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Estimation of the noise emissions generated by a single vehicle while driving

César Asensio *, Ignacio Pavón, Carlos Ramos, Juan Manuel López, Yolanda Pamiés, Diego Moreno, Guillermo de Arcas

Universidad Politécnica de Madrid, Instrumentation and Applied Acoustics Research Group, c/ Mercator 2, 28031 Madrid, Spain

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ABSTRACT

This article presents a method of calculation that allows us to separate the contribution of a specific vehicle to the overall noise pollution in an urban environment. This method will provide local authorities with new operating models so that the cost of noise can be allocated to a vehicle according to factors such as the number of people it affects, the distance traveled and journey time, the driving style and the type of vehicle and tires. The proposed methodology can be adapted to different noise emission and propagation models, and we select as a basis the CNOSSOS-EU framework for compatibility with the European noise mapping strategy.

This method will make it possible to reduce road traffic noise using two long-term strategies: (a) separate distributions of the costs of noise among the vehicles that generate it, with the aim of achieving (b) an increase in pro-environmental behavior with regard to this pollutant.

1. Introduction

The latest European Environment Agency and World Health Organization estimates are that road traffic noise causes 100,000 cases of premature death annually in Europe and is associated with an annual environmental noise burden of 1.6 million lost healthy life years (disability-adjusted life years — DALYs) in Western European urban areas (Basner and Mcguire, 2018; WHO Regional Office for Europe, 2011; Juraga et al., 2015). In fact, the WHO recognizes noise as the second most common cause of illness in the EU from exposure to pollutants, behind only motor vehicle-generated particulate matter. The estimated social costs of environmental noise across the EU amount to 40 billion euros per year, of which 90% is related to road traffic (passenger cars and heavy vehicles), representing approximately 0.4% of the total EU GDP. According to the Commission's 2011 White Paper on Transport, external costs related to transport noise will increase to approximately 20 billion euros per year by 2050 if no action is taken (Directorate General for Mobility European Commission and Transport, 2011; European Economic and Social Committee, 2015).

The EU recognizes that more effort is needed to reduce noise pollution in Europe and is indeed undertaking a thorough process of assessment and review of noise pollution with the aim of improving the effectiveness of mitigating it. In 2015, Annex II of Directive 2002/49/EC was modified, and a calculation method for the assessment of environmental noise, known as CNOSSOS-EU, was published (European Parliament, 2002; Paviotti and Kephalopoulos, 2016). Furthermore, following the latest WHO update on the effects of noise on health, Annex III of the Directive was approved, which describes the methods for calculating the burden of disease caused by exposure to different levels of environmental noise. The quantification of the disease burden related to environmental noise poses an emerging problem for policy makers that has not yet been sufficiently addressed, whose cost estimation is not yet fully realized and which will need to be addressed with multidisciplinary approaches and solutions.

* Corresponding author.
E-mail address: c.asensio@upm.es (C. Asensio).

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In 2011, Directive 2011/76/EU, known as the "Eurovignette Directive" (European Parliament, 2011), established a method by which EU member states could integrate and internalize the health costs of environmental pollution through any type of road and motorway tax structure. The revenue from these charges should be invested in sustainable transport, with the decision on whether to adopt transport charges being left to individual member states. It was envisaged that the charges passed on to heavy goods vehicles could vary according to the type of road, the type of vehicle and, in the case of noise, the driving period (day or night) by establishing models for the calculation of costs. The aim of this directive was to establish differentiated noise charges to reward the quietest vehicles (Moliner et al., 2013).

There are other examples in the EU in which the introduction of transport noise charges is being progressively introduced, such as in the case of implementing regulation (EU) 2015/429. This regulation is a good example of the implementation of policies to internalize the external costs of transport, where the cost of noise pollution is discriminated against according to the characteristics of the emitter, the population exposed to different pollution levels, the noise sensitivity of the area affected, the population concerned and the composition of the train, which ultimately passes on noise charges for the use of railway infrastructure (European Parliament, 2015).

Another example of the application of noise charges is that at airports where noise charges are established, the aim is to discourage the use of the noisiest aircraft by adding penalties to the amount to be paid for landing by aircraft that exceed the established noise certification limits.

At present, noise charges are only applied to railways, aircraft and heavy road transport to internalize noise costs; they are applied to the latter in a very limited and contained way and only in some EU countries. In general, the distribution of costs is very coarse and does not discriminate among the time of use of the infrastructure, the specific area traveled through, the population exposed, or the specificity of noise emissions according to the speed of traffic, driving style, vehicle category, etc. It therefore seems necessary to move towards a more equitable and differentiated distribution, both in the identification of noise emission costs and in the responsibility for the contribution of emission levels and their correspondence to the effect on DALYs of each individual vehicle. Currently, traffic noise control in European urban environments focuses on (a) acoustic inspection of vehicles; (b) sound-absorbing pavement; (c) tire noise models; (d) acoustic barriers; (e) acoustic insulation of facades; (f) absorbent plant facades; (g) urban planning; and (h) traffic restrictions (Kamal and Bas, 2021; Lavrentjev and Rämmal, 2020; Fredianelli et al., 2019; Sánchez-Dehesa et al., 2011; Licitra et al., 2017, 2019; Del Pizzo et al., 2020; Praticò, 2014; Praticò and Anfosso-Lédée, 2012; Vázquez et al., 2020; Paje et al., 2014).

