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Noise exposure of cyclists in Ho Chi Minh City: A spatio-temporal analysis using non-linear models

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ABSTRACT

The auditory and non-auditory effects of noise on health are today well known. A number of studies have recently shown that cyclists represent a population that is especially strongly exposed to noise in urban environments, particularly because of their proximity to road traffic. These studies have however very rarely examined the case of the cities of the South, despite the fact that these cities are known to have higher levels of exposure to noise. The objective of this article is therefore to analyze variations in cyclists' levels of noise exposure in Ho Chi Minh City (Vietnam) by integrating three dimensions: that is, the characteristics of the trip, neighbourhood effects, and the temporal dimension. Three participants cycled more than 1000 km in the city, equipped with noise dosimeters and GPS watches, for a total of 3300 one-minute segments, each of which measured noise intensity (LAeq dB(A)). It is not surprising that the levels of exposure registered were particularly high (average 78.8 dB(A)), notably compared with earlier studies conducted in Europe and North America. The use of generalized additive models in particular made it possible to highlight the effect of the complex interaction between the slope and the cyclists' speed on the levels of noise exposure, the effect and duration of the morning and afternoon rush hour periods, and the spatial distribution of residual environmental noise. One of the main findings was that in sectors with the highest levels of exposure to noise (central neighbourhoods or areas near the airport), these levels are up to four times higher than in more peripheral or rural areas.

1. Introduction

Noise is a problem inherent to cities, linked to their concentration of population and activities. Although the perception of noise is relative, it is considered to be the second most important nuisance after air pollution [42]). Indeed, the health impacts of prolonged noise exposure are well recognized today, "including increased risk of ischaemic heart disease as well as sleep disturbance, cognitive impairment among children, annoyance, stress-related mental health risks, and tinnitus" [43]. These effects have now been clearly documented in health studies; we provide three literature reviews that stress the necessity of reducing environmental noise, considering its auditory and non-auditory effects [5,21,36].

In urban areas, the major portion of environmental noise is generated by transportation, and by road traffic in particular. According to McCallum [25], the intensification of the latter is moreover the main cause of the increase in noise levels and in the population's exposure. So it is hardly surprising that, over the past two decades, many studies have looked at noise exposure in a number of cities around the world. But in a recent systematic review of exposure to air and noise pollution stemming from road traffic, Khan et al. [23] note that the cities of the South have been little studied. Indeed, out of 57 articles selected, European and North American cities were clearly overrepresented compared to cities in the South, which only included four case studies (Macau and Beijing in China, Seoul in Korea, and Delhi in India).

This is all the more surprising in that many cities in the South, especially those in East and Southeast Asia, are currently experiencing major changes, the combined effects of which are increasing noise levels. For example, the East Asia and Pacific region is undergoing particularly strong urban growth, with the population rising from more than 605 million city-dwellers in 1990 to 1.3 billion in 2016 [41]. At the same time, motor vehicle ownership and road traffic have also skyrocketed during this period. Jraiw [22] estimates that traffic volume per square mile in the much denser Asian urban areas is about 80% higher than in the United States. In the same vein, the Asian Development Bank [4] estimates that the fleet of motor vehicles has doubled about every five to seven years. This sharp increase in the number of motor vehicles mainly involves two- or three-wheeled mopeds or scooters. For example, the latter are said to represent "half of all vehicles in India's five

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major cities, three quarters in Bangalor, and two-thirds in Ho Chi Minh City" [16].

If bicycles were a very widespread mode of transport in Eastern Pacific Asia during the 1990s [35], this rising level of vehicle ownership has helped to reduce the modal share of active transportation. The latter, however, still plays an important role due to its accessibility and flexibility [11] and represents, for example, more than 7% of urban travel in Ho Chi Minh City [38].

In this context, it is especially relevant to examine the question of the environmental noise exposure of urban populations in East and Southeast Asia. In this paper, we will focus in particular on cyclists' exposure to noise in Ho Chi Minh City (Vietnam).

1.1. Cyclists' environmental noise exposure in urban areas

Road traffic is the most important source of environmental noise. Cyclists are a population with an especially high exposure to noise since they travel directly next to traffic and have no cabin to protect them. In Ho Chi Minh City (HCMC), this is all the more so because cycling infrastructures are non-existent and cyclists have to wend their way between cars and scooters.

Since the early 2000s, studies on cyclists' exposure to noise have proliferated. Cyclists' noise exposure is however less often examined than is their exposure to air pollution. This is notably explained by the fact that cyclists' increased physical activity does not mechanically increase their noise exposure, as it does their exposure to air pollution. Indeed, a higher ventilation rate multiplies the doses of gaseous and particulate pollutants that cyclists inhale.

In studies focusing on urban cyclists' noise exposure, one can distinguish between two streams. In the first stream, it is a question of comparing cyclists' exposure levels to those seen with other modes of transport, mainly in the case of motorists and public transit users. In Montreal, Canada, Apparicio et al. [3] found that, during rush hours, cyclists were exposed to higher noise levels than were motorists but lower levels than public transit users (68.8, 66.8, and 74.0 dB(A) respectively). Similarly, Okokon et al. [29] reported higher noise exposure levels for cyclists than for public transport users or motorists in Helsinki, Finland (73, 71, and 67 dB(A) respectively), Thessaloniki, Greece (75, 74, 71 dB(A)), and Rotterdam, the Netherlands (70, 71, not available for motorists). Finally, Yao et al. [44] observed even greater discrepancies in Toronto, with an average of 81.8 dB(A) for cyclists, 78.1 for bus riders, 79.8 for subway users, and 67.6 for motorists. If we refer to the thresholds established by the WHO, these results are worrisome. Indeed, levels higher than 55 dB(A) during the day and evening are considered as a serious annoyance; and levels higher than 70 dB(A) may have significant impacts on health, including hearing impairment [7].

In the second stream of studies, it is a matter of analyzing the characteristics of the trip that together increase or reduce cyclists' exposure levels. The present study falls within this category. In a pioneering work, Boogaard et al. [8] studied cyclists' exposure to noise and air pollution in eleven Dutch cities. More specifically, they built linear regression models in order to predict cyclists' levels of exposure to air pollution, with predictors such as the type of road that the cyclist was travelling on, the presence of various types of vehicles (cars, scooters, etc.), and time. They unfortunately did not apply the same method for noise exposure, and only its correlation (moderate, 0.21–0.60) with air pollution was reported. This variability in correlation was moreover corroborated by Tenailleau et al. [37], who noted that the discrepancies between environmental noise exposure and exposure to air pollution (in this case, nitrogen dioxide – NO_2) had a certain structure associated with the local morphological and socio-spatial environment.

More recently, Apparicio et al. [2] looked at cyclists' exposure to noise and air pollution in several central districts of Montreal. This study also proposed a linear modelling exercise, with the level of noise measured with a dosimeter as the dependent variable. More specifically, the authors used a SAR-Lag regression [1] in order to take spatial autocorrelation into account. The independent variables considered include the windspeed, day of the week, time of day, type of street taken, vegetation, density of the built environment, green spaces, and diversity of land uses. Notably, the models revealed that noise varied significantly depending on the time of day and was at its maximum between 7:00 a.m. and 9:00 a.m. The number of intersections crossed tended to decrease noise exposure, as did the fact of passing through a park or travelling in more densely built-up areas. Finally, noise exposure levels were highest on arterial roads and lowest on off-street bicycle paths. The authors were also able to emphasize that the fact of using bike lanes and shared bike lanes did not reduce the exposure to noise or air pollution. It is interesting to note as well that this study reported a very weak correlation between noise exposure and exposure to air pollution (in this case, NO_2).

