a normal situation in the city. The variation in traffic flow or the number of overnight stays in the city has also been considered as indicators of the change in economic activity during the lockdown. The obtained results have been used to evaluate the impact of a significant reduction in mobility. This reduction, experienced during the mentioned lockdown, led to a substantial decline in economic activity. The present work aims to determine whether this reduction is sufficient to attain the enhancements in acoustic and air quality advocated by the authorities. It should be kept in mind the close relationship between economic activity and traffic volume (Dadashova et al. 2021; Patatoukas and Skabardonis 2016), as well as the fact that road traffic is the primary source of noise in cities worldwide (European Environment Agency 2020). Therefore, a decrease in traffic flow and urban mobility will be accompanied by a decline in economic activity. This reduction in traffic will result in a decrease in noise levels and air pollution. During the lockdown imposed by the Spanish government, there was a clear decline in economic activity, due to the mandated closure of nearly all direct customer-facing businesses and restrictions on public movement without a valid reason. Thus, the per capita GDP in the city of Cáceres decreased from 20,393 € in 2019 to 18,553 € in 2020, a value lower than the per capita GDP in 2017 (National Institute of Statistics 2022). Additionally, data on the reduction in city traffic volume and mobility are available. Therefore, an examination has been conducted to determine whether this reduction is sufficient to meet the quality goals established by the authorities.

Methodology

Cáceres (39° 28′ 28″ N, 6° 22′ 18″ W) is a city of approximately 96,000 inhabitants (National Institute of Statistics 2021), although during the school year its population exceeds 100,000 inhabitants due to the influx of an important number of university students. It is located in the centre of the Extremadura region, in southwestern Spain (see Fig. 1a). Cáceres has an important historic center, which has been declared a World Heritage Site by UNESCO, and a large amount of green space (Barrigón Morillas et al. 2013;

(a)

(b)

Fig. 1 **a** Location of the city of Cáceres. **b** Locations of the measurement points within the city. Points 1, 2, and 3 show the noise monitoring stations; Env. station shows the air quality monitoring station

Rey-Gozalo et al. 2019a). Its inhabitants possess about 75,000 vehicles (73% cars, 13% motorcycles, and 12% heavy vehicles), according to data from the Cáceres City Council (2022). Although no updated official statistics are available, the last survey on commuting to the workplace, which was carried out by the National Institute of Statistics in 2011, showed a strong preference by the inhabitants for the use of private vehicles (with 45.5% travelling by car, 8.4% by public transport, and 20.6% on foot). This situation does not seem to have reversed, given the annual increase in the number of vehicles registered in the city, according to the data published on the website of the Cáceres City Council (2022). The 85.57% of the population was employed in 2020 in the service sector, according to data from the National Institute of Statistics (2021). Only 4.22% of the population was engaged in industrial activities (including those working in the construction sector). There is only one company that can be considered an industry (with around 240 employees), but it has fairly low levels of emissions of both noise and chemical pollutants, and it is located more than 4 km away from downtown.

Three long-term sound level measurement systems had been established in the city of Cáceres before the mobility restrictions due to the COVID-19 pandemic declared on 14 March 2020 (see Fig. 1b). The measurement points were selected in order to collect information in different areas of the city and were located in streets with a certain diversity in terms of their architectural and urban characteristics following the categorization method. This method involves classifying urban roads according to their functionality as communication routes (Rey-Gozalo et al. 2020). In the present study, the focus has been primarily on analysing the temporal variation of noise levels rather than their spatial variation, although not completely disregarding it. Point 1 in Fig. 1b represents an avenue in the city centre with one lane of traffic in each direction, parking on both sides, a wide, landscaped central promenade, and a continuous flow of vehicles during working hours. Point 2 corresponds to a street with one lane of traffic in each direction and parking on both sides, in a residential neighbourhood, with several supermarkets nearby. Point 3 corresponds to a street with a single lane of traffic and parking on both sides, in a residential area close to several bars and nightclubs. If the urban road and streets of Cáceres are classified considering the Categorisation Method (Barrigón Morillas et al. 2002; 2005a), point 1 would be located in a Category 3 street, point 2 in a Category 4 street, and point 3 in a Category 5 street.

Class 1 sound level meters with semi-outdoor systems were used as monitoring stations and were mounted on residential buildings according to ISO 1996–2:2017 (Barrigón Morillas et al. 2016). Since the microphones were placed on balconies several meters above the ground, no acoustic screening effect was expected to arise from vehicles parked on the streets (Montes González et al. 2018b; 2020).

To study the impact of lockdown on environmental noise levels in Cáceres, data obtained from February 2020 to the end of June 2020 were considered in the analysis (on the 14th of March, a state of emergency was declared in Spain due to COVID-19, and on 22 June, the "new normal" started). Table 1 shows the different phases of the lockdown, with the different degrees of mobility that were permitted during this period.

The Spanish government (2023) declared a state of emergency throughout the country on 14 March 2020, initially for 15 days, with strong measures that severely restricted the movement of people and economic activity. This situation lasted until 2 May, when the "de-escalation" process started; this took place in different phases (from phase 0 to phase 3) until 22 June, which is when the "new normal" began. This was quite different from life in early March, with mandatory masks, a mandatory safety distance of 1.5 m, and strict capacity limitations for enclosed spaces, although all economic activity was functioning. The lockdown and capacity reduction measures in shops, bars, etc. severely affected the city's economy. As mentioned above, 85–86% of the population was employed in the service sector, and this was the sector most affected by the restrictions.

Day (L_d), evening (L_e), night-time (L_n), and day-evening-night (L_{den}) noise indicators were calculated for each day of the period under study (ISO 1996–1:2016). L_d is the equivalent continuous sound pressure level when the reference time interval is the day, the 12 h between 7 and 19 h. L_e is the equivalent continuous sound pressure level when the reference time interval is the evening, the 4 h between 19 and 23 h. L_n is the equivalent continuous sound pressure level

Table 1 Duration of the different stages of lockdown considered in this study

Stage	Length	Description
A	2020/02/01–2020/03/13	Pre-COVID-19 period
B	2020/03/14– 2020/03/29	State of emergency declared for the whole country: closure of schools, suspension of all types of events, closure of non-essential businesses (only large supermarkets or some specific services were allowed to open), prohibition of walks or outdoor sports practice
C	2020/03/30–2020/04/09	Conditions imposed in the previous period hardened, with a ban on attendance at work except for essential activities across the country
D	2020/04/10–2020/04/25	Return to the situation in Stage B
E	2020/04/26–2020/04/03	Walks and individual outdoor sports practice allowed
F	2020/05/04–2020/05/10	Beginning of the process back to normal
		Phase 0: small shops (by appointment) and take-away restaurants allowed to open
G	2020/05/11–2020/05/24	Phase 1: bar terraces allowed to open with occupancy limitations; places of worship allowed to open with a capacity limit of one third; small shops allowed to open with capacity limitations
H	2020/05/25–2020/06/07	Phase 2: voluntary opening of infant education up to six years of age and the final years of non-university education. Expansion of the capacity of small businesses. People allowed to enter restaurants, but only seated and with limited capacity. Expansion of the capacity of terraces. Re-opening of shows and cultural activities with limitations. Nightlife venues closed
I	2020/06/08–2020/06/21	Phase 3: new increases in the capacity of small businesses. New increases in the capacity of restaurants and bar service. Restaurants with terraces allowed to open 50% of the tables permitted in previous years based on their municipal licences. Opening of discos and night bars with limited capacity, with dancing prohibited. Closing time set at 1:00 am
J	2020/06/22–2020/06/30	New normal

when the reference time interval is the night, the 8 h between 23 and 7 h. L_{den} noise indicator is defined as shown in Eq. 1:

$$L_{\text{den}} = 10 \cdot \lg \frac{1}{24}\left(12 \cdot 10^{\frac{L_d}{10}} + 4 \cdot 10^{\frac{L_e+5}{10}} + 8 \cdot 10^{\frac{L_n+10}{10}}\right), \quad (1)$$

Each station started measuring at different times: at point 1, measurements started on 1 February; at point 2, they started on 10 February; and at point 3, on 1 March. The measuring stations operated continuously during the study period, except when stations 2 and 3 were inoperative for a few days due to technical problems. Specifically, station 2 had problems between 30 May and 2 June, and station 3 had problems between 30 April and 4 June.