With this paper, we aim to initiate a path to the implementation of future policies based on participatory noise management, which will make it possible to reduce emissions in certain areas with high environmental noise protection, using two long-term strategies: (a) a differentiated distribution of the costs of noise among the vehicles that cause it, with the aim of achieving (b) an increase in pro-environmental behavior with regard to this pollutant. This is an approach that aims to complement traditional practices, with the aim of moving towards sustainable transport by charging the costs associated with the noise of each vehicle according to its individual contribution.

This new approach aims to restrict, dissuade or discourage vehicle access to certain acoustically sensitive areas in a city. To this end, it is necessary to establish equitable mechanisms that allow the contribution to noise pollution by each vehicle to be broken down independently and differentiated, discriminating among the type of vehicle, time spent in the area, route, type of driving and population affected. It is based on the main assumption that charging users for the costs associated with the traffic noise generated by their own vehicles will succeed in discouraging the use of private vehicles and changing the behavior of the noisiest drivers (Ibarra et al., 2012), leading to a reduction in noise pollution in certain areas requiring noise protection. To achieve this, we propose facilitating tools for the implementation of participatory traffic management models, which allow drivers to be co-responsible for polluting emissions, in pursuing sustainable mobility in cities.

In this paper, we aim to provide technological tools that drivers can use to determine the effect that their driving has on other people and to modify their behavior or routes to reduce these effects. The method that we describe will determine the contribution of a vehicle to community noise based on the population it affects along its route, the distance traveled, journey time, level of exceedance of the limits in an area and time period and noise emissions, which depend on the type and state of maintenance of the vehicle and road surface, the speed of the vehicle, the acceleration and the type of driving. With this method, vehicle movements and their dynamic constants are monitored to determine the noise emissions in the form of instantaneous noise maps along the route, cumulative noise maps of the area and the number of people affected. In this way, it will be possible to determine the noise share and costs of each individual vehicle, taking into consideration the type of vehicle, time of day and population density in the pricing criteria described (Swärdh and Genell, 2020).

According to the proposed hypothesis, the monetizing of these models by local authorities and the information given to the user while using the vehicle will allow drivers to define and adjust their routes according to economic and environmental criteria. The method described in this paper will serve as a starting point for the implementation of future participatory traffic management policies, through which users will determine their own routes and schedules, adding economic factors (from the user's point of view) or environmental factors (from the city's point of view) to the decision-making process.

Based on this new method, we will enable initiatives dealing with transparency and participation in environmental management, addressing new mechanisms for democratizing environmental noise and the fair and differentiated distribution of costs, with a multidisciplinary approach aimed at applying concepts such as "polluter pays" as applied in the Eurovignette directive, "pay to use" as applied in several European cities with low-emission zones (LEZs) implemented (applying access tolls or congestion charges), or the "pay-as-you-drive" concept, which is becoming increasingly relevant in the car insurance sector. These concepts have not yet been applied to traffic noise management in cities (Tselentis et al., 2016; Bolderdijk et al., 2011; Istamto et al., 2014).

It will also allow (a) monitoring of the access and length of stay of the noisiest vehicles in restricted areas or periods, (b) quantification and calculation of the costs related to the harmful effects of environmental noise, and (c) modification of the private vehicle demand using equitable pricing tools based on environmental criteria (European Parliament, 2020).

2. Methodology

The methodology presented in this paper aims to characterize the temporal evolution of the noise emitted by a single vehicle in transit and to determine the impact it has in the study area. The aim is therefore to generate a dynamic noise map that is updated instantly based on the vehicle's emissions, which in turn are determined by its own traveling conditions. In addition, the cumulative effect will be determined, integrating the noise emissions that the vehicle generates over a given assessment period (usually a day, evening or night). This will generate a second dynamic noise map, which will be refreshed at the same rate as the instantaneous maps but will show the cumulative effect of all the maps included within the assessment period considered, up to the instant displayed. The instantaneous level dynamic map does not take the assessment period into consideration. However, the cumulative maps will take into account the start, current and end times of the assessment period. Once the final time of the period has been reached, the accumulated map will become static and will show the cumulative sound emission levels that the vehicle has generated during the whole evaluation period, for example, by means of the indicators L_d, L_e and L_n. Thus, the instantaneous map will reflect the value $L_p(t)$, while the accumulated map will reflect ($L_{eq,T}(t)$ for $0 < t \leq T$).

Dynamic noise maps are not new. Typically, they are intended to capture the dynamics of noise beyond the long-term statistical representation. For this reason, it is very common to find projects and initiatives that incorporate measurements into the maps to capture the temporal evolution of noise over time. Some of these initiatives are based entirely on measurements at fixed or mobile measurement locations, the results of which are subsequently interpolated spatially to produce the map. The main drawback of this approach is the low spatial resolution. Therefore, the most commonly developed dynamic maps are based on an acoustic model of the area to be mapped and a recalibration by means of measurements at selected points. The measurement rate determines the update interval of the map. With increasing advances in technology, some variations of these approaches have emerged that incorporate smart city sensor networks or even citizen collaboration through smartphone measurements. The researchers on the Life-Dynamap project conducted a review of all these projects in compiling the state of the art prior to their new approach (Cerniglia et al., 2015; Wei et al., 2016). This Life-Dynamap project has gained the most relevance in recent years, as it is financed by the European Commission and has been implemented in two large cities, Rome and Milan. The project uses low-cost sensors that were developed entirely to discriminate traffic noise from other sources, and it integrates these measurements with noise models. Thanks to the measurements, the system is able to readjust the road emission models by section and update the noise maps periodically (Sevillano et al., 2016).