This research made it possible to better understand the factors of the urban environment that contribute to cyclists' exposure to noise pollution. Despite their relevance, these studies present several limitations. First, they do not take into account or distinguish between spatial and temporal autocorrelation, which may lead to bias in the estimation of their parameters. Nor do they consider the existence of spatial tendencies related to noise (systematic differences between neighbourhoods, dense sectors, effects of infrastructures, etc.). Added to this is the fact that they use typologies of roads specific to the cities studied, which makes it difficult to reutilize the results for the purposes of comparison. Finally, they only model linear relations between dependent and independent variables, which probably does not constitute a valid hypothesis for all the predictors. The example of the time of day is proof of this. The observations performed by Phan et al. [32] in HCMC clearly indicate that road traffic follows hourly patterns, with both a morning and a late afternoon rush hour. In this context, the relationship between the time of day and the noise level is certainly not linear. The traditional response to this problem is to add dummy variables for each period of the day, but this means making an arbitrary division that is not easy to justify. In addition to this is the fact that the distance to the noise sources plays a part in exponentially reducing noise intensity, since noise spreads in space in the form of a sphere, with the intensity of noise distributed over the entire surface of this sphere.

1.2. Research objectives

The aim of the study is twofold. First, it is a question of analyzing variations in cyclists' levels of noise exposure in Ho Chi Minh City by integrating three dimensions: the characteristics of the trip, neighbourhood effects, and the temporal dimension, in paying particular attention to the day and time of the cyclist's travel, the type of road, and the number of intersections crossed. Second, once these dimensions have been controlled for, it is then a matter of identifying the spatial pattern of the noise exposure over the entire study area.

2. Description of the study area: Ho Chi Minh city

With 8.4 million inhabitants and a density of nearly 4,000 inhabitants per km^2 in 2016, HCMC is the largest city in Vietnam. Intersected by the Saigon River, it is also the country's economic centre, especially due to the presence of its port. HCMC has been characterized by strong demographic growth, as the population increased from 4.64 million inhabitants in 1995 to 8.4 million in 2016, due in particular to a very high level of migration from rural areas.

HCMC is today comprised of 23 districts, of which 17 are urban and 6 rural (Fig. 1). The city largely developed around two distinct centres corresponding to the two older cities of Saigon and Cholon, which were merged. “Until 1945, development of the urban fabric occurred along roads connecting the two central cores; over the next twenty years, intensive occupation of the central areas continued both legally and illegally” [6] *[our translation]*. Together with this densification of the central portion, secondary centres also mushroomed, and urbanization spread along the main roads.

The liberalization process launched in 1986 (the *Doi Moi* program) affected urban planning, which had previously been a highly centralized area of responsibility in Vietnam. This resulted in particular in more permissive and transparent legislation regarding property ownership and land tenure as of 2003 [28].

From a morphological viewpoint, there is no separation between residential and commercial or industrial areas because of the lack of a truly restrictive zoning plan [20,28]. This strongly mixed land use thus contributes to the high noise levels. More generally, the master plan is said to serve more as a negotiating tool with the central government.

HCMC is thus a very active city experiencing strong development, and with a complex structure. The colonial grid layouts are still present in the central sectors where skyscrapers have recently been erected. The map of HCMC’s urban structure developed by Downes et al. [15] in fact notes the presence of a central business district, surrounded by a strong density of shophouses and a few rare and small parks. Agricultural areas directly encompass the city, invaded (mainly to the east and south) by new urban developments. The airport constitutes an enclave to the northwest, around which shophouses have cropped up in irregular fashion. Finally, groups of villas stand on the periphery, not far from the newly developing areas. One can thus expect to see higher noise levels in the central sectors, as well as near the airport, and lower levels in the peripheral areas (villas and agricultural areas).

Road traffic in HCMC is typical of that in other major Southeast Asian cities. Scooters are by far the most popular mode of transport, due to their low cost and ability to weave in and out of very dense traffic. In a recent survey of 1,248 people, 75% of respondents stated that scooters were their most regular means of transportation, 7% rode bicycles, 7% walked, and only 4% used cars and 4% took public transportation [38]. Scooters are also known to be noisy vehicles that particularly affect the feelings of discomfort experienced by impacted populations [30].

In September 2007, Phan et al. [32] carried out an acoustic survey in HCMC and made 24-hour recordings of noise levels along several major roadways. They also used cameras to count the number of vehicles passing near the measuring devices. Their data show peaks of vehicle circulation between 7:00 a.m. and 10:00 a.m., and between 4:00 p.m. and 6:00 p.m. The noise levels reported (LAeq, hourly average) are relatively constant during the day after 7:00 a.m., with an Lden mean (daily mean) of over 69 dB. They also found that horns were used very regularly (12% of the total time measured), which increase exposure levels an average of 0 to 4 dB, and that they significantly contribute to the feelings of discomfort of the local population [31]. Phan et al. [33] also conducted a survey of 1,503 HCMC residents and recorded average exposure levels of between 75 and 83 dB (Lden): “It indicates that the respondents in both Hanoi and Ho Chi Minh City—especially those of the latter city—were more exposed to high levels of noise than Europeans.”

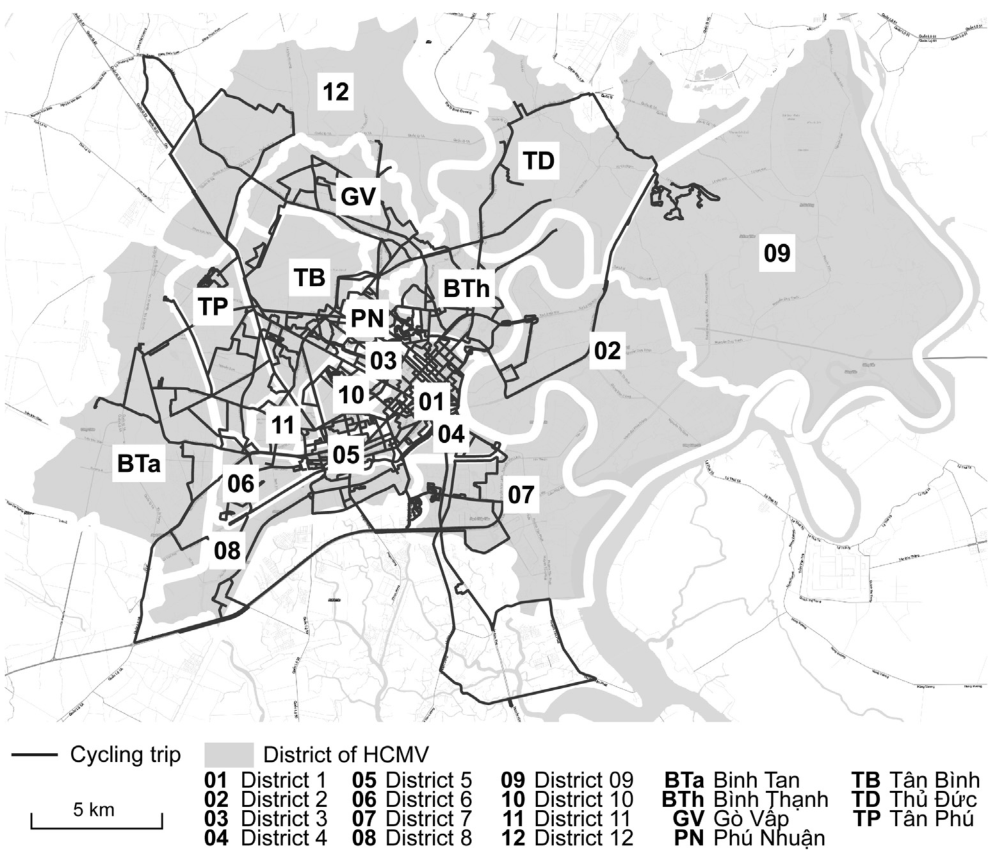

Fig. 1. Study area and sample routes.