It is necessary to bear in mind that road traffic is the main source of noise in cities worldwide (European Environment Agency 2020). In the case of the city of Cáceres, road traffic is also the main source of variability in the recorded sound levels, as shown in previous studies (Barrigón Morillas et al. 2002; Barrigón Morillas et al. 2005a; Barrigón Morillas et al. 2005b; Rey Gozalo et al. 2019b). These works demonstrate how solely the number of vehicles passing by the sound level meter (without considering the type of vehicle, its age, speed, or specific characteristics of the street or its geometric configuration) can account for 85% of the variability in the registered equivalent sound pressure level in different types of urban roads, and how the estimated noise levels in the road traffic noise map of the city have low uncertainty compared to in-situ sound measurements. However, traffic volume data are not always available in cities or they are not as comprehensive as desired. For the present work, data were provided by Cáceres City Council (private communication) on the number of vehicles that were in circulation, on a month-by-month basis, between January 2019 to June 2020. Only 10 streets had sensors to determine traffic volume per month. These streets were classified as Category 1 (five streets), Category 2 (three streets), and Category 3 (two streets) (Barrigón Morillas et al. 2002; 2005a). None of the streets where urban noise measurements were conducted had a traffic volume sensor. A model of the urban environment of point 1 was performed with Predictor v11.20 software for environmental noise. From the monthly average vehicle flow data of category 3 streets, the noise level values were estimated in point 1 using NMPB-Routes-96 method (NMPB-Routes-96 1995; XPS 31–133 2001). Tool 3.5 and Tool 4.5 of the Good Practice Guide for Strategic Noise Mapping (WG-AEN 2007) were used to estimate the percentage of heavy vehicles and vehicle speed. This model provides an approximation of the variation in the L_d indicator that could be awaited with the expected decrease in flow on the street where point 1 is located if the traffic flow behaviour is similar to that of category 3 streets for which traffic volume data is available. Since traffic volume data was not available for any Category 4 and 5 streets (which are the type of streets where points 2 and 3 are located), it was not possible to model the environmental noise for points 2 and 3.

Since road traffic is considered the main source of mobility in cities (Mattioli et al. 2020), a parameter that quantifies this mobility could be used as an alternative to traffic flow. In this sense, mobility data provided by the Secretary of State for Transport, Mobility and the Urban Agenda (2022) were also considered. A study carried out by the Ministry for Transport, Mobility and the Urban Agenda aimed to characterise daily vehicle mobility in the country, in order to assess the effectiveness of the measures adopted to restrict this mobility and to support decision-making during the pandemic. As explained on their website, this analysis used the positioning of mobile phones as its main source of data, in compliance with current regulations on personal data protection. This information was complemented by data on land use and information on the transport network. A comparison of mobility was carried out with the period from 14 to 20 February 2020.

Just like road traffic is the main source of noise, it is also one of the primary sources of atmospheric pollution related to NO_x (around 35% of NO_x EU emissions are attributed to road transport), although this is not the case for PM_{10} (around 10%) (European Environment Agency 2023). Therefore, the previous hypothesis, which suggested the existence of a relationship between mobility and sound levels, was also proposed for the air pollutants PM_{10} and NO_2. Thus, daily air concentration data for PM_{10} and NO_2 provided by the General Office for the Environment of the Regional Government of Extremadura (private communication) were taken into account in this study. These data were measured at the only suburban air quality monitoring station in the city, as shown in Fig. 1b. This station forms part of the Air Quality Monitoring Network of Extremadura. The data were collected using methods set out in the standard protocols established by the European Union's air quality monitoring networks, and equipment was routinely calibrated and maintained based on these standards. The location of the station in relation to the noise level measurement points can be seen in Fig. 1b. During certain periods, the station was unable to correctly assess the presence of PM_{10}; the intervals for which no PM_{10} data were available were from 2020/4/3 to 2020/4/16, from 2020/5/5 to 2020/5/7, from 2020/5/15 to 2020/5/20, and from 2020/6/5 to 2020/6/23.

In this study, daily data of meteorological variables such as average temperature, precipitation volume, wind speed, and hours of sunshine (AEMET OpenData 2023) were also available, which could also show a notable relationship with mobility or atmospheric pollutants.

A Spearman's rank correlation test was employed to assess the degree of association between mobility and atmospheric pollutants (chemicals and noise) using the cor.test function in R software version 4.3.1 (refer to Tables 7 and 8 in Appendix A). This non-parametric test was chosen due to the variables not meeting the assumptions of normality (Shapiro–Wilk test), homoscedasticity (Breusch-Pagan test), and linearity (RESET test) (Hollander et al. 2014). Meteorological variables (temperature, wind speed, precipitation, and sunshine hours) could potentially act as confounding variables, meaning variables that exhibit a significant association with atmospheric pollutants (chemicals and noise). Therefore, if this is the case, Tables 7 and 8 in Appendix A do not represent the specific portion of variance explained by the mobility variable (Stevens 2002).

Regarding the relationship between sound and meteorological variables, considering the proximity between the sound source and receiver, the influence of meteorological variables on sound propagation should be minimal, as indicated by the calculations in ISO 9613–2 (1996). A correlation analysis between atmospheric pollutants and meteorological variables was performed using the Spearman's rank test, and the results are presented in Tables 9 and 10 in Appendix B. Based on the findings shown in Tables 9 and 10 (Appendix B), the effects of meteorological variables that exhibited a significant association with atmospheric pollutants were removed to express the true level of association (the specific part of variance explained by the mobility variable) between mobility and atmospheric pollutants. Partial Spearman correlations using the ppcor package in R software were used to control for potential effects of meteorological variables (Kim 2015). Furthermore, the confidence interval of the partial correlations was calculated using the RVAideMemoire package in R software.

Results

Noise indicators

Figure 2 shows the daily values obtained for L_d, L_e, and L_n at the three measurement points. Vertical lines indicate the different stages of the lockdown. The acoustic quality objectives for noise in sectors with predominantly residential land use, according to the Spanish government (*Real* Decreto 1367 2007), are marked horizontally. These values are 65 dB for L_d and L_e and 55 dB for L_n (black horizontal lines). The strong recommendation of the WHO (2018) for road traffic noise, whereby the value of L_n should be below 45 dB, is also indicated with a red horizontal line.

