TESIS DOCTORAL Cáceres 2015

43.50.Rq Environmental noise, measurement analysis, statistical characteristics.

Escuela Politécnica UEX Cáceres
40 años

Avda. de las Arenas, Cáceres

UNIVERSIDAD DE EXTREMADURA

Carlos Prieto Gajardo

Análisis de medidas anuales de niveles sonoros urbanos. Estudio de la capacidad predictiva de medidas de corta duración.

Departamento de Física Aplicada

Dirigida por: **Dr. Juan Miguel Barrigón Morillas** y **Dr. Guillermo Rey Gozalo**

UNIVERSIDAD DE EXTREMADURA

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ANÁLISIS DE MEDIDAS ANUALES DE NIVELES SONOROS URBANOS. ESTUDIO DE LA CAPACIDAD PREDICTIVA DE MEDIDAS DE CORTA DURACIÓN

TESIS DOCTORAL

Para la obtención del

GRADO DE DOCTOR INTERNACIONAL
POR LA UNIVERSIDAD DE EXTREMADURA

Carlos Prieto Gajardo

Cáceres, 2015

Juan Miguel Barrigón Morillas, Doctor en Ciencias Físicas y Titular de Universidad del Departamento de Física Aplicada de la Universidad de Extremadura, y **Guillermo Rey Gozalo**, Doctor en el programa de Física y Matemáticas y Titular de la Facultad de Ciencias de la Salud de la Universidad Autónoma de Chile,

CERTIFICAN

Que la presente memoria de Tesis Doctoral, titulada *"Análisis de medidas anuales de niveles sonoros urbanos. Estudio de la capacidad predictiva de medidas de corta duración"*, ha sido realizada por **Carlos Prieto Gajardo**, bajo su dirección, en el Departamento de Física Aplicada de la Universidad de Extremadura.

Que revisado el trabajo, expresan su conformidad para que éste sea sometido a defensa frente al Tribunal correspondiente, ya que consideran que reúne los requisitos necesarios para optar al grado de Doctor Internacional.

Que habiéndose realizado la Memoria de Tesis por la modalidad de compendio de publicaciones, declaran que el doctorando ha sido responsable del trabajo experimental y una pieza fundamental en su diseño, en el análisis de los resultados, en la obtención de las conclusiones y en la redacción de los trabajos publicados.

Que ninguna de las publicaciones compendiadas en esta Tesis ha sido ni será utilizada por otros para la realización de una Tesis Doctoral.

Cáceres, septiembre de 2015.

Fdo.: Dr. Juan Miguel Barrigón Morillas

Fdo.: Dr. Guillermo Rey Gozalo

"No abras los labios si no estás seguro
de que lo que vas a decir, es más hermoso
que el silencio". **Proverbio árabe**

AGRADECIMIENTOS

A Juan Miguel, por su inconmensurable esfuerzo y dedicación.

Sus orientaciones, conocimientos, persistencia, manera de trabajar, motivación y paciencia han sido fundamentales en mi bonita e inolvidable etapa como investigador en formación.

A su manera, ha sido capaz de ganarse mi lealtad y admiración.

TÍTULO DE DOCTOR CON MENCIÓN INTERNACIONAL

Con el fin de obtener la Mención Internacional en el Título de Doctor, se han cumplido, en lo que atañe a esta Tesis Doctoral y a su defensa, los siguientes requisitos:

- Durante su etapa de formación, el doctorando ha realizado una estancia superior o igual a tres meses fuera de España, en una institución de enseñanza superior de otro estado europeo, cursando estudios o realizando trabajos de investigación que le han sido reconocidos por el órgano responsable del programa. En concreto, el doctorando ha acumulado tres meses en el Departamento de Ingeniería Civil de la Universidad de Coímbra, Portugal.
- La Tesis ha sido parcialmente defendida en una lengua oficial de la Unión Europea distinta de cualquiera de las lenguas oficiales en España.
- La Tesis ha sido informada por un mínimo de dos expertos pertenecientes a alguna institución de educación superior o instituto de investigación de un estado miembro de la Unión Europea distinto de España.
- El tribunal ha sido constituido con, al menos, un experto perteneciente a alguna institución de educación superior o centro de investigación de un estado miembro de la Unión Europea distinto de España, con el título de doctor, y distinto del responsable de la estancia del doctorando y de los informes señalados anteriormente.

FINANCIACIÓN

La principal entidad financiadora de esta Tesis Doctoral ha sido la siguiente:

- Beca y contrato en prácticas de formación e incorporación de personal investigador prevista en el programa de formación, incorporación y movilidad de recursos humanos del IV Plan Regional de I+D+i. Las entidades financiadoras de dicha beca-contrato fueron la Junta de Extremadura (Consejería de Economía, Comercio e Innovación) y el Fondo Social Europeo. La duración de esta beca-contrato fue del 15 de enero de 2011 hasta el 14 de enero de 2015.

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RESUMEN

La necesidad de movilidad y progreso del hombre, el desarrollo de los medios de transporte, el actual crecimiento y avance económico y social de las ciudades y la consecuente evolución en los estilos de vida de las urbes desarrolladas, ha supuesto un aumento de los niveles sonoros urbanos y de los índices de contaminación del aire, apareciendo una considerable reducción del bienestar en la población.

Esta problemática asociada al ruido en las urbes desarrolladas ha sido cada vez más importante y está considerada, según la Organización Mundial de la Salud, el tercer tipo de contaminación más peligrosa (por detrás de la contaminación en el aire y en el agua) debido a los efectos nocivos que causa en la calidad de vida y salud de las personas y convirtiéndose en una fuente de trastornos con efectos físicos, psicológicos, económicos y sociales.

Así, la Comisión Europea se refiere al ruido urbano como uno de los principales problemas medioambientales en Europa, enfatizando en la necesidad de tomar medidas e iniciativas para reducir dicha contaminación acústica ambiental. En el ámbito legislativo, el documento más reciente en la Unión Europea para evaluar y gestionar el ruido ambiental es la Directiva 2002/49/EC.

Por todo ello, este trabajo busca y propone una serie de estrategias de medida, metodologías de análisis y procedimientos de evaluación para determinar los patrones espacio-temporales del ruido ambiental y predecir/estimar los indicadores acústicos de larga duración (anuales) a partir de medidas realizadas durante periodos de muestreo inferiores.