3. Methodology

3.1. Data collection and design

For the purposes of this study, we directly collected new data on cyclists' exposure to noise in HCMC. Three participants cycled through the streets of the city Monday to Saturday from July 8 to July 20, 2017. They were accompanied by local guides so that they could travel through many different areas in the various districts of the city. Their trips were recorded using triathlon watches (Garmin Forerunner 920XT) equipped with GPS. Noise levels were measured with Class 1 dosimeters (Brüel & Kjaer Type 4448). We will be looking in particular at the LAeq measurement, that is, the average noise intensity at a one-minute time resolution. This noise intensity is measured in decibels A (dB(A)), that is, a decibel scale adjusted according to sound frequency. Higher frequency (more high-pitched) sounds correspond to higher dB(A) levels since the human ear reacts more strongly to high-pitched than low-pitched sounds. More specifically, we used the 3 dB(A) exchange rate, which means that an increase of 3 dB(A) on our scale corresponds to a doubled noise intensity. The observations therefore correspond to one-minute segments for which we know the average noise exposure level, as well as a series of other indicators that we will describe in greater detail further on in this section. Some 1035 km were travelled through the city in this manner, for a total of 55 h of collection, corresponding to 3300 observations (Fig. 1).

3.2. Methods of analysis

The first part of our analysis will be essentially descriptive and will compare the mean levels of noise exposure recorded by day of the week, time of day, and district. To compare these means, we will use bootstrapping to obtain confidence intervals through multiple random sampling. Then, in keeping with the first objective, various regression models will be constructed, with the measure of noise exposure (dB(A)) as the dependent variable and the trip characteristics and spatial and temporal dimensions as the explanatory variables.

3.2.1. Independent variables in the regression models

For each one-minute segment, we decided to introduce variables relating to the number of intersections crossed, types of roads taken, travel speed and slope (trip characteristics), day of the week and time of day (temporal dimension), and district (spatial dimension). Several hypotheses can be formulated regarding each predictor.

Concerning the type of road taken, data from Open Street Map (OSM) [12,18] were used to calculate the time spent on each of seven categories of segment for a specific observation period (that is, one minute): trunk, primary, secondary, tertiary, residential, service, and unknown. Note that the latter category corresponds to roads that did not yet exist in the OSM database or did not have a specified type. These were mainly minor, residential, or informal streets. Overall, we expected that noise levels would decrease from the trunk category to the residential street category.

As for the speed of the cyclist's travel, this can be considered as a complementary proxy to traffic. This indicator can provide certain information on the traffic, as vehicles around the cyclist are subjected to the same constraints as the latter. We can thus expect that when stopped, vehicles produce less noise, and that when accelerating, or when traffic is moving well, they produce more noise.

Along the same lines, a greater number of intersections crossed may mean slower and possibly less noisy traffic. On the other hand, it is also possible that a greater number of intersections means more vehicles speeding up again around the cyclist, leading to higher noise levels.

As for the slope, we can hypothesize that it has a direct impact on the noise generated by vehicle engines: when vehicles ascend a slope, noise exposure levels should be higher, and, conversely, when vehicles descend, noise levels should be lower, as there is less demand on vehicle engines.

In order to take the temporal variability of traffic into account, the days of the week are introduced in the form of dummy variables, with Saturday as the reference day; the time of day is introduced as a continuous variable, expressing the number of minutes passed since 7:00 a.m. We can then expect to observe peaks of noise exposure during the morning and evening rush hour periods.

3.2.2. Use of generalized additive models

As mentioned above, noise exposure is modelled using generalized additive models (GAM). Briefly put, a GAM is an extension of the generalized linear model (GLM). It thus makes it possible to predict a dependent variable transformed by a link function, based on a series of independent variables, by specifying a distribution of the dependent variable influenced by the independent variables (e.g. Gaussian, Poisson, scaled t-distribution, etc.). A GAM also allows one to adjust for certain predictors of non-parametric functions f_i rather than simple coefficients and thus to overcome the limitation of the linearity of GLM models [19,39]:

$$g(y) = \beta_0 + \beta x_1 + \cdots + \beta x_{n1} + f_{n2}(x_{n2}) + \cdots + f_n(x_n) + \varepsilon \tag{1}$$

with independent variables *1* to n_1 introduced linearly, and variables n_2 to n, in a non-linear fashion.

The curves estimated by these models can be observed through the predictions made by the model. More simply put, one can produce a graph representing the effect of a non-linear term. To do this, it is a matter of making this term vary within its interval while keeping all other variables at fixed values and of representing the values predicted by the model. If bivariate terms or interactions are used, the principle remains the same, but two variables are allowed to vary and the final graph then shows a heat map rather than a simple curve (for example: vis.gam function of the MGCV package, based on an original idea and design by Mike Lonergan).

Of note is the fact that several studies modelling noise according to the characteristics of the urban environment have already used GAM models such as land use regression, by Goudreau et al. [17] and Ragettli et al. [34]. Lin et al. [24] also employed this method to model the concentration of fine particles according to environmental noise (collected by a moving electric vehicle) and several meteorological variables. Dekoninck et al. [13] had also performed the same exercise, but, in this case, for the concentration of black carbon. This method has however, to our knowledge, never been used to model noise exposure.

In order to assess neighbourhood effects, we decided to build a generalized additive mixed model (GAMM) incorporating the hierarchization induced by neighbourhoods as a random effect. More specifically, we model a specific intercept according to the neighbourhood in which the observation is located in order to take the systematic difference in noise exposure by neighbourhood into account.

$$g(y_{ij}) = \beta_0 + \beta x_{1ij} + \cdots + \beta x_{n1ij} + f_{n2}(x_{n2ij}) + \cdots + f_n(x_{nij}) + u_{0j} + \varepsilon \tag{2}$$

with i being the observation, j the neighbourhood, and u_{0j} the intercept for neighbourhood j.

Given that the observations are located in both space and time, it is therefore appropriate to control for the phenomena of spatial [1] and temporal [9] dependence. One condition for the application of regression methods is that the observations must be independent; otherwise, the parameters obtained are biased. When this is applied to spatio-temporal data, we then expect that the residuals will be randomly distributed in space and time. To measure the spatial dependence of our models, we will use the classic Moran's I [26], which will be calculated on the model residuals and a proximity matrix. The index is thus written as:

$$I = \frac{N}{\sum_i \sum_j w_{ij}} * \frac{\sum_i \sum_j w_{ij}(X_i - \bar{X})(X_j - \bar{X})}{\sum_i (X_i - \bar{X})^2} \quad (3)$$

with N being the number of observations, j the series of observations neighbouring i, and w_{ij} the value of the matrix of proximity between pairs i and j. A negative value corresponds to a negative spatial autocorrelation, that is, a systematic dissimilarity between observations neighbouring one another. Conversely, a positive value corresponds to a positive spatial autocorrelation, that is, a systematic resemblance.