Table 11 in Appendix C show the mean values of the noise indicators L_d, L_e, and L_n along with the standard error of the mean for the different stages considered. A noteworthy drop in the L_d and L_n levels during stages B, C, D, and E (representing the most severe restrictions due to the state of emergency) can be seen from Fig. 2, although these are not as prominent for L_e. For L_d on weekdays, there is initially a drop of almost 3.5 dB at point 1 (Fig. 2a and Table 11 in Appendix C) during stage B with respect to stage A, and this difference reaches more than 5 dB in stage C (with stricter limitations on movements). This drop is reduced as time progresses, and the values during stages I and J are only slightly lower than in stage A, with a reduction of a little more than 1 dB. The particularly high values during stage F were due to road works. At point 2 (Fig. 2b and Table 11 in Appendix C), there is a drop of about 3 dB during stages B, C, D, E, and F compared to stage A. This reduction is lessened in the following stages; in the last two stages (I and J) the difference is maintained and is slightly less than 2 dB. At point 3 (Fig. 2c and Table 11 in Appendix C), the drop is more moderate (about 2 dB in stages B and C with respect to stage A), and from stage D onwards, levels similar to those pre-COVID-19 are reached again. It can also be seen that in the last two stages, the levels at this point are similar to those of stage A.

In the case of L_e, the drops are more moderate, and it can even be seen that the values are higher than in the pre-COVID-19 period at points 2 and 3. This is due to some specific situations that occurred during the period under study: (a) there was applause on balconies and windows for health personnel throughout this period, from the first day of the state of emergency, at 8:00 pm, and (b) there were protests against the measures taken by the Spanish government with pots and pans, which occurred from the beginning of April at 9:00 pm. In addition, parades were held on some days with ambulances, police cars and music, to cheer up the children forced to stay at home during the lockdown. These noisy activities produced higher L_e values than before the pandemic, but decreased as the anti-COVID-19 measures were relaxed, with values returning in stage J to levels similar to those before the declaration of the state of emergency (stage A).

The most important drop in L_n on weekdays occurs at point 1, in stages B, C, D, and E, with values of between 5 and 6 dB with respect to stage A. Again, the values rise throughout the period under study. In the last stages for all three points, an increase of almost 1 dB is seen compared to the pre-pandemic levels; this was primarily due to the arrival of warmer weather and the widespread use of bar terraces, since it was permitted to be outside in these establishments. It should be noted that in Cáceres, evenings and nights are cool in March, with temperatures of between 6.7 and 17.7 °C (Agencia Estatal de Meteorología 2023), and it is not normal practice to be outside on bar terraces, whereas temperatures are higher in June and are between 16.0 and 29.9 °C (Agencia Estatal de Meteorología 2023).

For the three noise indicators, a considerable reduction can be seen at some days of the weekends in stages B, C, D, and E (the most restrictive state of emergency), with values of between 5 and 9 dB in relation to some weekend days

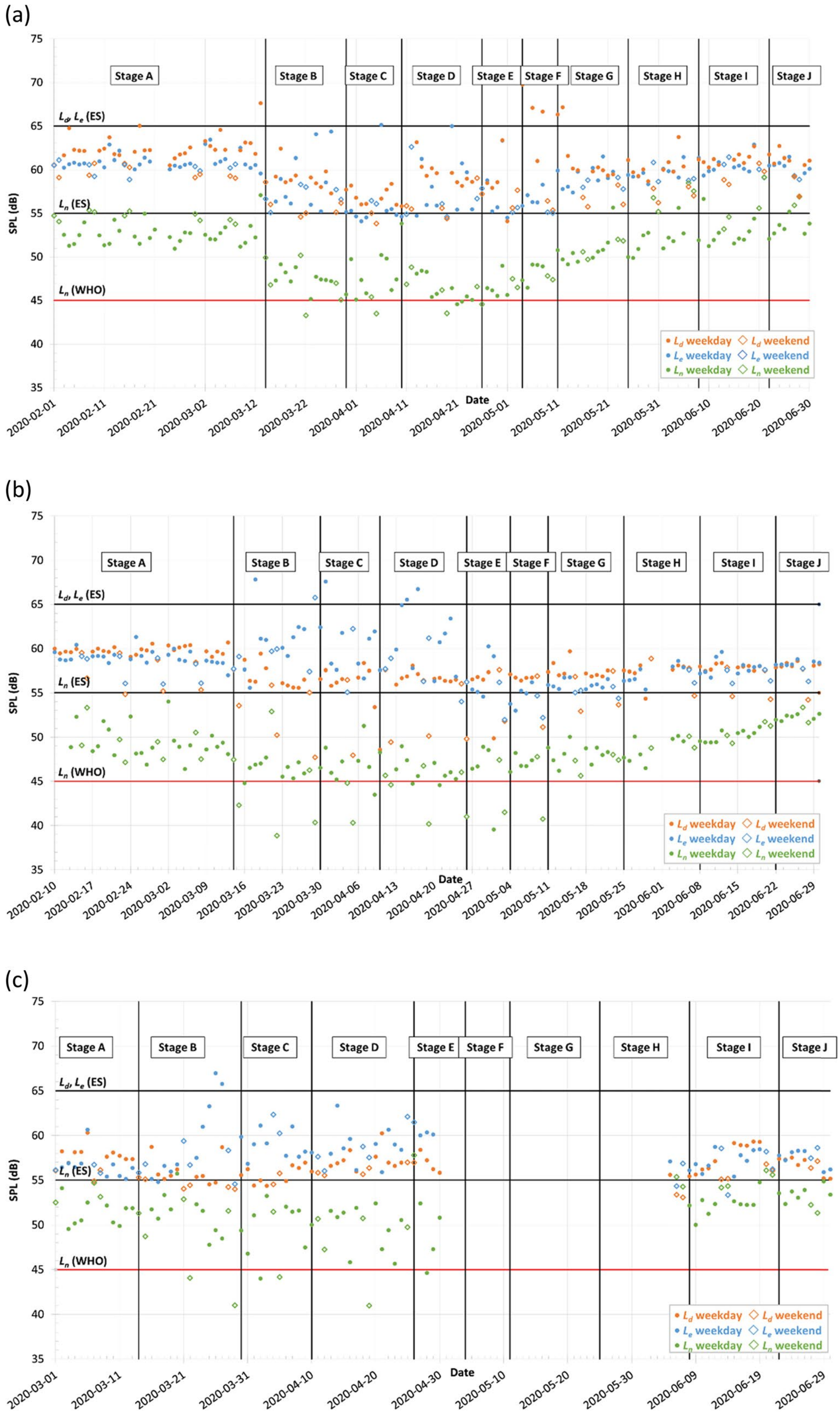

Fig. 2 Variation in the sound indicators L_d, L_e, and L_n over the period considered: **a** point 1, **b** point 2, and **c** point 3

of the pre-COVID-19 stage (stage A). For some weekend nights during the state of emergency, there was even a drop of more than 10 dB relative to the pre-COVID-19 period. At weekends, average drops in L_d of between 3 and 5 dB are observed at points 1 and 2, but there is almost no reduction in L_d at point 3. The comparison with L_e is distorted by the balcony noise mentioned above, which continued at weekends. The largest drops can be seen at night, with average decreases in L_n of about 8 dB at point 1 and about 5 dB at points 2 and 3 in stages B, C, D, and E.