El objetivo global será, por tanto, realizar un análisis detallado de la variabilidad espacial y temporal del ruido urbano, empleando diferentes técnicas estadísticas y analíticas, de forma que los resultados de este estudio permitan diseñar estrategias de estimación de los indicadores de larga duración recogidos en las normativas y legislaciones internacionales, que mejoren las estrategias actualmente existentes, tanto en una reducción del tiempo de medida como en una reducción de los errores cometidos en las estimaciones y que, finalmente, puedan tener una aplicación efectiva en el control del ruido a través del diseño urbanístico.

La consecución de este objetivo global implica alcanzar un conocimiento preciso de la variabilidad y estructura espacio-temporal del ruido urbano, considerando los enfoques estadístico y analítico y analizando las dependencias con la estructura de las vías urbanas, fundamentalmente mediante el empleo del, ya contrastado en otros trabajos, "Método de Categorización".

La principal fortaleza del estudio reside en la gran base de datos utilizada, que parte del conocimiento de los niveles de ruido ambiental repartidos a lo largo de cinco años de muestreo en continuo (2007-2011) correspondientes a más de 45 estaciones de medida, localizadas en ciudades de distinto tamaño y con diferentes condiciones climatológicas y sociodemográficas (Madrid, Málaga, Cáceres y Plasencia).

Todo el trabajo realizado, así como las conclusiones obtenidas en cada una de las metodologías llevadas a cabo, marca una referencia en cuanto se refiere al análisis de los niveles sonoros urbanos y al estudio de la capacidad predictiva de las medidas de corta duración, abriendo las puertas a nuevas líneas de investigación enmarcadas en la presente Tesis Doctoral.

La presente memoria ha sido estructurada en tres apartados. En primer lugar, se hace un recorrido a través de la historia asociada con la problemática de la contaminación acústica ambiental, desde cuando sus efectos e importancia no eran significativos, hasta los actuales efectos nocivos que causa en la salud y el bienestar de la población. El ruido se ha convertido en uno de los principales contaminantes ambientales y objetivo prioritario de diferentes normativas y legislaciones nacionales e internacionales. Son diversas las fuentes sonoras existentes en las ciudades pero es el tráfico rodado el que predomina espacial y temporalmente. Por ello, gran parte de los objetivos indicados en este primer apartado, se centran en el análisis espacial y temporal de esta fuente ruido. También se analizará la importancia de otras fuentes puntuales sobre el paisaje sonoro urbano y medidas de control del ruido del tráfico rodado.

En el siguiente apartado, se ponen de manifiesto los resultados obtenidos en los distintos trabajos publicados en revistas de impacto internacional.

Por último, se discuten los objetivos más importantes derivados de dichos resultados y las principales conclusiones que se extraen de los mismos.

ABSTRACT

The need for mobility and human progress, the development in transportation, the current economic and social progress and the evolution of lifestyles in the developed cities as a result has led to an increase in noise levels and air pollution levels and therefore reducing significantly the populations' welfare.

This issue related to noise in developed cities has become increasingly important and has been considered, according to the World Health Organization, the third most dangerous kind of pollution (after air and water pollution) due to the adverse effects it has on people's quality of life and health. Due to this it has turned into a source of disorders with physical, psychological, economic and social effects.

Thus, the European Commission states urban noise as one of the main environmental problems in Europe, emphasizing the need to take action and initiatives to reduce this environmental noise pollution. On the legislative front, the latest document in the EU to assess and manage environmental noise is Directive 2002/49/EC.

This paper seeks and proposes a number of measurement strategies, analytical methodologies and assessment procedures to determine the spatial and temporal patterns of environmental noise and predict/estimate the acoustic long-term indicators (annual) from measurements made during short-term sampling periods.

The overall aim will be to conduct a detailed analysis of the spatial and temporal variability of urban noise by using different statistical and analytical techniques. The results of these studies will allow us to design estimation strategies for long-term indicators listed in the international regulations and legislations and improve existing strategies, both in a reduction of measurement time and a reduction of errors in the estimates that will lead to an effective application in noise control through urban design.

The pursuit of this global aim implies achieving a precise knowledge of variability and space-temporal structure of urban noise, taking into account the statistical and analytical approaches and analyzing the dependencies with the structure of urban roads, mainly through the use of the, already contrasted in other studies, "Categorization Method".

The main strength of the study lies in the large database used, consisting in the knowledge of environmental noise levels spread over five years of continuous sampling (2007-2011) corresponding to more than 45 measurement stations, located in cities of different sizes and with different climatic and sociodemographic conditions (Madrid, Malaga, Caceres and Plasencia).

All the work carried out as well as the conclusions reached in each of the methodologies implemented, is a reference to the analysis of urban noise levels and the study of the predictive ability of short-term measurements, therefore opening ways to new research framed in this PhD thesis.

The report has been structured in three sections. First, there is a tour through the history related to the problem of environmental noise pollution, from when its effects and importance were not significant to the current adverse effects on populations' health and welfare. Noise has become one of the main environmental contaminants and also a main priority of the different national and international regulations and legislations. There are different sound sources in the cities but traffic dominates spatially and temporally, due to this, most of the aims outlined in this first section focus on the spatial and temporal analysis of this noise source. The importance of other sources on the urban soundscape and control measures of road traffic noise will also be analyzed.

The results obtained in studies published in different international impact journals are disclosed and finally, the most important goals derived from these results and the main conclusions drawn from them are also discussed.

PUBLICACIONES

Artículos en Revistas Internacionales incluidas en ISI-JCR

[1] Barrigón Morillas, J. M., **Prieto Gajardo, C.** (2013). "Uncertainty evaluation of continuous noise sampling," *Applied Acoustics 75*, 27-36.

[2] Rey Gozalo, G., Barrigón Morillas, J.M., Gómez Escobar, V., Vílchez-Gómez, R., Méndez Sierra, J.A., Carmona del Río, F.J. & **Prieto Gajardo, C.** (2013): "Study of the Categorisation Method Using Long-Term measurements". *Archive of Acoustics 38*(3), 397-405.

[3] **Prieto Gajardo, C.**, Barrigón Morillas, J.M., Gómez Escobar, V., Vílchez-Gómez, R., Rey Gozalo, G. (2014): "Effects of singular noisy events on long-term environmental noise measurements". *Polish Journal of Environmental Sciences 23*(6), 2007-2017.

[4] **Prieto Gajardo, C.**, Barrigón Morillas, J.M. (2014): "Stabilisation patterns of hourly urban sound levels". *Environmental Monitoring and Assessment 187*(1), 1-16.