To measure temporal dependence, we use the ACF correlation index on the model residuals, defined as follows:

$$ACF = \frac{\sum_{t=h+1}^{T} (y_t - \bar{y})(y_{t-h} - \bar{y})}{\sum_{t=1}^{T} (y_t - \bar{y})^2} \quad (4)$$

It is simply the correlation between observation t and observation t-h (h being the time lag). As with Moran's I, a negative value corresponds to a negative temporal autocorrelation, that is, a dissimilarity between successive observations. Conversely, a positive value corresponds to a positive temporal autocorrelation, that is, a resemblance between successive observations. In sum, in order to respect the conditions for the application of regression models, the above two indicators must be close to 0 when they are calculated on the residuals. If not, they are considered as spatially or temporally dependent.

Finally, we will also present a more complete GAM model that takes into account spatial and temporal autocorrelation as well as the heavy tailed distribution of our data. To do this, the scaled t-distribution is used as the conditional distribution of our dependent variable in order to take into account its heavy tailed shape [40]. For temporal autocorrelation, we introduce an autoregressive (AR) model for errors in our model. The formula for our error term is then written as:

$$\varepsilon_i = \phi \varepsilon_{i-1} + \upsilon_i \quad (5)$$

which corresponds to the classic AR(1) process, with ϕ being an unknown autoregressive coefficient to be estimated [10]. This type of model is usually called a generalized additive model with autoregressive terms (GAMAR).

In order to take spatial autocorrelation and the presence of spatial tendency into account, we introduce a further term into the model, that is, a surface estimated by the model between the X and Y coordinates of the segments' centroids: that is, *s(x,y)*. This term allows us to capture variations in noise intensity in space when all other parameters are controlled for [14]. To picture this term, one has to imagine the dependent variable as a third dimension "of relief" above the geographic coordinates. The model then attempts to find a drape between the points of this space in three dimensions.

4. Results

4.1. Descriptive statistics

The mean noise level recorded during the trips was 78.84 dB(A) (with a 95% confidence interval of 78.75 to 78.94, obtained by bootstrapping with 5000 replications). Regarding the days of the week (Fig. 2.a), Monday and Wednesday were the noisiest days (means of 79.56 dB(A) and 79.17 dB(A) respectively) and Saturday the least noisy day (77.72 dB(A)). Concerning the time of day (Fig. 2.b), the highest noise levels were recorded in the morning (8:00 a.m.: 79.55 dB(A), and 9:00 a.m.: 79.48 dB(A)) and the lowest levels were in the mid-day period (12:00p.m.: 77.20 dB(A), and 2:00p.m.: 77.83 dB(A)). We found that meannoise levels varied significantly from one neighbourhood to another (Fig. 2.c), with the minimum means observed in the district 02 and rural areas (76.53 dB(A), 77.21 dB(A)) and the maximum observed in districts 12 and TB (80.15 dB(A), 80.17 dB(A)).

The results of this first descriptive analysis show that there are important temporal and spatial variations (by neighbourhood) that must then be controlled for in the subsequent regression models.

One can consider these inter-neighbourhood variations as a form of spatial autocorrelation. If we estimate the spatial autocorrelation of noise exposure levels with Moran's I using a distance matrix, we can see that the autocorrelation is greatest at a distance of 300 m (0.38) and always significant. This indicates a positive spatial autocorrelation, but probably at a finer scale than that of the neighbourhood.

4.2. GAMM model: Evaluating the neighbourhood effect

In order to measure the neighbourhood effect, a GAMM model was constructed by introducing a different intercept for each neighbourhood (random effect of the model). The other linearly controlled parameters are the time spent on each type of road, the day of the week, the number of intersections crossed by the cyclist, and the proximity to major arteries. Added to this are two non-linear parameters: the time of day, and the interaction between the slope of the segment travelled and travel speed. We will only analyze here the random part of the model and its validity criteria. The results of the other independent variables will only be described in detail for the final model.

With this first GAMM, we obtain an adjusted R^2 of 0.428. The addition of a different intercept for each neighbourhood helps to explain 4.63% of the total deviance and significantly improves the model without the random effect (AIC difference: 224.75; p-value of the chi^2 test on the fREML scores: >0.001). This indicates a substantial effect of the random part of the model, and thus a real variation in terms of noise exposure from one neighbourhood to another, all other things being equal. The fixed part of the model is of course more explanatory, as noise exposure is an immediate phenomenon that is more influenced by micro-characteristics (trucks passing, horns blowing, the density and fluidity of traffic, etc.) than by *meso*-characteristics (density of the neighbourhood, level of activity, presence of infrastructure, etc.). By observing the values of the intercepts and the standard deviations of their estimates (Fig. 3, the 0 represent the global intercept of the model), it can be clearly seen that the exposure levels are lower in peripheral areas (02, 07, TD, and 01 neighbourhoods, and rural areas) than in central neighbourhoods (09, TB, GV, 11, and 10). The differences observed here are of course smaller than those seen with the descriptive analyses (Fig. 2.c), since all the other parameters are controlled for.

It should be remembered that a difference of 3 dB(A) corresponds to a doubling of noise intensity, which means here that in rural areas, the mean noise exposure is already nearly twice as low as in neighbourhood 09, regardless of the time of day or type of road that the cyclist is travelling on.

Although interesting, this GAMM model presents a problem of both spatial and temporal dependence. Indeed, the model residuals are significantly autocorrelated with a maximum Moran's I value of 0.177 ($p < 0.001$), obtained with a matrix of proximity of 400 m. As for the ACF temporal correlation coefficient, it is highest (0.469) when the correlation with the previous observation is calculated