The method presented in this article has two fundamental differences with respect to all these initiatives. First, it is not intended to characterize the noise produced by traffic as a whole but the emissions of a single vehicle. Second, the noise dynamics are not collected directly through noise measurements but indirectly through vehicle location and speed measurements (or any other parameter that the selected emissions model may consider). The method we describe is more similar to that used to obtain the dynamic map produced by the overflight of an aircraft based on a segmentation of the route followed, the type of aircraft and thrust parameters (such as NPD curves), with the difference that the new method includes a propagation model that allows the effect of terrain, buildings and weather conditions to be incorporated into the map, and it speeds up the process of the prior calculation of the propagation models involved (Jäger et al., 2021; Wunderli et al., 2018, 2017; Bopst, 2017; Notario, 2014).

For each discrete position where the vehicle moves, a point-to-point calculation model (see Fig. 1) is applied to obtain the sound levels (L_p) that the vehicle is producing at all the receivers in the study area according to the location of the vehicle, the power it is emitting (L_w) and the attenuation experienced due to the sound during its propagation (A).

The sound power level will vary over time, depending on the driving conditions, the type of pavement the vehicle is driving on, its speed, etc. As the vehicle changes its position over time, so does the attenuation between the sound source and each receiver, and consequently, for each reception position, the instantaneous noise level will vary, as shown in Eq. (1):

$$L_p(t) = L_w(t) - A(t) \tag{1}$$

The emission model will determine the sound power level, Lw(t), by taking as inputs the vehicle's driving conditions, which change over time. In addition, a propagation model will be applied to determine the sound attenuation between the location of the vehicle at each instant and the location of a given receiver, A(t). To do this, it will be necessary to track the position of the vehicle over time to calculate the attenuation associated with that position. This calculation can take quite a long time, depending on the number of obstacles considered, the order of reflections, etc. Additionally, it must be calculated for each possible receiver of interest, from any position of the vehicle. However, we must take into account that, for each propagation condition considered, the point-to-point attenuation (A, in Fig. 1) will not vary with time; rather, it is the change of position of the vehicle that makes A(t) time dependent. Therefore, if we know in advance the attenuation of sound for each possible position that the vehicle may occupy, we will be able to speed up the calculation procedure considerably. For each position of the vehicle, we will have a vector of attenuations in advance, whose coefficients will determine the attenuation between the position of the vehicle, i, and the receiver at location j.

Thus, the proposed method requires an emission model to calculate the power emitted by the vehicle under study and a propagation model, both of which can be as sophisticated and complex as required, depending on the application. By tracking the vehicle position and using as many parameters as the emission model requires, the acoustic emissions and the attenuation vector to apply will be determined. From the sum of the power level and the attenuation vector, the instantaneous noise map can be calculated in a very fast and efficient way. The details of the models selected initially are given below.

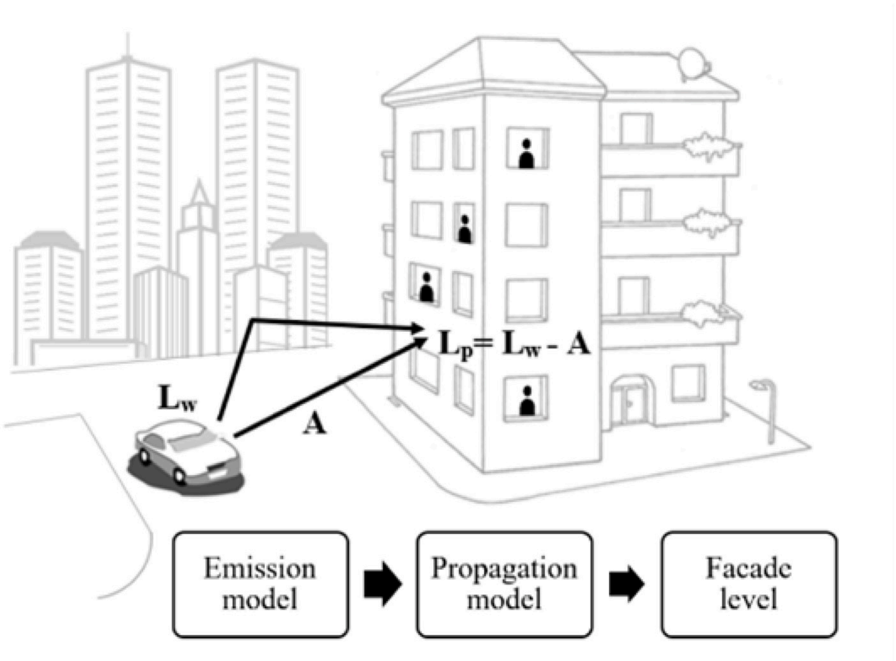

Fig. 1. Overall point-to-point prediction method.