[5] Barrigón Morillas, J.M., Ortíz-Caraballo, C., **Prieto Gajardo, C.** (2015): "The temporal structure of pollution levels in developed cities". *Science of the Total Environment 517*, 31-37.

[6] **Prieto Gajardo, C.**, Godinho, L., Amado-Medes, P.A., Barrigón Morillas, J.M. (2015): "Numerical Analisis of Acoustic Barriers with a Diffusive Surface Using a 2.5D Boundary Element Model". *Journal of Computational Acoustics 23(3).*

[7] Rey Gozalo, G., Barrigón Morillas, J.M., **Prieto Gajardo, C.** (2015): "Urban Noise Functional Stratification for Estimating Average Annual Sound Level". *Journal of the Acoustical Society of America 137(6), 3198-3208.*

Artículos en Actas de Conferencias o Congresos Científicos Internacionales

Las referencias [5] y [11] fueros presentaciones en poster.

[1] Prieto Gajardo, C., Barrigón Morillas, J.M., Gómez Escobar, V., Vílchez-Gómez, R., Méndez Sierra, J.A., Carmona del Río, F.J., Rey Gozalo, G. "Efectos del mundial de fútbol sobre los niveles sonoros de ruido". Proceedings of EEA European Symposium on Environmental Acoustics and on Buildings Acoustically Sustainable. Iberian Meeting on Acoustics. 42nd Spanish Congress on Acoustics. Cáceres, Spain, 2011.

[2] Vílchez-Gómez, R., Barrigón Morillas, J.M., Blázquez Aparicio, L.R., Gómez Escobar, V., Méndez Sierra, J.A., Rey Gozalo, G., Prieto Gajardo, C., Carmona del Río, F.J. "Estudio del ruido en una factoría tabaquera". Proceedings of EEA European Symposium on Environmental Acoustics and on Buildings Acoustically Sustainable. Iberian Meeting on Acoustics. 42nd Spanish Congress on Acoustics. Cáceres, Spain, 2011.

[3] García Dávila, P.M., Méndez Sierra, J.A., Carmona del Río, F.J., Barrigón Morillas, J.M., Gómez Escobar, V., Vílchez-Gómez, R., Rey Gozalo, G., Prieto Gajardo, C. "Caracterización de la potencia sonora de máquinas empleadas en las canteras". Proceedings of EEA European Symposium on Environmental Acoustics and on Buildings Acoustically Sustainable. Iberian Meeting on Acoustics. 42nd Spanish Congress on Acoustics. Cáceres, Spain, 2011.

[4] Rey Gozalo, G., Barrigón Morillas, J.M., Rubio Alamillo, E., Gómez Escobar, V., Méndez Sierra, J.A., Vílchez-Gómez, R., Carmona del Río, F.J., Prieto Gajardo, C. "Análisis de la estratificación del ruido de la ciudad de Plasencia a través de medidas de larga duración". Proceedings of EEA European Symposium on Environmental Acoustics and on Buildings Acoustically Sustainable. Iberian Meeting on Acoustics. 42nd Spanish Congress on Acoustics. Cáceres, Spain, 2011.

[5] Barrigón Morillas, J.M., Gómez Escobar, V., Rey Gozalo, G., Vílchez-Gómez, R., Méndez Sierra, J.A., Trujillo Carmona, J., Prieto Gajardo, C., Carmona del Río, F.J. "Sound quality in urban environments and its relationship with some

acoustics parameters". Proceedings of 41st International Congress and Exposition on Noise Control Engineering 2012, INTER-NOISE. New York, United States, 2012.

[6] Prieto Gajardo, C., Barrigón Morillas, J.M., Vílchez-Gómez, R., Gómez Escobar, V., Rey Gozalo, G., Méndez Sierra, J.A., Carmona del Río, F.J. "Patrones de estabilización de los niveles sonoros horarios". Oral communication. Proceedings of EAA European Symposium on Environmental Acoustics. VII Iberian Acoustics Congress. 43th Spanish Congress on Acoustics. Évora, Portugal, 2012.

[7] Prieto Gajardo, C., Barrigón Morillas, J.M., Vílchez-Gómez, R., Gómez Escobar, V., Rey Gozalo, G., Méndez Sierra, J.A., Carmona del Río, F.J. "Acondicionamiento de la cámara reverberante de la Universidad de Extremadura". Proceedings of EAA European Symposium on Environmental Acoustics. VII Iberian Acoustics Congress. 43th Spanish Congress on Acoustics. Évora, Portugal, 2012.

[8] Prieto Gajardo, C., Barrigón Morillas, J.M., Vílchez-Gómez, R., Gómez Escobar, V., Rey Gozalo, G., Méndez Sierra, J.A., Carmona del Río, F.J. "Acondicionamiento de la cámara de transmisión de la Universidad de Extremadura". Proceedings of EAA European Symposium on Environmental Acoustics. VII Iberian Acoustics Congress. 43th Spanish Congress on Acoustics. Évora, Portugal, 2012.

[9] Rey Gozalo, G., Barrigón Morillas, J.M., Gómez Escobar, V., Vílchez-Gómez, R., Méndez Sierra, J.A., Carmona del Río, F.J., Prieto Gajardo, C. "Aplicación del método de categorización a localidades de diferentes tamaños". Proceedings of EAA European Symposium on Environmental Acoustics. VII Iberian Acoustics Congress. 43th Spanish Congress on Acoustics. Évora, Portugal, 2012.

[10] Méndez Sierra, J.A, Montero Moreno, I.M., Vílchez Gómez, R., Barrigón Morillas, J.M., Gómez Escobar, V., Carmona del Río, F.J., Rey Gozalo, G., Prieto Gajardo, C. "Medición del efecto doppler en tráfico rodado". Proceedings of EAA European Symposium on Environmental Acoustics. VII Iberian Acoustics Congress. 43th Spanish Congress on Acoustics. Évora, Portugal, 2012.

[11] Prieto Gajardo, C., Barrigón Morillas, J.M., Gómez Escobar, V., Rey Gozalo, G., Vílchez-Gómez, R., Méndez Sierra, J.A., Carmona del Río, F.J. "Categorization Method to Study Environmental Noise in Málaga". Proceedings of DAGA 2013 / EAA Euroregio, International Conference on Acoustics, including the 40th Italian (AIA) Annual Conference on Acoustics and the 39th German Annual Conference on Acoustics (DAGA). Merano, Italy, 2013.