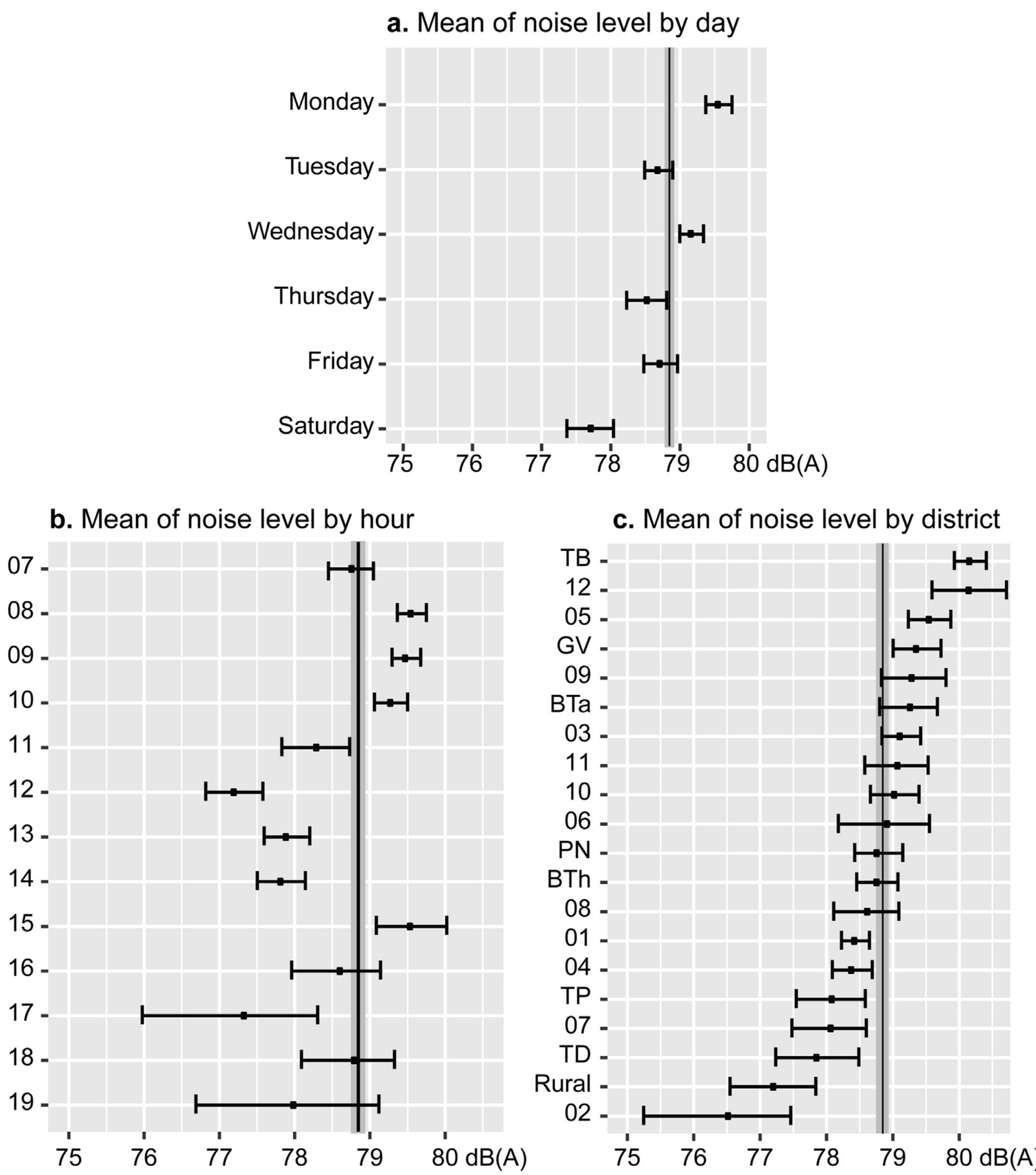

Fig. 2. Noise mean values by day, hour, and district.

(lag = 1). Finally, as shown in Fig. 4a (right side), the distribution of the model residuals is close to normality (skewness = −0.057), with however a few extreme values that tend to distort it (kurtosis = 6.337). Moreover, the scatter plot in Fig. 4.a (left side) clearly shows that the model is poorly adjusted for these extreme values (lower than 70 dB(A) or higher than 90 dB(A)).

The mean level of noise exposure in our sample is approximately 79 dB(A). Levels below 70 dB(A) would thus be less than eight times lower than the mean for the entire set of data. Similarly, levels above 90 dB(A) would be more than sixteen times higher than the mean observed. Although this model is informative as to the effect of the neighbourhoods, we will not describe the other parameters in any greater detail as the model is not adequately adjusted; we will however do this for the model in the next section.

4.3. Final GAMAR model: Integration of all dimensions

In order to determine the effect of the trip characteristics and of the temporal and spatial dimension, we provide a second, better adjusted model that includes two other parameters: that is, an AR1 temporal autocorrelation structure (ϕ is estimated at 0.469, based on the residuals of the first model), and a bivariate spline on the X and Y coordinates of the segments' centroids, termed *s(x,y)*. This second model no longer includes the random term for the neighbourhoods. Indeed, in controlling for the concurvity of the model terms, it appears that the effect of the neighbourhoods and of the spatial term mostly overlap. The more complex *s(x,y)* spatial term thus covers the effect of the neighbourhoods, which can then be removed from the model. This is not surprising, as it can be explained by the fact that noise is a continuous phenomenon. It is not limited to the boundaries of the neighbourhoods and varies at a finer scale, as indicated by the Moran's I obtained on the noise exposure levels presented in the first section of the results.

4.3.1. Assessment of the model

The adjusted R^2 of the final model is 0.41, that is, slightly below that of the preceding model (0.428). A direct comparison based on the R^2 values of these two models is however difficult, as the

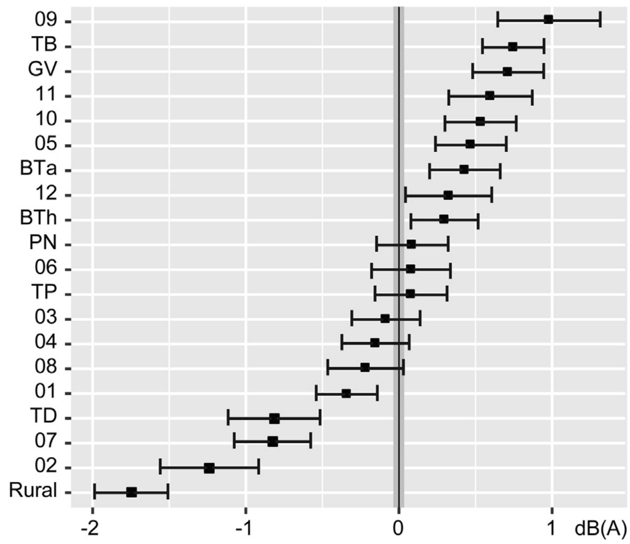

Fig. 3. GAMM Intercepts for the districts.

second includes an AR1 temporal autocorrelation structure. So it is preferable to compare the values of their respective fREML [39]. It is evident that the second model is far better adjusted than the first (7205 versus 4997), which represents a major improvement given the fact that only one predictor is added: that is, *s(x,y)*.

Aside from a better quality of adjustment, this latter model offers two other important improvements. First, the spatial and temporal dependence observed in the first model is corrected (Fig. 5). And, second (Fig. 4b), the residuals are very close to a normal distribution (skewness = 0.008, and kurtosis = 3.078, p-value with the Shapiro test = 0.53). Also, rather than removing the previously mentioned extreme values, we decided to change the conditional distribution of the model for a scaled t-distribution (see methodology).

4.3.2. Analysis of the linear parameters of the model: Trip characteristics

Table 1 (linear terms) presents the results for the predictors linearly added to the model. Only one variable was found not to be significant: the number of intersections crossed.

Regarding the days of the week, the coefficients show that Saturdays were the days with the lowest mean noise exposure, and that Mondays and Wednesdays were the days with the highest levels: 2.15 dB(A) higher for both. The design of this study does not enable us to state that noise exposure levels were systematically higher on Mondays and Wednesdays or lower on Saturdays because we do not have a long enough range of time in our study to make these inferences. On the other hand, we can highlight the systematic variability from one day to another and note the appropriateness of controlling for this in modelling exercises.