Regarding the acoustic quality objectives (*Real* Decreto 1367 2007) of the Spanish government, it can be seen from Fig. 2 that these objectives had already been achieved before the pandemic at the three points of interest. It can also be observed that as the restrictions were lifted and the weather conditions improved, the L_n quality objectives were exceeded during weekends, which was less often the case in the period prior to the declaration of the state of emergency.

If the value recommended by the WHO for L_n is considered, it can be seen that it was usually exceeded at all three points. Values below this level were only achieved on some Sundays and public holidays during the most severe period of lockdown, and this recommended threshold was largely exceeded as the restrictions were reduced and good weather arrived.

Although the Spanish government does not set acoustic quality objectives for L_{den}, it is noted that this noise indicator, together with L_n, is preferred for strategic noise maps. Having established quality objectives for L_d, L_e and L_n, a value for the L_{den} indicator can be obtained from its definition (Eq. 1), where $L_d = 65$ dB, $L_e = 65$ dB and $L_n = 55$ dB. This gives a value of $L_{\text{den}} = 66.3$ dB. The WHO (2018) also sets a threshold for road traffic noise (the predominant sound source throughout the day in the urban environments evaluated here) and strongly recommends that this does not exceed a value of $L_{\text{den}} = 53$ dB. The results obtained for the three points in the different stages considered here are shown in Fig. 3. The quality objective set by the Spanish government is shown with a black horizontal line, and the WHO value with a red horizontal line. It can be seen from Fig. 3 that the acoustic quality objectives of the Spanish government are always met at all three points, but that the WHO recommendations for L_{den} are exceeded. The measured values were close to the recommended limit on only two days at point 2, corresponding to two particularly quiet Sundays in stage F.

The L_e values measured during the lockdown period do not correspond to the levels that would be expected under normal conditions, meaning that the calculated L_{den} values are also affected by this problem. To address this issue, three possibilities were considered for estimating L_e. The first (*estimate 1*) involved calculating the mean difference between L_d and L_e during the pre-pandemic period and taking $L_{e\_\text{estimated}}$ as the L_d value for a given day minus the mean difference between L_d and L_e. Another possibility (*estimate 2*) involved calculating the average difference between L_e and L_n during the pre-pandemic period, and taking $L_{e\_\text{estimated}}$ as the value of L_n on a given day plus the mean difference between L_e and L_n. Finally, as a lower limit on $L_{e\_\text{estimated}}$, the value of L_n for that day was taken (*estimate 3*). To check the accuracy of these L_{den} estimates, they were compared with the actual values measured on the days prior to the declaration of the state of alarm. The results of this comparison can be seen in Fig. 8 and Table 12 in Appendix D. When "Estimate 1" is indicated in Fig. 8 (Appendix D), it shows the result of subtracting "*estimate 1*" from the real L_{den} value. Similarly, "Estimate 2" reflects the result of subtracting "*estimate 2*" from the actual L_{den} value, and "Estimate 3" indicates the result of subtracting "*estimate 3*" from the actual L_{den} value. In Fig. 8 (Appendix D), it can be observed that the majority

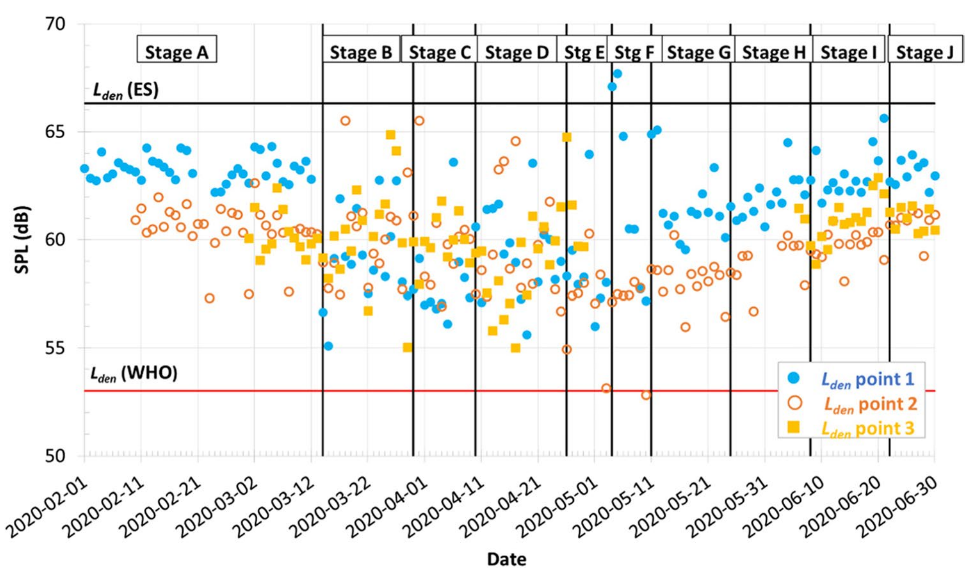

Fig. 3 Variation in the noise indicator L_{den} during the period considered at the three measurement points

of differences for "*estimate 1*" and "*estimate 2*" are between [−0.5 dB, +0.5 dB]: 84.2% and 76.3%, respectively, for point 1; 87.9% and 63.6%, for point 2, and 100% and 76.9% for point 3. In the case of "*estimate 3*," most of the time, the difference is 1 dB or more (89.5% for point 1; 97.0% for point 2, and 15.4% for point 3), and it is positive on all points and all days; that is, the values of L_{den} obtained based on the approximation $L_e = L_n$ impose a lower limit on L_{den}. Some statistical parameters for the differences between the real values of L_{den} during stage A and the different estimates considered for the three points are shown in Table 12 (Appendix D). It can be seen that *estimate 1* is slightly better than *estimate 2*. Furthermore, *estimate 3* represents a lower bound of the real value, as mentioned before. One can conclude that the estimates of L_e based on the mean differences between L_d and L_e or the mean differences between L_e and L_n are acceptable, in view of the closeness between the measured and estimated values.

Using these three estimates of L_e, the values of L_{den} were recalculated, and the results are shown in Fig. 4. The horizontal blue line indicates the maximum value of L_{den} recommended by the WHO. At point 1, values below the WHO recommendation were not achieved on any day, even with the approximation $L_e = L_n$. At points 2 and 3, values lower than those recommended by the WHO may have been achieved on some days, but these were Sundays or public holidays, and never working days. In view of the results of this study, it can be concluded that reaching the WHO's recommended values for L_{den} is very difficult in urban environments, even under conditions of extreme reductions in traffic.

Mobility

As mentioned above, the economic sector related to services was the most affected by the lockdown. And within this sector, the one related to tourism experienced a complete halt. Likewise, the number of overnight stays dropped precipitously, as shown in Table 2 (Cáceres City Council, private communication); in other words, the number of visitors and hence the vehicular traffic arising from these visits decreased noticeably. This number of overnight stays is another indicator of the variation in economic activity in the city, where, as mentioned in the Introduction, there was a 9% decrease in per capita GDP in 2020 compared to the per capita GDP in 2019. As stated above, this economic halt is evident due to the mandated closure of nearly all direct customer-facing businesses and restrictions on public movement without a valid reason during the lockdown imposed by the Spanish government (Table 1).