[12] Barrigón Morillas, J.M., Gómez Escobar, V., Rey Gozalo, G., Vílchez-Gómez, R., Trujillo Carmona, J., Méndez Sierra, J.A., Carmona del Río, F.J., Prieto Gajardo, C., Atanasio Moraga, P., Montes González, D. "El Método de Categorización. Ventajas e inconvenientes de un muestreo estratificado". Proceedings of EAA European Symposium on Environmental Acoustics and Noise Mapping. Iberian Meeting on Acoustics. 44th Spanish Congress on Acoustics. Valladolid, Spain, 2013.

[13] Barrigón Morillas, J.M., Montes González, D., Merchán Álvarez, A., Atanasio Moraga, P., Gómez Escobar, V., Vílchez-Gómez, R., Méndez Sierra, J.A., Rey Gozalo, G., Prieto Gajardo, C., Maderuelo Sanz, R., Martín Castizo, M., Trujillo Carmona, J., Carmona del Río, F.J. "Caracterización del paisaje sonoro rural. Alcántara, un pueblo de la raya extremeña". Proceedings of EAA European Symposium on Environmental Acoustics and Noise Mapping. Iberian Meeting on Acoustics. 44th Spanish Congress on Acoustics. Valladolid, Spain, 2013.

[14] Barrigón Morillas, J.M., Atanasio Moraga, P., Retortillo Osuna, L., Montes González, D., Gómez Escobar, V., Vílchez-Gómez, R., Méndez Sierra, J.A., Rey Gozalo, G., Prieto Gajardo, C., Maderuelo Sanz, R., Martín Castizo, M., Trujillo Carmona, J., Carmona del Río, F.J. "Caracterización del paisaje sonora natural. El Parque Nacional de Monfragüe". Proceedings of EAA European Symposium on Environmental Acoustics and Noise Mapping. Iberian Meeting on Acoustics. 44th Spanish Congress on Acoustics. Valladolid, Spain, 2013.

[15] Barrigón Morillas, J.M., Vílchez-Gómez, R., Gómez Monroy, M.G., Izquierdo Maldonado, M., Talavero Lorenzo, P., de la Montaña Gutiérrez, D., Trujillo

Carmona, J., Rey Gozalo, G., Gómez Escobar, V., Méndez Sierra, J.A., Prieto Gajardo, C., Carmona del Río, F.J. "Estudio de la relación entre la molestia percibida y ciertos parámetros acústicos". Proceedings of EAA European Symposium on Environmental Acoustics and Noise Mapping. Iberian Meeting on Acoustics. 44th Spanish Congress on Acoustics. Valladolid, Spain, 2013.

[16] Gómez Escobar, V., Barrigón Morillas, J.M., Vílchez-Gómez, R., Méndez Sierra, J.A., Rey Gozalo, G., Prieto Gajardo, C., Maderuelo Sanz, R., Martín Castizo, M. "La acústica y la inteligibilidad en recintos universitarios". Proceedings of EAA European Symposium on Environmental Acoustics and Noise Mapping. Iberian Meeting on Acoustics. 44th Spanish Congress on Acoustics. Valladolid, Spain, 2013.

[17] Prieto Gajardo, C., Barrigón Morillas, J.M. "Assessment of uncertainty in estimating long-term indicators". Contributed paper. (CD ISBN: 978-83-61402-28-2). Proceedings of 7th Forum Acusticum 2014 joined with 61st Open seminar on acoustics and polish journal acoustical society – Acoustical society of Japan special session Stream. Kraków, Poland, 2014.

[18] Prieto Gajardo, C., Cortesão Godinho, L.M., Amado-Mendes, P.A., Barrigón Morillas, J.M. "Aplicación y desarrollo de nuevas configuraciones de diseño en barreras acústicas mediante difusores QRD". Proceedings of EAA European Symposium on Smart Cities and Environmental Acoustics. 8th Iberian Congress on Acoustics. 45st Spanish Congress on Acoustics. Murcia, Spain, 2014.

[19] Barrigón Morillas, J.M., Méndez Sierra, J.A., Sánchez Corraliza, M.R., Gómez Escobar, V., Vílchez-Gómez, R., Prieto Gajardo, C., Rey Gozalo, G., Montes González, D., Atanasio Moraga, P. "Percepción del entorno, el ruido, sus efectos y la molestia ocasionada". Proceedings of EAA European Symposium on Smart Cities and Environmental Acoustics. 8th Iberian Congress on Acoustics. 45st Spanish Congress on Acoustics. Murcia, Spain, 2014.

[20] Sánchez Purificación, A., Méndez Sierra, J.A., Gómez Escobar, V., Vílchez-Gómez, R., Barrigón Morillas, J.M., Prieto Gajardo, C., Maderuelo Sanz, R., Ferrera Llera, C. "Estudio del impacto acústico del aeropuerto de talavera la real

(Badajoz)". Proceedings of EAA European Symposium on Smart Cities and Environmental Acoustics. 8th Iberian Congress on Acoustics. 45st Spanish Congress on Acoustics. Murcia, Spain, 2014.

[21] Fernández González, M., Barrigón Morillas, J.M., Atanasio Moraga, P., Montes González, D., Rey Gozalo, G., Gómez Escobar, V., Vílchez-Gómez, R., Méndez Sierra, J.A., Prieto Gajardo, C. "Caracterización del paisaje sonoro rural en la comarca de Campo Arañuelo". Proceedings of EAA European Symposium on Smart Cities and Environmental Acoustics. 8th Iberian Congress on Acoustics. 45st Spanish Congress on Acoustics. Murcia, Spain, 2014.

[22] Prieto Gajardo, C., Rey Gozalo, G., Barrigón Morillas, J. M., Gómez Escobar, V., Vílchez-Gómez, R., Méndez Sierra, J. A., Trujillo Carmona, J., Maderuelo Sanz, R., Montes González, D., Atanasio Moraga, P. "Estructura temporal del ruido urbano y Método de Categorización". Proceedings of IX Congreso Iberoamericano de Acústica FIA 2014. Valdivia, Chile, 2014. (ISBN: 978-956-9412-13-4).

[23] Díaz Muñoz, S., Barrigón Morillas, J. M., Gómez Escobar, V., Rey Gozalo, G., Vílchez-Gómez, R., Méndez Sierra, J. A., Trujillo Carmona, J., Prieto Gajardo, C., Montes González, D., Atanasio Moraga, P. "Actualización de la situación acústica de la Ciudad Monumental de Cáceres y evaluación de la percepción de los transeúntes". Proceedings of IX Congreso Iberoamericano de Acústica FIA 2014. Valdivia, Chile, 2014. (ISBN: 978-956-9412-13-4).