It is not surprising that noise exposure is strongly associated with the type of road taken and follows the hierarchization of the OSM typology. Thus, compared with a street with an unknown

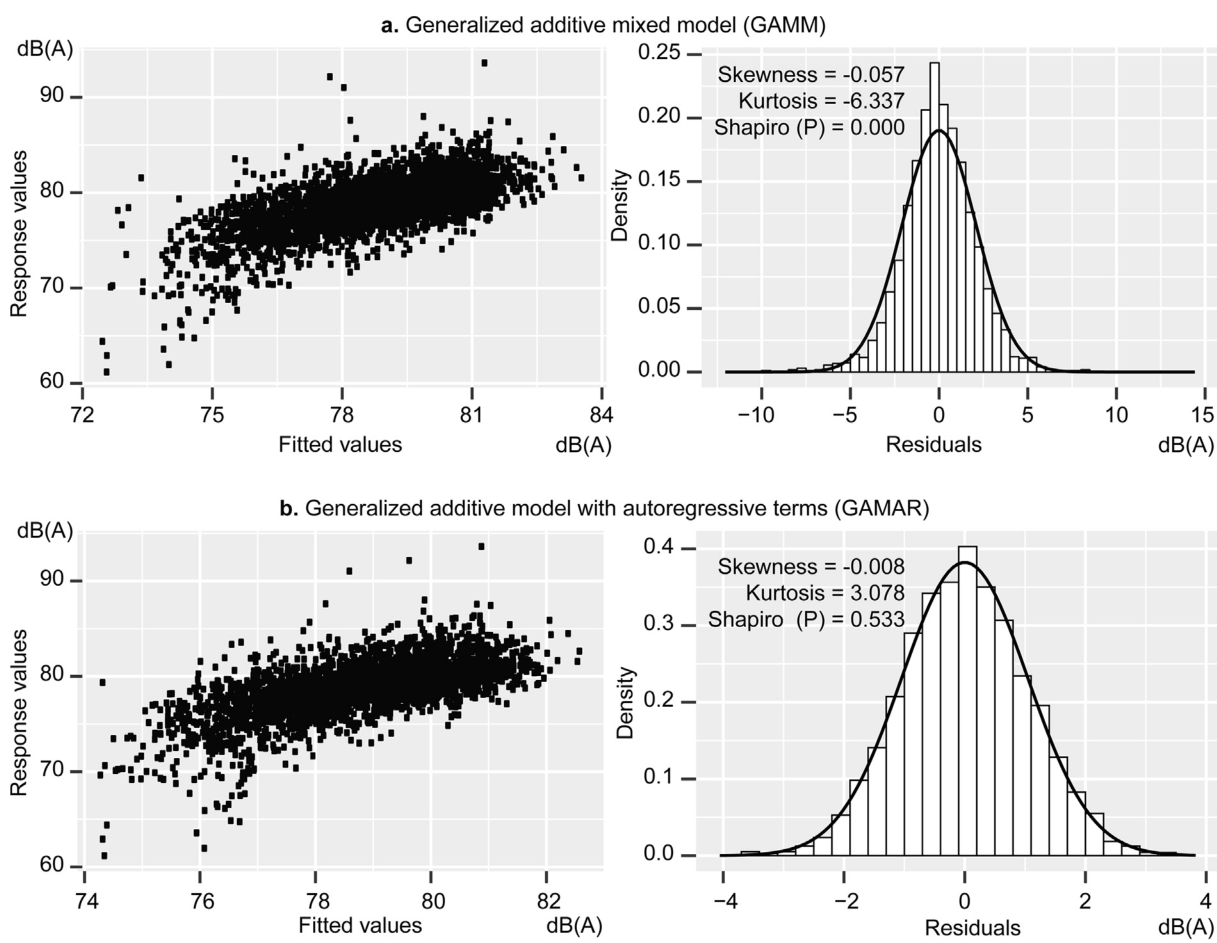

Fig. 4. Diagnostic plots of residuals (GAMM and GAMAR).

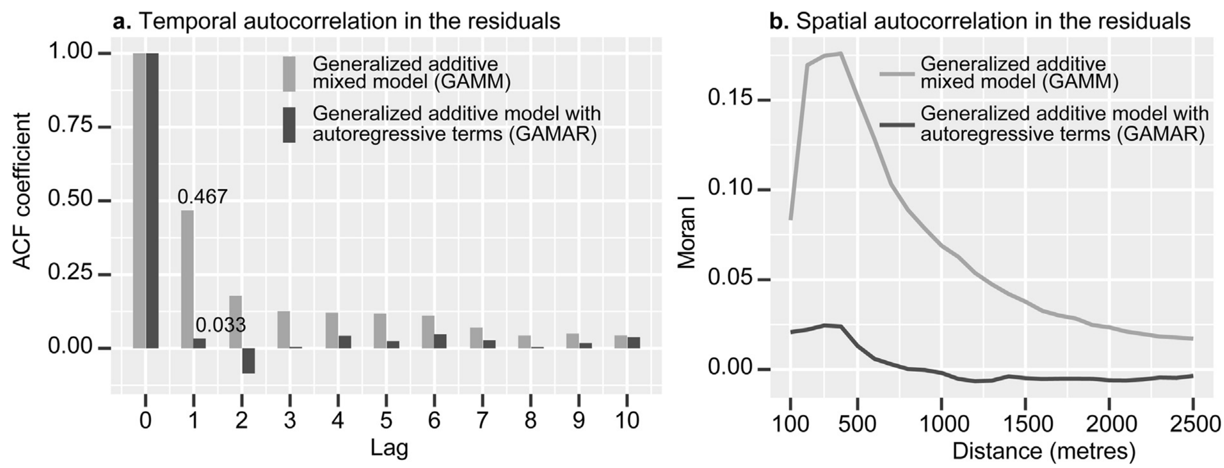

Fig. 5. Diagnostic plots of temporal and spatial autocorrelations.

Table 1
GAMAR regression.

Linear terms	Estimate	Std. Error	T	Pr(>|T|)
(Intercept)	75.114	0.411	182.593	0.000
Monday	2.152	0.275	7.817	0.000
Tuesday	1.634	0.274	5.960	0.000
Wednesday	2.153	0.262	8.205	0.000
Thursday	1.471	0.274	5.358	0.000
Friday	1.549	0.282	5.500	0.000
Saturday	Ref.			
Number of intersections crossed	0.014	0.010	1.419	0.156
Unknown type	Ref.			
Trunk	4.737	0.493	9.609	0.000
Primary	3.250	0.354	9.169	0.000
Secondary	2.939	0.367	8.017	0.000
Tertiary	2.123	0.349	6.085	0.000
Residential	0.229	0.353	0.648	0.517
Service	−1.081	0.424	−2.551	0.011
Non-linear terms	edf	Ref.df	F	Pr(>|F|)
s(Time from 7:00 a.m.)	4.817	5.845	10.570	0.000
te(Slope, Speed)	11.409	14.238	4.431	0.000
s(CoordX, CoordY)	18.866	23.744	5.656	0.000

typology, spending one minute on a trunk road increases mean noise exposure by more than 5.13 dB(A), with an increase of 3.41 dB(A) for primary roads, 3.07 dB(A) for secondary roads, and 2.24 dB(A) for tertiary roads, which are sizeable differences. Moreover, there is no significant difference between noise exposure on a residential street and on a street with an unknown typology, which indicates that these streets probably resemble residential streets. Finally, service roads are the roads with the lowest levels of exposure, which is explained by the fact that they are little used. The difference, compared with streets with an unknown typology, is not however very significant given the number of observations ($p = 0.017$, $n = 3300$). This leads one to believe that, in terms of noise exposure, service roads are close to streets with an unknown typology, and, by extension, residential streets.

4.3.3. Analysis of the non-linear parameters of the model

The results obtained for the three non-linear predictors are reported in Table 1 (non-linear terms). Each has a significant effect (p-value < 0.000). In examining the estimated degrees of freedom (edf), it is not surprising to see that the spatial term shows more “wiggliness” than the interaction between slope and speed and the time of day. So this is the term with the most complex pattern. For each of these terms, we intend to analyze the values predicted by the model, in keeping all other variables at their mean value and in using Monday as the day of the week, with 30 s spent on a primary road and 30 s on a secondary road.