2.1. Emission and propagation model

The proposed method requires a model for calculating the sound power emitted by a vehicle. For this purpose, we decided to take as a reference the CNOSSOS-EU framework (Kephalopoulos et al., 2014) for traffic noise. This method is in accordance with the European Union directive 2002/49/EC, so its use will make it possible to obtain results consistent with those obtained in the noise maps produced by the member states in agglomerations or major roads. However, this emission model is only used to provide the sound power emitted by the source, so any other model that can provide this parameter could be applied. Furthermore, it should be taken into account that the model must be slightly adapted to consider only one vehicle and instantaneous traffic conditions instead of the long-term statistical data used by the regular CNOSSOS-EU framework (Anfosso-Lédée et al., 2010; Bertellino et al., 2016; Coelho et al., 2011).

The elements that mainly determine the generation of noise are the type of vehicle and its speed, together with the type of road surface and other variables derived from the driving conditions. The CNOSSOSS-EU model does not include factors such as the condition of the vehicle and the pavement or the type of driving, which could lead to new versions of the emission model that would make it possible to describe the vehicle's emissions more accurately. Nevertheless, the proposed methodology imposes hardly any restrictions on the emission model used, so the method would be compatible with all kinds of improvements.

In any case, all these parameters are included in the calculation of the sound power level emitted by the vehicle when driving, which is expressed in the two terms that comprise it: the propulsion noise produced by the engine and exhaust and the rolling noise, the latter being a direct result of the contact of the vehicle's tires with the road surface on which it is traveling.

The expressions for calculating the sound power level emitted by rolling (L_{WR}) and propulsion (L_{WP}), both in dB, are shown in Eqs. (2) and (3), respectively, and are valid for average speeds between 20 and 130 km/h [].

$$L_{WR} = A_R + B_R \cdot log(\frac{v}{V_{ref}}) + \Delta L_{WR} \tag{2}$$

$$L_{WP} = A_P + B_P \cdot P(\frac{v - v_{ref}}{V_{ref}}) + \Delta L_{WP} \tag{3}$$

The calculations are made in the octave frequency bands from 125 Hz to 4000 Hz, and in each band, the total sound power level emitted is calculated from the energy sum of the above contributions, as shown in Eq. (4).

$$L_W(v) = 10 \cdot log(10^{0.1 \cdot L_{WR}} + 10^{0.1 \cdot L_{WP}}) \tag{4}$$

This sound emission is modeled by a point source located at a height of 5 cm above the ground in the position of the vehicle.

After describing the emissions, the sound propagation model describes the effects experienced by the sound wave, from the source to the receiver, by means of a sum of attenuations. The basis of the proposed propagation model also has its origin in the CNOSSOS-EU method, which takes into account the attenuation due to the distance traveled, the atmosphere, barriers and elements that reflect the incident sound to a greater or lesser extent, such as buildings. As a general rule, the noise level at any point in space is expressed by Eq. (6), where A stands for the sum of attenuations to which the power level of the transmitter L_W is subjected in order to obtain the level at reception point L_p.

$$L_p = L_W - A \tag{5}$$

2.2. Proposed methodology

To carry out the time analysis described above, it is necessary to track the position of the vehicle over time. It is necessary to define a time window of fixed duration, for example, 1 s, in which the spatial coordinates of the vehicle will be taken. During this time window, the vehicle, depending on the speed at which it is moving, will have traveled a segment of length L, which will allow the vehicle's route to be discretized. In each of these segments, as it is occupied by the vehicle, we can determine the sound power emitted, depending on the driving speed and according to the emissions model already defined. This segment will be modeled using a point source located at the midpoint of the segment.

The speed is assumed to be constant in each segment under consideration and is logged at regular intervals along with the position of the vehicle. Both data can be acquired by means of a GPS receiver, although a connection with the vehicle's onboard diagnostics (OBD) device can provide more accurate speed data (and other data from the control unit, i.e. rpm, can complete the information). Although these parameters are not strictly necessary for the application of the proposed CNOSSOS-EU-based emission model, they could be used to customize the model or used in more complex models without the need to change the methodology significantly.

The type of vehicle will affect the results obtained and could involve changes in the input parameters of the emission model used. Corrections or adaptations could also be made depending on the manufacturer, model and maintenance status of the vehicle. Such improvements to the emission model have not been considered at this stage and in any case are outside the scope of the proposed methodology.

The location of the vehicle allows us to determine the type of road surface the vehicle is driving on (if these data are available in the area to be mapped) and therefore to incorporate the corrections attached to this factor into the emission model. In our case, we considered a type of pavement that was homogeneous throughout the entire area of study (not relevant in this article). The output of the emission model varies with time, $L_w(t)$, and each time instant is intimately linked to a specific position of the path.

In the case of attenuation, its dependence on time is derived from the fact that the sound source varies its position over time. For a fixed location of the source, we can define the attenuation of the sound from that location to each receiver.

For simplicity, we consider this attenuation to be uniform throughout the assessment period in both the short and the long term. Thus, for each position adopted by the vehicle, we have a constant row vector A_i, whose elements A_{ij} reflect the attenuation of sound from position i to receiver j.

The number of receivers n is predetermined and constant for the area of study. The location of these receivers is also fixed and matches the position of either a calculation grid to obtain a noise map (as exemplified in this article) or a facade receiver to obtain the sound level on the most exposed facades of every building in the area.