[24] Amado-Mendes, P., Prieto Gajardo, C., Godinho, L., Barrigón Morillas, J.M. "Numerical modeling of diffusive acoustic barriers". Proceedings of 40th IAHS World Congress on Housing. Sustainable Housing Construction. Funchal, Portugal, 2014.

[25] Barrigón Morillas, J. M., Prieto Gajardo, C., Vílchez-Gómez, R., Rey Gozalo, G. "Uncertainty in the assessment of urban noise through continuous sampling". Proceedings of 44th International Congress and Exposition on Noise Control Engineering 2015, INTER-NOISE. San Francisco, United States, 2015

[26] Rey Gozalo, G., Barrigón Morillas, J. M., Trujillo Carmona, J., Vílchez-Gómez, R., Gómez Escobar, V., Montes González, D., Atanasio Moraga, P., Méndez Sierra, J. A., Prieto Gajardo, C. "Study on the relation between road traffic noise and urban characteristics". Proceedings of 44th International Congress and Exposition on Noise Control Engineering 2015, INTER-NOISE. San Francisco, United States, 2015.

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"…Muchos afirman… que el hombre ha matado el silencio. Es muy injusto decir eso, porque el silencio ¡no existe! A veces huimos de la gran ciudad para escapar del bullicio, pero no hacemos sino trocar unos ruidos por otros. Cuando se acercan las vacaciones, deseamos conscientemente cambiar de ocupación: la máquina de calcular, por la bicicleta; o la de escribir, por el arpón submarino. También de un modo consciente deseamos cambiar de paisaje: la ventana del inquilino de enfrente por la montaña, el campo o la playa. Pero de una manera inconsciente, lo que anhelamos, sin saberlo, es cambiar de ruidos: el bocinazo, el frenazo, el chirriar de las máquinas, las radios del vecino, por otros menos desapacibles como el rumor del viento entre los pinos o la honda y angustiada respiración del mar... No hay bosque, por oculto y lejano que se halle, por tranquilo que esté el aire que lo envuelve, que no tenga su propio idioma sonoro... No hay arroyos en las proximidades, no hay pájaros, no hay insectos, y las copas están quietas. Con esto y con todo, hay un pálpito indefinible, indescifrable. Se dice entonces que se oye el silencio. Es una manera de decir porque lo cierto es que "algo" se oye… mientras que el silencio es inaudible.

He aquí una palabra, "silencio", que el hombre ha inventado para expresar una realidad que no ha experimentado jamás, para describir lo que nunca ha conocido: porque todo en él y alrededor de él es un cúmulo de mínimos estruendos..."

[Torcuato Luca de Tena Brunet†]

INTRODUCCIÓN

Evolución histórica de los niveles sonoros urbanos. Antecedentes

Ya desde tiempos muy lejanos, el ruido ambiental estuvo presente en la humanidad. Incluso, la naturaleza en sí misma alberga una inmensa variedad de sonidos que podrían alcanzar altas intensidades durante periodos de corta o larga duración. El origen del ruido, entendido como sonido no deseado o molesto, es prácticamente tan antiguo como la existencia del hombre; pues, previo al nacimiento del lenguaje, ya se observó cómo gritando de forma salvaje se conseguían efectos intimidatorios o molestos.

Pero no fue hasta los siglos VIII y VII a. C., con el desarrollo de las civilizaciones griega y romana, cuando se crearon las primeras referencias normativas acerca del ruido y la contaminación ambiental, o cuando el tratamiento acústico empieza a tener cabida en las construcciones arquitectónicas. Durante el siglo VI a. C., en algunas ciudades griegas no se permitía tener animales domésticos que perturbasen o alterasen el sueño de los ciudadanos durante la noche e, incluso, los orfebres y artesanos, con oficios especialmente molestos, tenían la obligación de trabajar fuera de la ciudad (Embleton, 1996). Además, tanto en la época romana como en la Europa del siglo XV, no estaba permitida la circulación de carruajes de caballos durante el período correspondiente a la noche, con el fin de garantizar la tranquilidad en la ciudad y el descanso de sus habitantes (Berglund et al., 1999; Shaw, 1996).

En los siglos posteriores, XVI y XVII, las referencias normativas que trataban el ruido ambiental aumentaron en aras de erradicar ciertas actividades que resultaban molestas para la población (Schafer, 1994). No obstante, hubo que esperar hasta el siglo XIX, con el desarrollo de la Era Industrial y como consecuencia de la Revolución Industrial, para observar el problema de la contaminación acústica urbana de una manera similar a como la conocemos hoy en día.

Esto vino provocado, fundamentalmente, por el incremento de los medios de transporte (vehículos de motor, primeras líneas de tranvías y ferrocarriles, aviones…), el desarrollo de las ciudades y crecimiento de la población, la construcción de edificios y barriadas obreras alrededor de los núcleos urbanos, la actividad industrial, etc.

La estructura urbana tiene una incidencia directa sobre la distribución del tráfico rodado, la emisión sonora, la propagación sonora y la evolución de los niveles sonoros urbanos (Tang and Wang, 2007).

Y no es hasta finales del siglo XX, en el año 1972, cuando la Organización de las Naciones Unidas (ONU) considera el ruido como un agente importante de contaminación, en el Congreso Mundial de Medio Ambiente celebrado en Estocolmo (Buss, 2007). Es a partir de ese momento cuando la contaminación por sonidos no deseados se hace patente y se considera perjudicial y nociva para la salud, suponiendo una degradación del ambiente y quebrantando el equilibrio entre naturaleza y sociedad característico de épocas anteriores (García and Garrido, 2003).

Pocos años después, en 1977, la Organización Mundial de la Salud (OMS) estudia las repercusiones del ruido en la salud y calidad de vida de las personas, cuyos primeros resultados fueron presentados en el informe *Criterios de salud aplicables al ruido* (WHO, 1983). Posteriormente, dicho organismo continuó con el proceso de investigación y recopilación de datos generando informes de referencia para tratar el ruido ambiental y proteger, así, la salud de los ciudadanos (*Community Noise* (Berglund and Lindvall, 1995) y *Guidelines for Community Noise* (Berglund et al., 1999)).

Dicha problemática también fue evaluada en 1992 por la Comisión Europea (CE), tratando el problema de la contaminación acústica en el V Programa Comunitario de Política y Actuación en Materia de Medio Ambiente. Así mismo, se redactó y elaboró el *Libro Verde de la Comisión Europea*, abordando, por primera vez, el ruido desde el punto de vista de la protección ambiental, sentando las bases y el marco político de las líneas futuras en contra de la contaminación acústica (Comisión Europea, 1996).