Figure 5 shows the average volume of vehicles per month in different streets of the city, based on data provided by the traffic sensors and distributed by Cáceres City Council. The monthly values for February, March, April, May and June are compared for 2019 and 2020. A drop of 51% in the overall traffic in the city was observed during the months of March and April, with reductions of 59% in May and 32% in June. If only Category 3 streets, for which there are traffic values, are considered, the reductions were 75% in March, 76% in April, 87% in May, and 18% in June. The acoustic levels in Cáceres were extensively studied during 2002 (Barrigón Morillas et al. 2002), 2005 (Barrigón Morillas et al. 2005a) and 2019 (Rey Gozalo et al. 2019b). In each of these studies, a statistically significant correlation between traffic flow (Q) and measured equivalent noise level (L_{eq}) was verified.

Using the results from the software model describe above, a comparison between the average decrease in traffic noise due to traffic flow variation between the years 2019 and 2020 on Category 3 streets and the L_d noise indicator decrease at point 1, also located in Category 3, is shown in Table 3. Since no measured acoustic data are available for 2019, the average value of the L_d noise indicator from 1 to 13 March 2020 is taken as the base value. It can be seen that the software model predictions for March, April, and June are fairly accurate, with variations of about 1.5 dB, as can be seen in the fifth column of Table 3. The highest variation for Q_{2020}/Q_{2019} occurs in May (0.13 in the second column of Table 3), due to the reduction in the number of vehicles circulating during this month. This can be explained due to the improvement in the weather compared to April (mean temperatures 5 °C higher in May; 9 rainy days in May compared to 19 in April; Agencia Estatal de Meteorología 2020) and the easing of the restrictions on mobility, which encouraged citizens to travel on foot instead of by car. The difference between the software model and the estimated variation for point 1 for May (5.5 dB) might be due to the fact that road works were being carried out in the central area of the avenue, which did not interrupt traffic but increased the measured L_d levels. The differences of around 1.5 dB for the other months can be considered acceptable since there is no disaggregated data available on the vehicles circulating on the avenue (point 1).

As mentioned above, the variation in mobility within the city of Cáceres according to the study carried out by the Secretary of State for Transport, Mobility and Urban Agenda was also considered. Figure 6 shows the percentage change in mobility in Cáceres, in relation to the reference period (from 14 to 20 February 2020). The published data start on 29 February 2020. There is clearly a sharp drop in mobility at the beginning of the state of emergency (stage B), which reaches a minimum in stage C (when only workers in key economic sectors were allowed to move about). Gradually, as the measures were relaxed, mobility increased until it reached values similar to those before the pandemic (stage J). The results of the Spearman's rank correlation test on the degree of association between % mobility and noise indicators are shown in Appendix A, Table 7. It can be seen that at each of the three points, there is a statistically significant correlation between the measured values of the daily sound levels L_d and L_n and

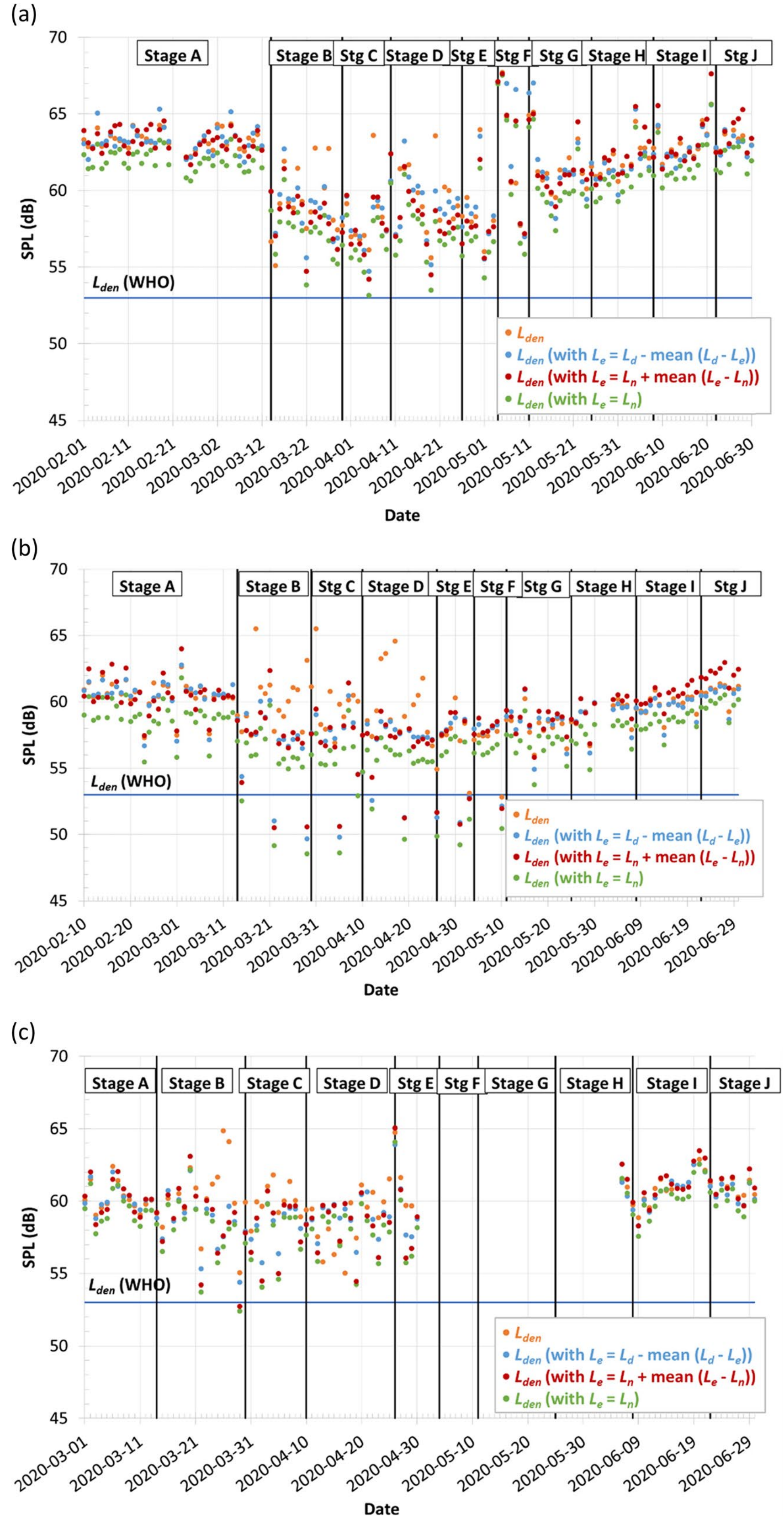

Fig. 4 L_{den} values considering different estimates for L_e at **a** point 1, **b** point 2, and **c** point 3

Table 2 Number of overnight stays in Cáceres during 2019 and 2020 in the period under study

	Overnight stays				
Year	February	March	April	May	June
2019	16,939	25,993	53,279	38,325	24,376
2020	17,456	4835	0	0	1147

Table 3 Comparison between the variation expected in road traffic noise due to the change in traffic volume (Q) in Category 3 streets and at point 1 ($L_{d,\text{sA}}$ corresponds to the mean L_d value from 1 to 13 March, stage A; $L_{d,\text{month}}$ is the mean L_d value for each month)

Month	Q_{2020}/Q_{2019} (Category 3)	$L_{d\,2020}–L_{d\,2019}$ (software model) (dB)	$L_{d,\text{month}}–L_{d,\text{sA}}$ (point 1) (dB)	Difference Point 1– software model (dB)
March	0.25	− 6.0	− 4.4[a]	1.6
April	0.24	− 6.1	− 4.5	1.6
May	0.13	− 9.4	− 3.9	5.5
June	0.82	− 3.4	− 1.9	1.5

[a] The days from the declaration of the state of emergency (14 March) to the end of the month are considered for $L_{d,\text{month}}$

the percentage variation of mobility in the city. For point 1, this statistically very highly significant ($p < 0.001$) correlation also holds for L_e and L_{den}. For point 2 and 3 L_{den}, the value of Spearman's rho indicates that the correlation is between highly significant ($p < 0.01$) and significant ($p < 0.05$), while it is very highly significant ($p < 0.001$) for point 1. This may indicate that the overall variation in mobility in the city affects main streets (as streets in Category 3) more than neighbourhood streets (Categories 4 and 5).