The number of potential vehicle locations m is also predetermined and constant for the study area, which is the key element that allows the dynamic mapping process to be greatly accelerated. The implementation of the system requires a previous phase of simulation of the study area, which allows the determination of the m vectors A_i, one for each possible location of the vehicle. The definition of the m locations is related to the segmentation of the routes followed by the vehicle and therefore to the precision of the method. In general, the definition of the possible locations of the vehicle is based on the axis of the roads considered, although it could also be based on the axis of each platform, each direction of traffic, each lane, or even any possible location along the width and length of the roadway (see Fig. 2). The greater the spatial resolution of the segments is, the higher the precision of the method and the greater the calculation time spent in the configuration phase of the system.

The full set of attenuation vectors must be known a priori and forms the attenuation matrix A. Thus, calculating the noise map at instant t, $L_{p,i}(t)$, requires knowing only the power emitted by the vehicle at that instant t, in which it occupies the position i, $L_{w,i}(t)$, and selecting the appropriate attenuation vector A_i based on the location of source i:

$$L_p(t) = L_{w,i}(t) - A_i \tag{6}$$

The graphic representation of the sound level requires linking each result Lp, j to a fixed location on the map. In this way, the data can be displayed using indicators placed at location j that update their color depending on the level (for example, by coloring the buildings being assessed). However, to obtain a dynamic noise map, the most advantageous option is to define the equispaced receivers in a grid and transform the vector of the n results into a matrix of $n_x \cdot n_y = n$ elements, whose correspondence in geographical coordinates is represented, after spatial interpolation, by a contour map.

2.3. The attenuation matrix

All of the attenuation vectors must be available beforehand to implement this methodology. To obtain them, environmental noise simulation models are applied. In this case, as mentioned, we select the CNOSSOSS-EU Method, and we choose noise mapping commercial software (NMCS) to carry out the calculations, since it allows us to automate some tasks, given that we have to calculate

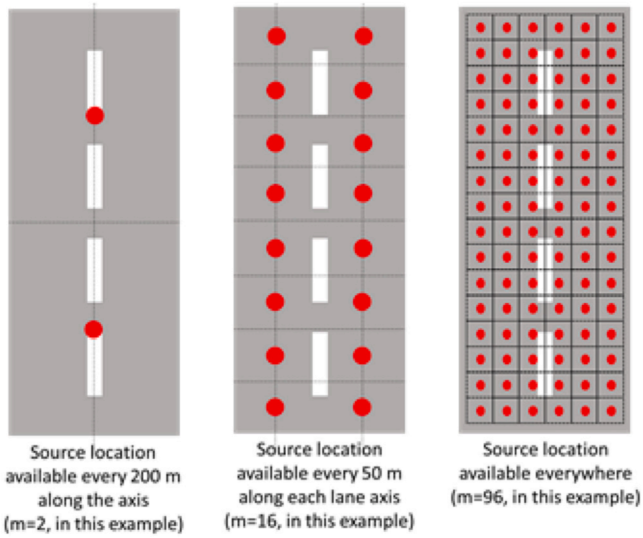

Fig. 2. Three plausible setups for defining the potential vehicle locations in a road segment.

a total of*m* attenuation vectors and *m* area maps. Each of these vectors has n elements, one for each location where the sound level is predicted.

The first step is to recreate, with the help of the simulation software, an acoustic model of the area under study. The greater the precision of the model, the greater the quality of the results achieved. Therefore, we must be as detailed as we can when defining features such as absorption coefficients for the soil, the shape and height of buildings, and the type and state of maintenance of road surfaces. The size of the calculation grid, the number of reflections considered, the maximum distance of the calculated rays, etc., are parameters that must be adjusted according to a cost-benefit criterion while bearing in mind that the calculation times will only affect the preconfiguration phase. For example, the use of a 100 × 100, 10 × 10 or 1 × 1 calculation grid will affect the time spent obtaining the attenuation matrix but will have little influence afterwards in obtaining the dynamic noise maps.

The vehicle is simulated by a point noise source located at position i with a reference sound power level ($L_{w,ref}$). After running the simulation, we obtain a noise map i composed of n results ($L_{p,ij}$. When subtracting it from the reference power level, we obtain the attenuation vector i, where each element Aij is calculated by means of Eq. (7).

$$A_{ij} = L_{w,ref} - L_{p,ij} \tag{7}$$

This process may require a significant amount of calculation time, depending on the parameters of the simulation and the number of receivers considered in the area. This process will be repeated for each potential source location, allowing the completion of attenuation matrix A, which is the main requirement for the execution of this calculation method. This is a time-consuming process, the advantages of which emerge later, during the calculation of the dynamic maps, which we can perform with a simple addition. The ability to calculate the attenuations for each point in space, some of which may never be used, requires extra calculation time. However, this time needs to be taken only once, and this can be done in advance. This allows a considerable reduction in time when calculating the dynamic noise maps. In addition, the attenuation matrix is common to any type of vehicle we may decide to include in the study, whose category and condition would only affect (if desired) the emission model. This solution has a high degree of compatibility not only with the method described by CNOSSOS-EU but also with any other method that establishes separate emission and propagation models.

When the vehicle begins to operate, its GPS position will allow us to select the attenuation vector to be used. It will also tell us the speed at which the vehicle is moving, so the emission model will provide us with the acoustic power emitted. A simple sum of this value with the attenuation vector will result in an instantaneous noise map.