Y fue en el año 2002, cuando la Unión Europea (UE) aprueba la Directiva 2002/49/EC sobre Evaluación y Gestión del Ruido Ambiental con el fin de tratar, controlar y prevenir los efectos del ruido (European Parliament, 2002).

En consecuencia, los estados miembros de la Comunidad tuvieron que centrar sus esfuerzos en analizar los niveles sonoros urbanos y las posibles fuentes originarias de contaminación acústica, elaborar mapas estratégicos de ruido y desarrollar políticas de ordenación y planificación urbana destinadas a crear lugares más habitables y con un menor impacto del ruido urbano sobre el medio ambiente (Department of the

Environment, 1992; National Physical Planing Agency, 1991). Dicha directiva en España fue plasmada en la Ley 37/2003, de 17 de noviembre, del Ruido (Ley 37/2003), desarrollada en dos Reales Decretos (Real Decreto 1367/2007; Real Decreto 1513/2005) (véase apartado "Normativas y referencias legislativas).

A pesar de todo ello, el tratamiento del ruido ambiental no ha sido objeto de preocupación primaria para los investigadores, técnicos o responsables de la calidad de vida de los ciudadanos, como podrían serlo otros tipos de contaminación. Dicho comportamiento, posiblemente sea en parte debido a que, en términos generales, el ruido no presenta un problema o peligro a corto plazo (excepto ciertas situaciones). Así mismo, la contaminación por ruido ha sido un símbolo asociado al progreso, a las ciudades desarrolladas, a la evolución de los modos de vida y, quizá, se ha llegado a asumir como una consecuencia, a veces no agradable, pero inevitable, del avance.

Hoy en día, la sociedad y los ciudadanos están concienciados de los efectos perjudiciales que tiene el ruido para la salud (véase apartado "Efectos de los niveles sonoros urbanos sobre la salud y calidad de vida") y, por ello, el problema de la contaminación acústica es cada vez con mayor frecuencia objeto de estudio y atención por los medios y responsables políticos. Así mismo, tanto la OMS como la Agencia Europea de Medio Ambiente (EEA) crean y publican informes anuales en los que se incluye el ruido como tema de investigación prioritaria, identificándolo como un indicador importante de la calidad ambiental urbana.

Efectos de los niveles sonoros urbanos sobre la salud y calidad de vida

La necesidad de movilidad y progreso del hombre, el desarrollo vertiginoso de los medios de transporte, el actual crecimiento y avance económico y social de las ciudades y la consecuente evolución en los estilos de vida de las urbes desarrolladas, ha supuesto, como ya se ha mencionado anteriormente, un aumento de los niveles sonoros urbanos y de los índices de contaminación del aire[1], apareciendo una considerable reducción del bienestar en la población (De Coensel, 2007).

Esta problemática asociada al ruido en las urbes desarrolladas ha sido cada vez más importante y está considerada, según la OMS, el tercer tipo de contaminación más peligrosa (por detrás de la contaminación en el aire y en el agua) debido a los efectos nocivos que causa en la calidad de vida y salud de las personas (Berglund et al., 1999) y convirtiéndose en una fuente de trastornos con efectos físicos, psicológicos, económicos y sociales (Banerjee et al., 2009; Birk et al., 2011; Chang et al., 2011; Di et al., 2012; Fyhri and Aasvang, 2010; Luquet, 1982; Marquis-Favre et al., 2005a; Marquis-Favre et al., 2005b; Mohammadi, 2009; Öhrström and Skånberg, 2004; Wang and Chang, 2005).

Según los datos de la Agencia Europea de Medioambiente (EEA), cerca de 450 millones de europeos (65% de la población) están expuestos a niveles sonoros urbanos superiores a los 55 decibelios (dBA), más de 110 millones se encuentran soportando niveles superiores a los 65 dBA y cerca de 10 millones a niveles por encima de 75 dBA (Doygun and Kuşat Gurun, 2008).

No en vano, diversos autores han evaluado los niveles de contaminación ambiental de las ciudades, observando que, en un alto porcentaje de los casos (entre el 70-100%) los valores de los indicadores sonoros son superiores a los recomendados por las referencias internacionales (Directiva 2002/49/EC) o la OMS (Environmental and Health Protection, 1991; Omiya et al., 1997; Onuu, 2000; Oyedepo and Saadu, 2010; Ozer et al., 2009; Skinner and Grimwood, 2005; Sommerhoff et al., 2004; Van Renterghem et al., 2012; Zannin et al., 2002; Zannin et al., 2013; Zannin and Sant'Ana, 2011).

[1] La contaminación del aire principalmente es provocada por todas aquellas sustancias que las personas introducen en la atmósfera con efectos nocivos sobre los seres vivos y el medio ambiente, como así lo es la contaminación acústica causada por el ruido ambiental (Birk et al., 2011; Can et al., 2011).

Fuentes de ruido urbano

En función de los escenarios o entornos sonoros, el ruido ambiental está compuesto por un conjunto de fuentes de diferentes características sonoras, temporales y espaciales. En el entorno sonoro más cercano que nos ocupa, la ciudad, estas fuentes se han intentado clasificar y evaluar para identificar su repercusión en la calidad de vida de los ciudadanos. Los tipos de fuentes que se encuentran en el "paisaje sonoro" de una urbe son muy diversos, aunque los estudios han demostrado que aquellas que tienen que ver con la actividad humana o con el funcionamiento de equipos para tal fin, producen una contaminación acústica más elevada.

Cabe destacar, entre otras, las fuentes sonoras derivadas del sector industrial, del comercio, del ruido comunitario y del transporte (dividido a su vez en tráfico aéreo, ferroviario y rodado), predominando ésta última claramente sobre las demás. A partir de encuestas y trabajos publicados (Bonvallet, 1949; Griffiths and Langdon, 1968; Meister, 1956; Purkis, 1964) se ha establecido que el tráfico rodado es la fuente dominante de contaminación sonora en áreas urbanas (Abbaspour et al., 2006; Ausejo et al., 2010; Banerjee et al., 2009; Botteldooren et al., 2006; De Coensel, 2007; Diniz and Zannin, 2004; Fothergill, 1977; Fyhri and Aasvang, 2010; Jagniatinskis et al., 2011; Nelson, 1987; Sommerhoff et al., 2004; Zannin et al., 2002), exceptuando, claro está, las zonas limítrofes con los aeropuertos, líneas de ferrocarril o industrias muy ruidosas (Gaja, 1984).