For the time of day, we find that noise exposure levels are especially high between 7:00 a.m. and 9:00 a.m., which corresponds to

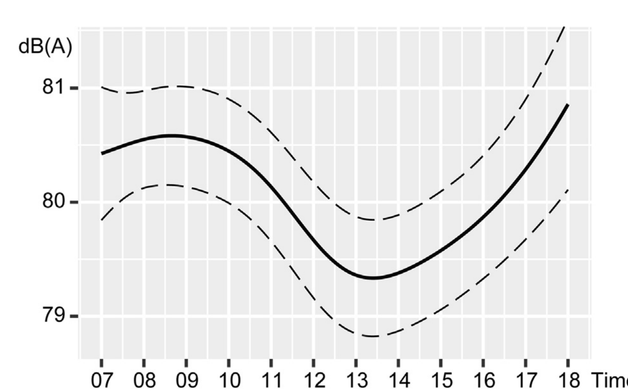

Fig. 6. Temporal trend of noise exposure.

the morning rush hour period (Fig. 6). The levels of exposure then diminish as of 10:00 a.m., to reach their mean minimum level around 1:00p.m. By 2:00p.m., noise exposure levels again increase, reaching levels comparable to those in the morning rush hour between 5:00p.m. and 6:00p.m. If night trips had been taken, the function would probably have then diminished after 6:00p.m. It is interesting to note that the differences between the upper and lower limits of the confidence intervals rise to more than two decibels between the time of day when noise exposure was highest (81 dB(A)) and the time when it was lowest (79 dB(A)).

Fig. 7 shows the term of interaction between slope and speed. We decided to mask sectors of interaction for which we had no data (in white on the figure; for example, a speed of 30 km/h with a positive slope of 3%). The graph reveals several interesting findings.

First, noise exposure is lowest when traffic is moving well (cyclist's speed of about 20 km/h) and when the slope is gentle (between −1 and +1%), shown by the circle in the centre of the figure. Second, when the speed increases (25 km/h and over), noise levels also tend to rise. We can thus surmise that in very fluid traffic, vehicles are moving faster and their engines therefore generate more noise. The same effect was notably found by Boogaard et al. [8] and Apparicio et al. [2]. Third, when the speed drops and is close to 0, noise levels also increase. This could perhaps be explained by motorists' more frequent use of the horn when traffic is congested in HCMC. Fourth, a positive slope of over 1% increases noise exposure levels as well, as vehicle engines must work harder, with the opposite of course being true when the slope is negative.

Finally, to illustrate the spatial pattern of noise exposure, the spatial term of the model can be mapped (Fig. 8). We must point out straightaway that this is not a map of the concentration of noise levels in Ho Chi Minh City. This map must be read in relative rather than absolute terms since, aside from space, all other terms are kept at their previously described values. So the map can be read as representing environments where, on average, all other things in the model being equal, noise exposure levels were highest. This term can thus be analyzed as an estimation of residual environmental noise that would have been measured by the dosimeters, presenting a spatial structure, but not explained by the other covariates in the model.

On this map, to avoid any risk of overinterpreting the results, we masked areas not covered during the data collection (particularly the airport area). This map shows that lower levels of exposure were recorded to the south and along the Saigon River. The Khen Doï canal in fact seems to mark the southern limit of the city's urbanization. These environments correspond to spaces that are as yet little developed, and even agricultural. Sectors with the highest exposure levels are found around the airport area and in the central neighbourhoods, characterized by strong population densities and dense built environments. Added to this is a second sector with high exposure levels to the northeast of the city, where there has been a resurgence of urbanization.

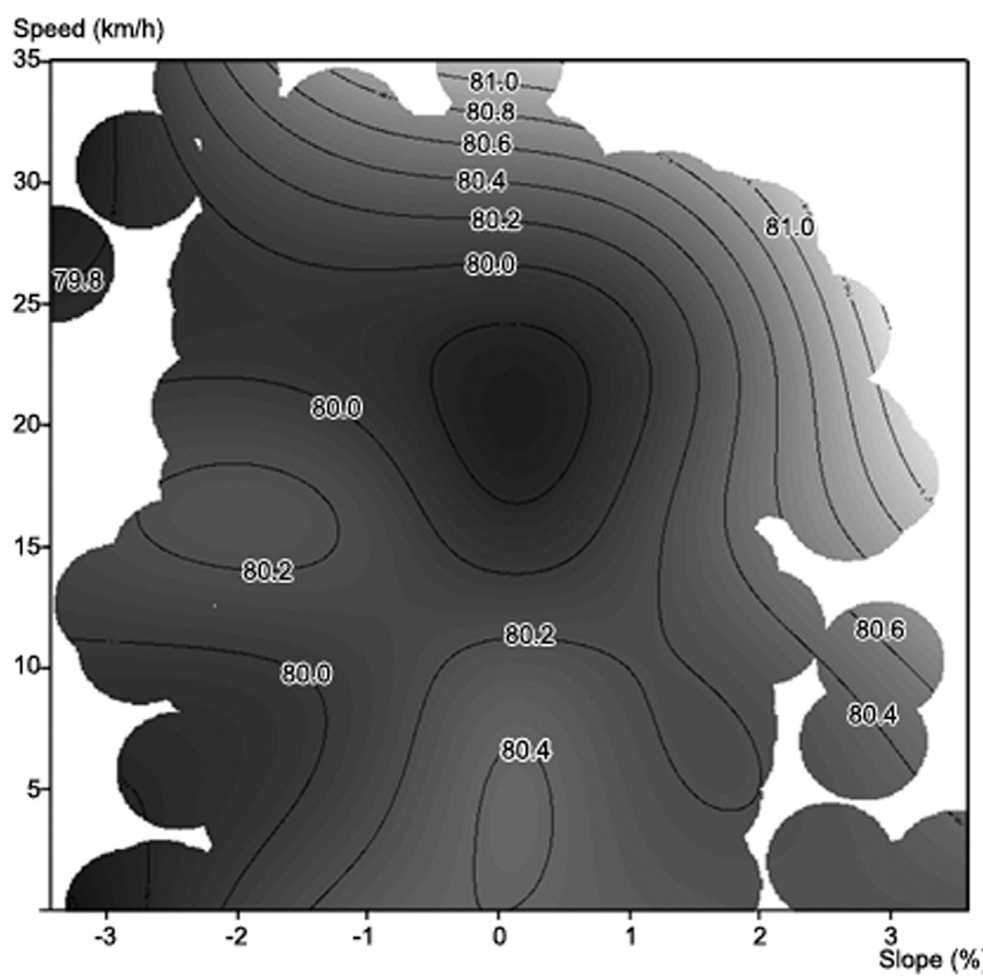

Fig. 7. Interaction between speed and slope for noise exposure.