Given the objectives outlined, it seems reasonable to update the dynamic maps at a rate of 1 s, which is the rate at which it will be necessary to acquire data from the GPS and the vehicle's control unit. Thus, we use the equivalent sound level at one-second intervals, $L_{Aeq,1s,j}$(t), as an indicator in each receiver j. The logarithmic sum of the noise maps in this vector format, $L_{Aeq,1s}$(t), will allow us to calculate the accumulated levels for any reference period T (in seconds) quickly and efficiently, according to Eq. (8):

$$L_{A,T}(t) = 10 \cdot log\left[10^{0.1L_{A,T}(t-1)} + 10^{0,1[L_{Aeq.1s}(t) - 10 \cdot log(T)]}\right],\ for\ t \leq T \tag{8}$$

2.4. Case study

With the objective of testing the methodology and validating the results, a pilot study was chosen, consisting of an evaluation of the noise emitted by a vehicle when doing a closed route on the South Campus of the Universidad Politécnica de Madrid. Fig. 3 illustrates the route and the working area, and Fig. 4 represents the speed recorded at each moment.

Fig. 3. Working area in which the methodology was developed. Aerial photography (left), digital terrain model (center) and acoustic simulation model with potential source locations (right).

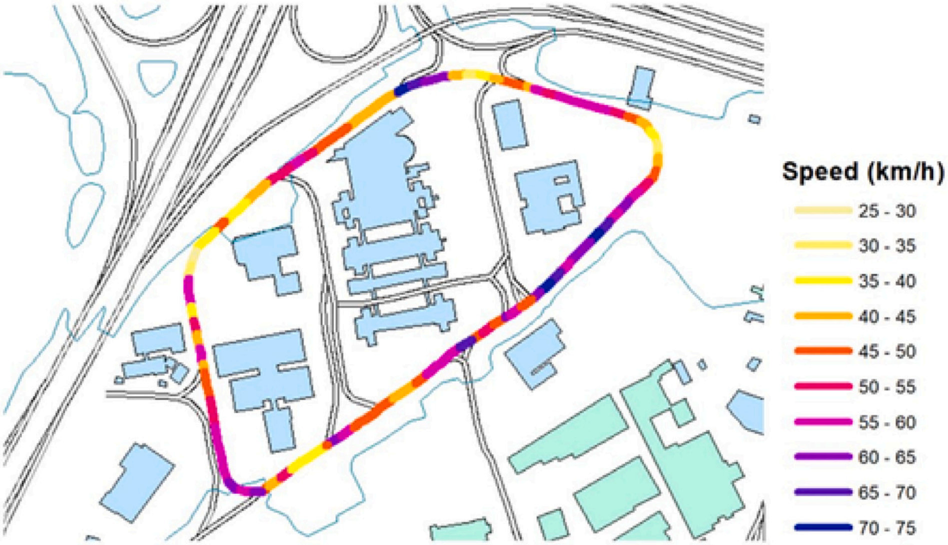

Fig. 4. Speed track.

The segmentation of the route was carried out in sections of 10 m so that m = 150 attenuation vectors were calculated for the study area. Fig. 5 shows a map view of three of these attenuation vectors for three possible locations of the vehicle, j = A, B and C. The attenuation increases with the distance to the source. Regarding the effect of spherical divergence, nearby buildings add attenuation caused by screening. The absorption effects of the soil and buildings are also considered, in addition to a favorable atmosphere propagation condition (which is reasonable in an urban environment, where the noise source is close to the buildings).

The combination of the vehicle power data with the calculated attenuation vectors gives us a dynamic noise map that captures the vehicle's acoustic emission, as shown in Fig. 6 (left). The levels in the map show the $L_{Aeq,1s}$ indicator and are therefore high for 1 s in the vicinity of the vehicle and very low in remote positions behind the buildings. As the vehicle continues to move, it emits over a wider area, as shown in Fig. 6 right (the levels have not been standardized with respect to the reference interval T, to show the comparative effect with the instantaneous emission; Fig. 6 left).

After evaluating the entire route covered by the vehicle, with several laps around the campus, and standardizing to the reference period T, we obtain the representation in Fig. 7.

As a validation of the calculation method, a simulation was carried out with the NMCS using the same input data that were used with the method proposed to obtain the maps in Fig. 7. In each road section, the location of the vehicle is imported along with its speed. Instead of carrying out the simulation using point sources, in the NMCS, we used road segments, where the number of vehicles in each segment was taken into account with the number of laps each vehicle took on the campus. The aim of this validation was, on the one hand, to check that there were no programming errors when applying the emission model or the new calculation method. In addition, it was intended to assess the differences when modeling each section of track using an omnidirectional point source or a short linear source. We observed that the maximum discrepancy between the generated model and the noise map was ±0.08 dBA. As this value was lower than 0.1 dBA, it was concluded that it was a sufficiently small difference that the proposed simplifications and the proposed method could be considered suitable.