Air pollution

The daily air concentration data for PM_{10} and NO_2 provided by the General Office for the Environment of the Regional Government of Extremadura for the period studied in the present work were analysed. Table 13 in Appendix E shows the values established by the Ministry for Ecological Transition and Demographic Challenge of the Spanish government for air quality (2020), and Table 14 in Appendix E shows the WHO's recommendations (2021).

The daily variation in the air pollutants PM_{10} and NO_2, together with L_{den} for point 1, can be seen in Fig. 7. Table 4 shows the average variation in these parameters over the different periods considered. The values for the air pollutants and L_{den} are shown together, in view of their possible dependence on road traffic in the cities. This dependence is shown in Table 7 (Appendix A) for L_{den}, and can be seen in Table 8 (Appendix A) for PM_{10} and NO_2. A decrease in NO_2 from stage B onwards is shown in Table 4; the level subsequently increases, although pre-pandemic values are not reached. There is also a drop in PM_{10} in stage B, and the value reaches a minimum in stage C. From this period onwards, PM_{10} levels increase faster than NO_2 levels, and reach values higher than in the pre-pandemic period in stages H, I, and J. Similar results have been reported by other authors (Tobías et al. 2020). In terms of the categories defined in Spanish legislation, the levels of PM_{10} and NO_2 correspond to good air quality. For PM_{10}, the annual limits established by the WHO were slightly exceeded in stages H and J, and in stage I, the value was within the established limit. For NO_2, the WHO annual limits were not exceeded in any of the periods. When the daily values are considered, it was observed that there was no day where the limit established by the WHO was exceeded for 24 h, either for PM_{10} or NO_2. L_{den} undergoes a drop in stage B, as already mentioned, reaching a minimum in stage C. From this stage onwards, L_{den} values start to rise, reaching levels similar to the pre-pandemic period in stages I and J.

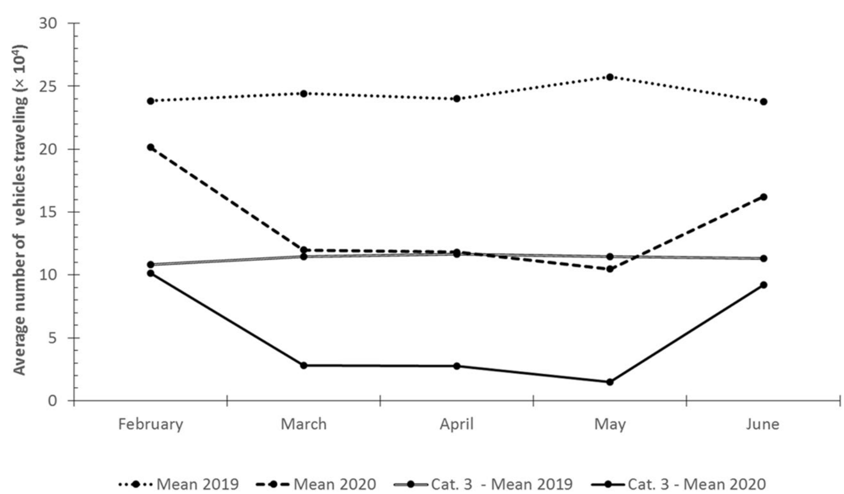

Fig. 5 Monthly average number of vehicles circulating on the main roads of Cáceres

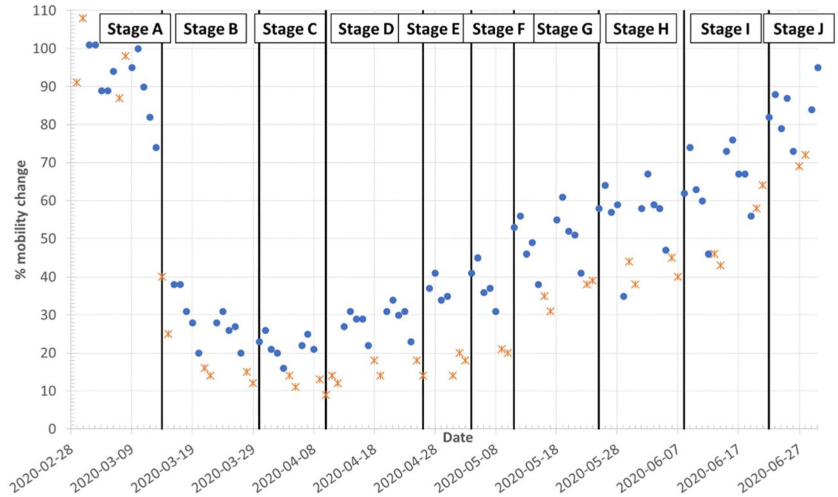

Fig. 6 Percentage change in daily mobility in vehicles in the city of Cáceres within the reference period established by the Secretary of State (from February 14 to 20, 2020)

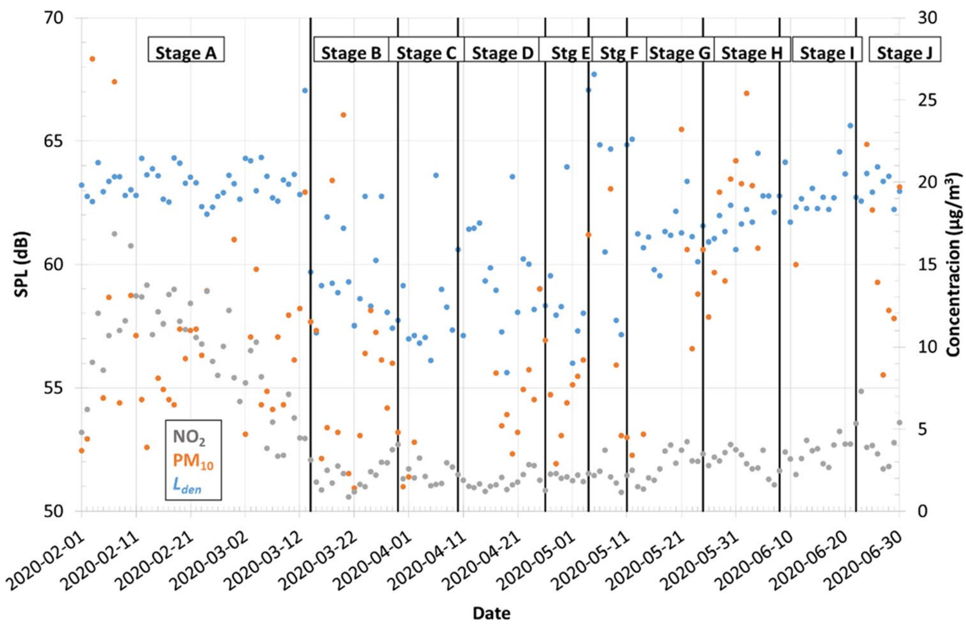

Fig. 7 Variation in air pollutants NO_2 and PM_{10} with values of L_{den} for point 1 during the different stages of the lockdown