El ruido ambiental producido por los vehículos en movimiento a lo largo de las vías de circulación urbana depende, en primer lugar, de las propias características de la fuente. Un vehículo supone una fuente sonora puntual en la que las características de potencia, composición espectral, etc., están directamente relacionadas con las condiciones de funcionamiento del vehículo[2] (velocidad de circulación, actividad del motor, tipo de vehículo y mantenimiento, etc.) (Favre, 1983).

Además, el ruido emitido depende en gran parte de las condiciones de propagación-emisión y del contexto (Guedes et al., 2011; Walerian et al., 2001a; Walerian

[2] En turismos, el ruido dominante a velocidades por debajo de 50 km/h procede del motor, por encima de estas velocidades, el ruido dominante es producido por el neumático y la carretera (Bendtsen, 1999; Björkman, 1997).

et al., 2001b), entendiéndose éste como la geometría de la vía, la superficie de rodadura, la pendiente de la vía, etc., que establecen las condiciones de propagación sonora, produciendo multitud de reflexiones y fenómenos de difracción simple y doble (Björkman and Rylander, 1997; Doygun and Kuşat Gurun, 2008). Por ello, para que un modelo de predicción de ruido ambiental sea apropiado como metodología de estimación, debe tener en cuenta la estructura de la ciudad, los diferentes tipos de vía y condiciones de propagación sonora, el flujo de tráfico, etc. (Steele, 2001).

En este trabajo se ha realizado una clasificación de las calles de varias ciudades (agrupándolas por categorías) de acuerdo a su funcionalidad, analizando la relación entre esta y los niveles de presión sonora. Ya en otros estudios se ha demostrado que el ancho de la calle, la textura del suelo, la composición del tráfico, el período del día, etc., influyen significativamente en los niveles equivalentes de presión sonora (Li et al., 2002; Malchaire and Hortman, 1975; Ozer et al., 2009; Romeu et al., 2011). Por ello, estratificar significativamente las calles de la ciudad en base a su funcionalidad supone una disminución en términos de variabilidad dentro de cada una las categorías y mejoras tanto desde el punto de vista del número de muestras como del tiempo de muestreo (Rey Gozalo et al., 2015).

Fuentes especiales. Eventos sonoros anómalos

Un aspecto importante a tener en cuenta en la evaluación, gestión y estimación de los niveles sonoros urbanos es la identificación y tratamiento de los eventos extraordinarios o anómalos (entendiendo como evento anómalo todo sonido que supera, en un porcentaje determinado, los niveles equivalentes medios de presión sonora (Beaumont and Semidor, 2005). Además, debido a que el sentido acústico de los humanos es más sensible a las fluctuaciones y a los eventos de ruido interrumpidos que a un nivel continuo de ruido de fondo (Alberola et al., 2005), tales sucesos contribuyen significativamente en la molestia en las personas (Björkman, 1991; Torija et al., 2007) y, por ello, se precisa de estudios que analicen en detalle tales variaciones.

Son numerosas las veces que los entornos urbanos tienen sonidos temporales que introducen altos niveles de presión sonora (Torija et al., 2007; Torija et al., 2011). Eventos sonoros como el tañido de campanas, vehículos con sirenas o a gran velocidad, pitidos, alarmas, fiestas locales, conciertos, etc., generan altos niveles sonoros durante periodos de corta o larga duración que influyen en el tiempo de muestreo necesario para caracterizar la variabilidad temporal del ruido urbano (De Muer, 2005; Torija et al., 2012) y que pueden repercutir a la hora de estimar los indicadores sonoros de larga duración, obteniendo resultados sobreestimados.

Autores como Öhrström y Rylander han demostrado que los niveles máximos de presión sonora equivalente y el número de eventos anómalos están estrechamente asociados con la molestia sobre las personas (Öhrström, 1991; Öhrström and Rylander, 1990). De hecho, un incremento en el número de eventos anómalos supone un aumento en la molestia si superan cierto umbral. Por ello, aquellos eventos de 70 dB o superiores que se dan durante un largo periodo de tiempo se podrían considerar, incluso, como perjudiciales para la salud (Sato et al., 1999).

Si tenemos en cuenta que los indicadores sonoros suelen ser promediados y medidos, según las referencias actuales, durante periodos de corta-media duración, los sucesos anómalos pueden influir gravemente en la estimación de las medidas (Gaja et al., 2003). La detección de eventos sonoros anómalos o extraños es, por tanto, necesaria para hacer una estimación precisa de los indicadores anuales a partir de medidas de corta duración.

Normativas y referencias legislativas

Como ya se anunciaba en el apartado "Evolución histórica de los niveles sonoros urbanos. Antecedentes", a partir del siglo XIX la gestión de los niveles sonoros urbanos se ha llevado a cabo mediante normativas y referencias de carácter nacional e internacional, que se han ido multiplicando a medida que se ha tomado conciencia del peligro que supone la contaminación acústica sobre la salud y la calidad de vida en las personas.

La Comisión Europea se refiere al ruido urbano como uno de los principales problemas medioambientales en Europa, enfatizando en la necesidad de tomar medidas e iniciativas para reducir dicha contaminación acústica ambiental. Así, en el ámbito legislativo, el documento más reciente en la Unión Europea para evaluar y gestionar el ruido ambiental es la Directiva 2002/49/EC (European Parliament, 2002). Esta directiva se apoya, a su vez, en las normas internacionales ISO de descripción, medida y evaluación del ruido ambiental (ISO 1996-1, 2003; ISO 1996-2, 2007) o de cálculo y atenuación del sonido en su propagación como (ISO 9613-1, 1993; ISO 9613-2, 1996).

En el ámbito nacional, se redactó y publicó la Ley 37/2003, de 17 de noviembre del Ruido, extendida y desarrollada en dos Reales Decretos (Real Decreto 1513/2005, de 16 diciembre, en lo referente a la evolución y gestión del ruido ambiental y Real Decreto 1367/2007, de 19 de octubre, en lo referente a zonificación acústica, objetivos de calidad y emisiones acústicas) que establecen la obligatoriedad de adoptar criterios básicos comunes para todo el territorio nacional. A su vez, existen otras referencias, como el Decreto 2414/1961 "Reglamento de actividades molestas, insalubres, nocivas y peligrosas" o el Real Decreto 1371/2007 "Documento básico de Protección frente al ruido".