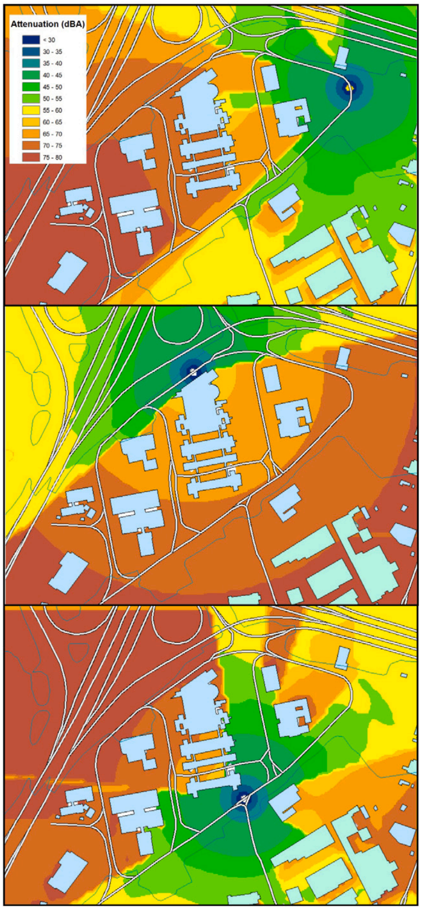

Fig. 5. Mapping of attenuation vectors from three different locations.

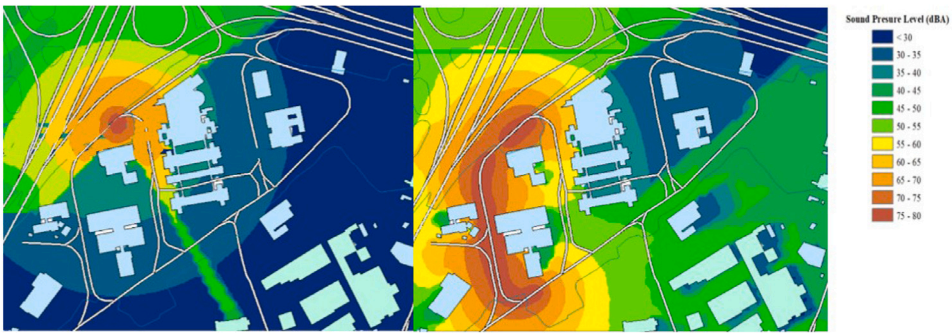

Fig. 6. (Left) Instantaneous map; (Right) cumulative map.

3. Discussion

The practical implementation of the proposed methodology is subject to the resolution of multiple constraints related to the degree of precision and accuracy required and the technological challenges and ethical issues to be addressed. Therefore, in addition to the theoretical framework described in this article, the authors would like to discuss some of these issues. To this end, it is easier to provide a holistic vision that, although it would be costly to implement today (beyond a pilot), can offer, in the medium term, new and ground-breaking possibilities for managing noise in low-noise-emission zones based on the real emissions of each vehicle and the number of people this noise affects. First, it should be noted that the proposed methodology requires that each vehicle be provided with a location system and a data transmission system. Although these are issues that are quite widespread because of the

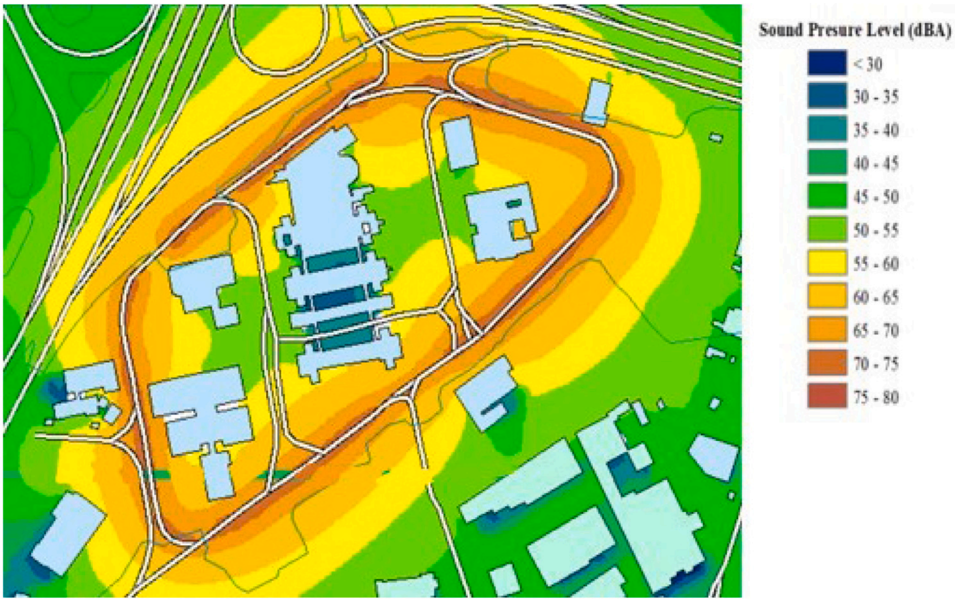

Fig. 7. Cumulative noise map over period T.

use of smartphones, the possible transmission of positioning data raises ethical issues that may involve a violation of civil liberties. However, this all depends on the exploitation strategy put forward by the managing authorities. Any citizen participation requires a voluntary transfer of data and certain data security and privacy constraints. In this case, citizens could participate voluntarily if, for example, in return, they obtain exemptions to environmental charges by proving their effective contribution to reducing noise pollution. This is a strategy used by some car insurance companies—offering benefits to customers who inform them about their use of the vehicle. Similarly, it cannot be considered the only operational option that the methodology be applicable to all vehicles. It could be that it is applied only to goods delivery services, rental vehicles, car sharing vehicles, or vehicles for hire.