As mentioned above, the results of the Spearman's rank correlation test for the degree of association between % mobility change and chemical pollutants PM_{10} and NO_2 are shown in Appendix A, Table 8. It can be seen that this correlation is statistically very significant in both cases. In the case of NO_2, this correlation is moderate, while for PM_{10}, it is weak. This result for PM_{10} is in line with previous findings reported by other authors (Pivato et al. 2023) and is due to the influence of other factors on the level of PM_{10}, such as domestic heating systems, agricultural activities, and livestock farms.

Influence of meteorological variables

Regarding the possible influence of meteorological variables on the previously shown results, the Spearman's rank correlation test was also applied. The results shown in Table 9 (Appendix B) confirm the low relationship between meteorological variables and noise indicators. In general, there are not many significant relationships, and when they exist, the rho value indicates a low degree of association. Regarding the relationship between noise indicators and precipitation, significant relationships between noise level and precipitation are only observed in point 1 for all periods (L_d, L_e, L_n, and L_{den}), while in points 2 and 3, it occurs in only one period, and it is not the same in both cases. In all cases where significant relationships occur, the coefficient is negative and ranges from − 0.241 to − 0.382. In other words, as precipitation increases, the noise level decreases. This could be related to various factors such as variations in tire-pavement noise generation due to changes in asphalt

Table 4 Average values of L_{den} (at point 1), NO_2, and PM_{10} during the different stages of the lockdown

Stage	Length	L_{den} (point 1) (dB)	PM_{10} (μg/m^3)	NO_2 (μg/m^3)
A	2020/02/01–2020/03/13	63.3	13.4	9.6
B	2020/03/14–2020/03/29	59.2	9.1	2.2
C	2020/03/30–2020/04/09	58.1	3.2	2.4
D	2020/04/10–2020/04/25	59.5	7.1	1.9
E	2020/04/26–2020/04/03	58.7	7.1	2.0
F	2020/05/04–2020/05/10	58.5	12.5	2.2
G	2020/05/11–2020/05/24	61.1	10.7	2.8
H	2020/05/25–2020/06/07	62.0	18.0	3.1
I	2020/06/08–2020/06/21	63.1	15.0	3.5
J	2020/06/22–2020/06/30	63.1	15.2	4.3

properties when wet, or variations in vehicle traffic conditions in terms of speed for visibility and safety reasons.

In the case of Table 10 (Appendix B), there is a higher degree of association between meteorological variables and atmospheric chemical pollutants as see for other authors (Huang et al. 2021; Pearce et al. 2011). A significant positive relationship is observed between PM_{10} concentration and temperature and the number of hours of sunshine. As for wind speed, this meteorological variable only shows a significant negative relationship with NO_2 concentration. Regarding precipitation, both for NO_2 and PM_{10} concentration, a significant negative relationship is obtained with association coefficients ranging between − 0.414 and − 0.471.

Considering the influence of a third group of variables (meteorological variables) on the relationship between noise indicators and chemical pollutants with respect to % mobility change, a partial correlation analysis was conducted. This way, the potential influence of meteorological variables was removed when testing the hypothesis of the relationship between noise indicators, chemical pollutants, and % mobility change. Results are shown in Tables 5 and 6. If Table 5 is considered and compared to the results shown in Table 7 (Appendix A), it can be seen that the same

Table 6 Spearman's rank partial correlation between PM_{10}, NO_2, and % mobility change

	PM_{10}	NO_2
Rho	0.181	0.706
Upper 95% C.I	0.417	0.792
Lower 95% C.I	− 0.038	0.592
p value	n.s	< 0.001
N	80	123

n.s. non-significant correlation ($p > 0.05$), *C.I.* confidence interval

statistically significant relationships are maintained (except for the statistically significant relationship for L_{den} in point 3) and the degrees of association are also almost the same. It can be concluded that the relationship between noise indicators and the % mobility is not affected by meteorological variables. It can be seen that the correlation between L_e and % mobility change in point 3 is negative. As explained in "Noise indicators" of "Results," the values of L_e (and, consequently, L_{den}) are affected by the events that occurred in the evenings on the balconies during the pandemic, with noisy demonstrations (applause, music, and pot-banging) in support of healthcare workers or against the anti-pandemic measures implemented by the government. Due to these circumstances and the characteristics regarding the intensity of these sound sources on the balconies, road traffic may not have been the predominant sound source during that time of day. Consequently, the results in L_e and L_{den} could have been influenced by these non-daily, unusual sound sources in a normal urban environment. One possible explanation is that reduced mobility results in more people staying at home, and consequently, more noise on balconies. Nevertheless, this correlation, although statistically significant, should be interpreted with caution. Comparing Table 6 with Table 8 (Appendix A), it can be observed that it remains almost the same for the case of NO_2 concentration, but the correlation disappears for PM_{10}, indicating that the relationship between this chemical pollutant and the % mobility change is much weaker, as mentioned before.

Table 5 Spearman's rank partial correlation between the noise indices (L_d, L_e, L_n, and L_{den}) and % mobility change

	Point 1				Point 2				Point 3			
	L_d	L_e	L_n	L_{den}	L_d	L_e	L_n	L_{den}	L_d	L_e	L_n	L_{den}
Rho	0.766	0.594	0.708	0.748	0.663	− 0.014	0.668	0.348	0.430	− 0.395	0.330	0.099
Upper 95% C.I	0.845	0.723	0.798	0.828	0.779	0.176	0.775	0.520	0.587	− 0.204	0.534	0.335
Lower 95% C.I	0.658	0.438	0.581	0.653	0.518	− 0.207	0.528	0.160	0.243	− 0.555	0.090	− 0.151
p value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	n.s	< 0.001	< 0.001	< 0.001	< 0.001	< 0.01	n.s
N	116	123	123	116	120	119	120	119	87	86	86	85

n.s. Non-significant correlation ($p > 0.05$), *C.I.* confidence interval

Discussion

As discussed in "Introduction," the WHO recommends changes in infrastructure to reduce the adverse health effects associated with high levels of noise. This recommendation ties in with SDGs 3 and 11 established by the UN for 2030, and more specifically with targets 3.9 (*by 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination*) and 11.6 (*By 2030, reduce the adverse per capita environmental impact of cities*). However, the data presented in this paper indicate that these are still far from being achieved.

Before discussing the findings, it would be interesting to highlight that the WHO recommendations are for traffic noise, but the noise indicators shown in the previous section reflect the environmental noise around the measurement point, not just the traffic noise. However, the categorization method developed by Barrigón Morillas et al. (2005a, 2005b) demonstrates that the noise level in city streets is stratified based on established categories determined by the road traffic use of these streets. Furthermore, it also demonstrates that urban noise is strongly correlated with traffic flow, which is the primary source of spatial variation in urban noise. Therefore, the city's noise is strongly linked to traffic flow, which is the main source of spatial variation in urban noise. In this regard, when there has been excessive noise in the evenings due to activities on balconies, it has been noted, and an estimation of what the L_e noise indicator value could have been without those activities has been considered, as explained later in this section.