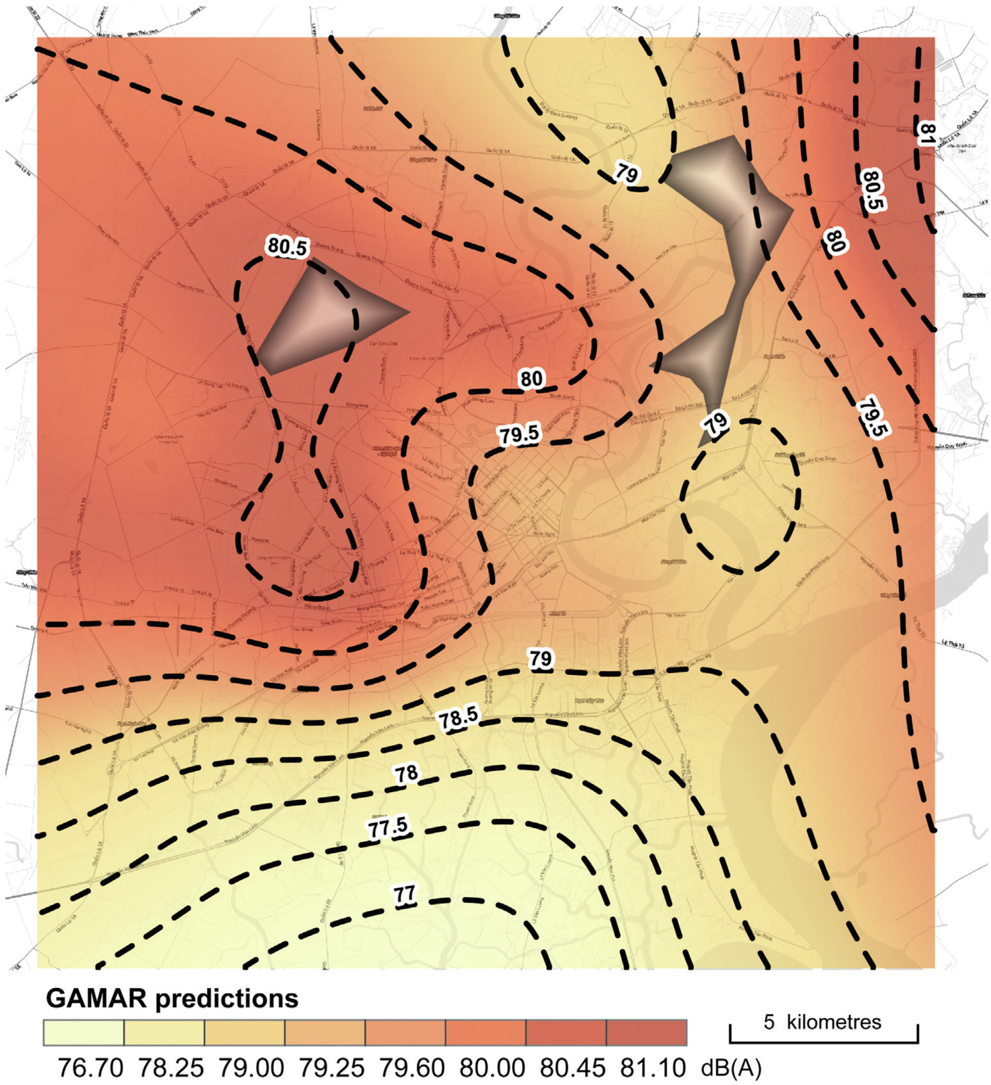

Fig. 8. Spatial trend of noise exposure.

5. Discussion

5.1. Limitations of the study

Even though we travelled over more than 1000 km, some sectors of the city were less well covered or little covered. Consequently, other data collections could conceivably be carried out with more participants and more trips in order to produce a more comprehensive profile of noise exposure in HCMC. Secondly, using a typology of roads as a traffic indicator does not enable one to distinguish between the effect of the traffic and the effect of the type of road. Indeed, noise is better disseminated in wide streets, whereas narrow streets mean it is more likely to reverberate. To our knowledge, there is however no set of data that includes, for example, building footprints that would allow us to derive complementary indicators.

5.2. Worrisome noise levels

It is important to note straightaway that the noise exposure levels recorded in HCMC are a concern. Indeed, a mean of 78.5 dB(A) directly raises the question of the impacts on health, since, as of 75 dB(A), the threshold of discomfort is largely surpassed, and 80 dB(A) is the level at which direct damage to hearing appears. Even though cycling is not the most popular mode of transportation in HCMC, it should be emphasized that scooter users are also concerned because they do not have any cabin either to isolate them from noise. And their levels of exposure are probably even higher than those that we measured due to their continuous proximity to their own engines. It is interesting to compare the noise levels recorded here to those found in other European and North American cities: from 63 to 65 dB(A) in eleven Dutch cities [8], 70.5 in Montreal [2], 70 in Rotterdam, 73 in Helsinki, and 75 in Thessaloniki [29].

5.3. Comparison with previous studies on HCMC

It is also interesting to note that our results corroborate the findings of earlier studies conducted in HCMC. First, regarding the temporal dimension, our results are in keeping with those of [27]; Phan et al., 2010a), who observed more intense road traffic as of 5:00 a.m., which reached an initial peak between 8:00 a.m. and 9:00 a.m., followed by a decrease until 1:00 p.m., when traffic started up again, between 5:00 p.m. and 6:00 p.m, with levels comparable to the morning period. This thus corresponds to the temporal tendencies shown in Fig. 6.

Second, Nguyen et al. [27] indicated that "all sites exposed to aircraft noise around the main airports in [HCMC] were also exposed to heavy road traffic noise." They reported in particular aircraft noise exposure indicators (LAeq, day 7:00 a.m.–7:00 p.m.) ranging from 52.0 dB to 65.8 dB in the ten locations studied, and road traffic noise exposure indicators varying from 69.3 dB to 76.9 dB, for combined totals ranging from 69.4 dB to 76.9 dB. These sectors thus seemed to be noisier than the rest of the city, which the spatial term was also able to show in our model.

Third, it is possible to relate the spatial term of the model to the map of the spatial organization of the city developed by Downes et al. [15] and described in the introduction. Sectors where noise exposure was systematically lower are concentrated around the Saigon River and to the south of the Khen Doï canal. In both cases, these are peripheral areas of low density (in terms of population and the built environment), comprised of rural areas, villas, or sites under development. The noise discrepancies between these areas are very strong, ranging from 73 to more than 78 dB(A). This means that in the central sectors or areas near the airport, noise exposure levels are up to four times higher than in rural or less dense environments.

The mapping of the spatial term is particularly interesting here because it can be used for planning and decision-making purposes. With the aim of protecting cyclists against noise, it would be possible to design bicycle routes that prioritize the use of these sectors, where exposure levels are lower.

Finally, the use of GAM models provided pertinent information on noise exposure, especially concerning the spatial and temporal dimension. They also made it possible to define the complexity of the interaction between speed and slope regarding noise exposure. The models could be applied in other cities and for other types of nuisances (air pollution, road accidents, etc.).

5.4. Pertinence of OSM data

The use of OSM data allowed us to effectively model the impact of the type of roads taken on cyclists' noise exposure in HCMC. OSM data are available for almost all big cities around the world. They thus provide a common nomenclature for types of roads in these cities. So it would be advisable to prioritize these data in the future, in order to facilitate direct comparisons between a number of cities.

6. Conclusion

It was not surprising to find that cyclists' levels of noise exposure in HCMC are very high compared with cities in the North, which can be explained in particular by the density of the traffic, the large proportion of scooters, and the frequent use of horns. The models showed that several trip characteristics together significantly increased noise exposure levels: the type of roads—with residential streets and service roads being the least noisy—the slope, and the cyclist's speed. The temporal dimension is also important, with significant variations according to the day of the week (Monday being the noisiest), and the time of day (especially the morning and evening rush hours). On a methodological level, the use of generalized additive models proved to be very effective in showing temporal variations, spatial variations, and the complexity of the interaction between slope and speed regarding noise levels.

Authors competing interesting

The authors declare that they have no competing interests.

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