The emission model used to determine the emitted sound power will require, in addition to information on vehicle dynamics, other types of input data, such as the vehicle type or tire type. The definition of the number of categories is closely linked to the intended use of the system itself. For example, the types of vehicles predefined in the emission model will vary if the system affects only heavy-duty vehicles or if it affects only mopeds. Similarly, the types of tires may also be dependent on weather conditions, the time of year, the geographical area, or simply the information available from tire type approval. These are all decisions to be made in view of a cost/benefit assessment in each implementation case, and the methodology is prepared for this.

Another of the most obvious points of discussion that the methodology may present concerns the sources of error in the model and the uncertainty of its results. It is evident that any proposed emission model will have some features that cannot be sufficiently controlled and whose variability may result in a significant deviation between simulations and reality. Although there are some such factors whose influence could be fixed, for example, by applying more sophisticated and customized emission models based on the emission data obtained during tire approvals, as is done in the case of aircraft noise, there will always be variables that influence the results and that cannot be completely controlled or whose monitoring would entail a disproportionate effort. There are many variables that we could list, from the type of vehicle or tire to the state of maintenance of the exhaust, the acceleration noise or horn sound, the effect on the attenuation matrix of nonfixed urban furniture or the other vehicles present on the road. To this end, we must add the costs or uncertainties arising from monitoring or the variability caused by weather conditions, depending on the specific case. Furthermore, if we want to assess emissions in relation to the number of people exposed to noise, we will make other simplifications, for example, by assigning the resident population in a building to a certain height, by not adequately separating bedrooms from other types of rooms, by not assessing the presence of people in buildings, etc.

We could also discuss the concept of validating the methodology. The proposed method is based on the selection of emission models and outdoor sound propagation models. When implementing the methodology on site, depending on the specific goals, the exploitation criteria and the cost–benefit analysis, the most appropriate models will be selected by the authorities in charge. In any case, the definition and validation of the models are outside the scope of this article. In addition, the methodology aims to determine the share of an individual vehicle in the overall noise pollution. For this reason, and in an attempt to create a robust, consistent methodology that is compatible with other noise management tools, we believe that the validation of the methodology should not be performed against the real world but against an internationally recognized method of assessing noise pollution. In the application example, we chose the CNOSSOS-EU method because we intend to quantify the individual contribution of a vehicle compared to traffic as a whole, the long-term assessment of which would also be carried out with this method. We believe that an analysis of the sources of uncertainty and its quantification would be more appropriate. However, this is highly dependent on the selected emission and propagation models, as well as on the constraints and decisions made during the operation. For this reason, we consider it to be beyond the scope of this article.

The authors would like to emphasize that the alternatives to this approach can only perform a partial assessment of some of the factors. Therefore, any attempt to pass on costs should be based on the time spent in an area and, at most, on some kind of vehicle categorization or speed limit. The proposed methodology, even assuming that remedying some sources of error would have a very high cost, would allow a more realistic estimation of emissions based on actual emission figures, with deviations but based on the areas traveled through, the distance covered and time spent, the type of vehicle and the number of people affected as well as the driving conditions. This is not a negligible achievement but a first step that would provide opportunities for future improvements based on a fairer differentiation and distribution of the marginal cost (Swärdh and Genell, 2020). The proposed methodology allows for the inclusion of more complex and sophisticated emission models, but even with the simplifications currently employed in the models used to draw strategic noise maps, we consider it an advance whose exploitation is worth exploring.

4. Conclusions

In this article, a novel calculation method is proposed and validated to assess the contribution of a single vehicle to the overall noise pollution of a city. It is a methodology based on pre-existing noise simulation models that are compatible with the CNOSSOS-EU methodological framework in Europe.

The validity of the method was tested in a small and controlled area, which allowed us to obtain dynamic noise maps generated by a vehicle, both instantaneous and accumulated. Unlike other initiatives, such as Dynamap, the noise maps are not updated according to changes in the traffic flow but rather changes in the emission of the vehicle being assessed (Sevillano et al., 2016).

The methodology is designed so that its implementation can be easily scaled up to a larger area, such as an LEZ in a city (Tretvik et al., 2014). In addition, the proposed methodology can be applied to determine the levels of facades in buildings as well as the population exposed to noise, which will require only small adjustments in the configuration stage.

Although the display of dynamic maps of individual vehicles is not a particularly useful tool for noise management by authorities in a city, it is conceived as an effective awareness raising tool, which can help users understand why they are being charged and discourage the use of particularly noise-sensitive routes.

On the other hand, cumulative emission maps can be useful for assessing the overall emissions from individual vehicles. The quantification of this individual acoustic contribution is a first step in estimating the economic and environmental costs due to each vehicle, taking into account its particular features, its time of use, the type of driving, the speed and area it travels through, or the population it affects.

Furthermore, if instead of a grid, we perform the calculations on the basis of the position of the vehicle relative to the most unfavorable receiver on the most exposed facade, this method will allow us to calculate the accumulated exposure in buildings. In this way, we can calculate the number of people exposed to the noise that our vehicle generates or other indicators, such as DALYs, which will evaluate emissions in terms of their effect on people's health.

Therefore, the methodology presented provides an innovative technological tool for managing noise in cities, whose application to environmentally protected areas will allow the economic costs of noise to be charged to the polluting actors in terms that are closely related to the effects produced.

Finally, it should be noted that this tool will also allow an aggregated analysis of the noise pollution produced by all participating vehicles. This will make it possible to produce a collaborative noise map with a reasonable degree of precision, which will make it possible to carry out detailed management, in real time if desired, of the areas where it is implemented.

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