From Eq. 1 and the WHO's recommendations for L_{den} (53 dB) and L_n (45 dB), an estimate of possible recommended values for L_d and L_e can be made. The range for L_d is between 50 and 52 dB, while the range for L_e is between 50 and 45 dB. If equal values for L_d and L_e are considered (as set out by the Spanish government), then $L_d = L_e = 50$ dB. However, if equal values for L_e and L_n are considered (with a high requirement for L_e), then $L_d = 52$ dB and $L_e = 45$ dB. Figure 2 shows that at point 1, both L_d and L_e are rarely lower than 55 dB; they never fall below this value in the pre-pandemic period, and only occasionally during the most restrictive times of the pandemic. In stage A (pre-pandemic) and stage J (end of mobility restrictions), values between 60 and 65 dB are observed for L_d and L_e, with L_d usually higher and L_e lower. At point 2, L_d reached values below or close to 50 dB on Sundays during the most stringent stage of lockdown (stage C), while on the other days, it was above 55 dB. Again, at point 2, the values of L_e were always above 55 dB; this demonstrates the effect that noisy events seem to have on noise indicators, which in many cases are used as indicators in strategic noise maps to make decisions about the acoustic situation in a given area (Montes González et al. 2023; Prieto Gajardo et al. 2014). At point 2, L_d was around 60 dB in stage A, and L_e was around 58 dB, while in stage J, both indicators were around 58 dB. At point 3, L_d did not reach values lower than 54 dB, and values of around 54 dB were achieved only on some Sundays in stages B and C. L_e had values of above 55 dB, except on some Sundays, where values fell to around 54 dB. In stages A and J, the values of L_d and L_e ranged between 55 and 60 dB. It can therefore be seen that the values strongly recommended by the WHO were difficult (if not impossible) to achieve, even on residential streets in a small-to-medium-sized city, during a period of time when economic activity was almost at a standstill.

Using the software model for Virgen de la Montaña Avenue (point 1), an estimate can be made of what the vehicle flow should be to achieve the values recommended by the WHO for L_{den} (53 dB) and L_n (45 dB). In the case of L_{den}, a value of 53 dB would be obtained with an average monthly vehicle volume of 14,000 vehicles/month. This volume would result in an L_n value of 43.3 dB, thus meeting both recommendations. If the goal is to ensure an L_n value of 45 dB, it could be achieved with a monthly vehicle volume of 20,000 vehicles/month, although in this case, an L_{den} value of 53.8 dB would be obtained, which is higher than the WHO's recommended value. The average number of vehicles on Category 3 streets measured between March and June 2019 was 114,639 vehicles. Therefore, according to the software model, this represents a reduction in vehicle volume of 88% in the first case and 82% in the second case. Taking into account the actual average reduction during the lockdown, the traffic volume decreased by 64% compared to the vehicle volume values of 2019. In other words, a further 20% reduction in vehicle volume would be needed compared to the lockdown period to achieve the values recommended by the WHO for the noise indicators L_{den} and L_n.

It can therefore be concluded that achieving the values strongly recommended by the WHO for the noise indicators in a city would require a drastic reduction in road traffic flow. Furthermore, electric vehicles are not expected to provide a solution, as several studies (Rey-Gozalo et al. 2022; Leupolz and Gauterin 2022; Altinsoy 2022) show that little change can be expected at current vehicle speeds in cities (generally above 30 km/h) unless this is accompanied by other, more effective measures, such as better road surfaces. However, these solutions may impose higher costs on the public treasury or even create a higher carbon footprint.

In regard to air pollution from internal combustion vehicles, better results might be possible, at least in the case of NO_2 concentration, if traffic circulation is reduced or the use of electric vehicles is increased, as shown in Fig. 6 and Table S7. Other authors (Muhammad et al. 2020; Nakada and Urban 2020) have published similar results. A reduction in air pollution in cities around the world has been observed experimentally when the circulation of internal combustion vehicles has been reduced. Replacing internal combustion vehicles with electric vehicles would improve air quality in cities; however, this electricity needs to come from sources that generate minimal carbon emissions, as otherwise, the problem is simply being moved elsewhere. Initiatives such as the European Commission's Lightyear Project (2020) for solar-powered self-driving cars have achieved promising results.

Conclusions

This study has analyzed air and noise pollution in the city of Cáceres during the period from March to June 2020, during which Spain underwent an abrupt halt in economic activity due to the measures taken by the Spanish government to tackle the COVID-19 pandemic. Data for the period prior to the declaration of the state of emergency in Spain (14 March 2020) were used as a reference to establish pre-pandemic noise and air pollution levels. The variations in these levels in the city were examined in the different phases of the lockdown, from almost total immobility to the return to a "new normal" at the end of June. As the city's main economic activity is oriented towards the service sector and tourism, the reduction in the use of private vehicles fell to levels that had never been seen before. These conditions made it possible to analyse the variation in noise levels and air pollution in three streets in the city.

In terms of noise levels, the most important drop was seen in Virgen de la Montaña Avenue (point 1), a wide street with one lane in each direction, parking on both sides and a wide, landscaped central promenade. There was a decrease of more than 5 dB in the L_d value during the most restrictive period of the lockdown. In Gredos Street (point 2), a road with one lane of traffic in each direction and parking on both sides, the value of L_d decreased by about 3 dB. In Dr. Fleming Street (point 3), which has one-way traffic and parking on both sides, the drop in noise levels was not as sharp, with a decrease of about 2 dB in L_d.

The noise quality objectives set by the Spanish government had already been achieved before the pandemic. However, this was not the case for the objectives set by the WHO; the recommendations for L_{den} and L_n were rarely reached, and this occurred only on Sundays or public holidays during the strictest period of lockdown.

The reduction in air pollution was notable for NO_2, and apparently for PM_{10}, during the period of strict lockdown. NO_2 values remained relatively low throughout the period under study, and this decrease was correlated with the decrease in the % mobility change. For PM_{10}, although there was a decrease in its concentration during the strict confinement, no correlation has been found with the % mobility change once the potential influence of meteorological variables has been eliminated.

The reduction in the use of private vehicles led to improvements in both air quality and noise levels. However, in the case of noise pollution, this improvement was not sufficient to achieve the noise quality objectives based on the indicators proposed by the WHO. Our results show that although replacing internal combustion vehicles by electric vehicles would lead to a certain improvement in air quality, the levels would still be well above the WHO recommendations for both L_{den} and L_n. It can be therefore conclude that in medium-sized cities such as Cáceres, a much more drastic reduction in traffic flow would be necessary to achieve compliance with the values established by the WHO for noise levels, as these are well below the minimum values that were obtained with the mobility restrictions imposed by the Spanish government to tackle the COVID-19 pandemic.

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Author contribution All authors contributed to the study conception and design. Material preparation and data collection were performed by J. M. B. M., G. R-G., and D. M. G. Analysis was performed by R. V-G. The first draft of the manuscript was written by R. V-G, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The datasets used or analyzed to support the findings of this study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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