La Directiva Europea 2002/49/EC establece, en su Anexo I, el nivel equivalente de presión sonora promediado a lo largo del año como el indicador estándar para la evaluación del impacto ambiental y la contaminación sonora. Dicho parámetro, se corresponde con el valor del nivel de presión sonora medido en decibelios (dB) de un sonido hipotético estable que, en un intervalo de medida T, tiene la misma presión sonora cuadrática media que el sonido que se mide y cuyo nivel varía con el tiempo.

De acuerdo a estas premisas y según la ISO 1996, su expresión matemática queda definida como:

$$L_{Aeq,T} = 10log\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2}\frac{p(t)^2}{p_0^2}dt\right) \qquad \text{Ec. 1}$$

Donde,

- $L_{Aeq,T}$ es el nivel sonoro continuo en dBA, determinado en el intervalo de tiempo T, entre los instantes t_1 y t_2.
- p_0 es la presión sonora de referencia (20 µPa).
- p(t) es la presión sonora instantánea.

De forma discreta, y a modo de ejemplo, si se dispone de medidas de nivel continuo equivalente de una hora de duración ($L_{Aeq,1h}$), el nivel equivalente correspondiente a un número determinado de horas se obtiene a partir de la expresión:

$$L_{Aeq,Nhoras} = 10log\left(\frac{\sum_{i=1}^{i=N} 10^{\frac{L_{Aeqi,1h}}{10}}}{N}\right) \qquad \text{Ec. 2}$$

Donde,

- N, es el número de horas
- $L_{Aeqi,1h}$ es el nivel equivalente (de una hora de duración) correspondiente a cada una de las horas contempladas en el período de N horas.

De la misma forma, si se tuvieran medidas de niveles sonoros de 1 minuto de duración, $L_{Aeqi,1m}$, el nivel sonoro de una hora se determinaría a partir de las 60 medidas de un minuto mediante la expresión:

$$L_{Aeq,1hora} = 10log\left(\frac{\sum_{i=1}^{i=60} 10^{\frac{L_{Aeqi,1m}}{10}}}{60}\right) \qquad \text{Ec. 3}$$

Es a partir de este indicador cuando surgen el resto de parámetros establecidos en la legislación internacional vigente para la gestión y evaluación del impacto de la contaminación sonora sobre la población.

El indicador de referencia para evaluar la molestia ocasionada por el ruido es el nivel sonoro corregido día-tarde-noche, que se representa como L_{den}, en decibelios A (dBA); demostrándose que si éste disminuye también se reducirá el número de personas que sufren los efectos dañinos sobre la salud. Se determina aplicando la fórmula descrita en la ecuación 4.

$$L_{den} = 10log\left[\frac{1}{24}\left(12 * 10^{\left(\frac{L_{day}}{10}\right)} + 4 * 10^{\left(\frac{L_{evening}+5}{10}\right)} + 8 * 10^{\left(\frac{L_{night}+10}{10}\right)}\right)\right] dBA \qquad \text{Ec. 4}$$

Donde,

- L_{day} es el nivel sonoro medio a largo plazo ponderado A, definido en la norma ISO 1996-2:1987, determinado a lo largo de todos los períodos diurnos de un año,

$$L_{day} = 10log\frac{1}{12}\left(\sum_{i=7}^{18} 10^{\frac{L_{Aeqi,1h}}{10}}\right) \qquad \text{Ec. 5}$$

- $L_{evening}$ es el nivel sonoro medio a largo plazo ponderado A, definido en la norma ISO 1996-2:1987, determinado a lo largo de todos los períodos vespertinos de un año,

$$L_{evening} = 10log\frac{1}{4}\left(\sum_{i=19}^{22} 10^{\frac{L_{Aeqi,1h}}{10}}\right) \qquad \text{Ec. 6}$$

- L_{night} es el nivel sonoro medio a largo plazo ponderado A, definido en la norma ISO 1996-2:1987, determinado a lo largo de todos los períodos nocturnos de un año.

$$L_{night} = 10log\frac{1}{8}\left(\sum_{i=23}^{6} 10^{\frac{L_{Aeqi,1h}}{10}}\right) \qquad \text{Ec. 7}$$

Al período día le corresponden 12 horas, al periodo tarde le corresponden 4 horas y al periodo noche le corresponden 8 horas. Además, la directiva 2002/49/EC (European Parliament, 2002), especifica que los Estados miembros pueden optar por reducir el período vespertino en una o dos horas y alargar los períodos diurno y/o nocturno en consecuencia, siempre que dicha decisión se aplique a todas las fuentes, y que faciliten a la Comisión información sobre la diferencia sistemática con respecto a la opción por defecto.

Además, también resulta interesante tener en cuenta el nivel sonoro corregido día-noche (L_{dn}) definido como:

$$L_{dn} = 10log\left[\frac{1}{24}\left(16 * 10^{\left(L_{Aeq,d}/_{10}\right)} + 8 * 10^{\left(L_{Aeq,n}+10/_{10}\right)}\right)\right]dBA \qquad \text{Ec. 8}$$

Donde,

- $L_{Aeq,d}$, nivel sonoro medio diurno, es el nivel sonoro medio a largo plazo ponderado A, definido en la norma UNE-EN-ISO 1996-2:1997, determinado a lo largo del período 07-23 horas.
- $L_{Aeq,n}$, nivel sonoro medio nocturno, es el nivel sonoro medio a largo plazo ponderado A, definido en la norma UNE-EN-ISO 1996-2:1997, determinado a lo largo del período 23-07 horas.

Objetivos y desarrollo actual del tema

De acuerdo a las Directivas Internacionales mencionadas anteriormente, se recomienda que, para estimar la respuesta de las personas a la molestia causada por la contaminación sonora, la evaluación de los niveles sonoros urbanos, generalmente causada por los flujos de tráfico rodado (Barrigón Morillas et al., 2005; Rey Gozalo et al., 2013; To et al., 2002), se lleve a cabo durante intervalos de tiempo de larga duración, por lo general, un año. Las medidas de los niveles sonoros son, además, requeridas para confirmar los modelos de predicción.

Por otro lado, la Directiva Europea 2002/49/CE no menciona las dificultades prácticas de seguir tales especificaciones de manera rigurosa, es decir, realizando medidas durante largos periodos de tiempo (y, por ello, generalmente los investigadores realizan medidas de corta duración). Además, si no se valoran los niveles durante un año de medida, pueden producirse errores en la estimación de los niveles sonoros debido a la variabilidad del ruido ambiental.

De hecho, varios autores han demostrado que los niveles sonoros urbanos producidos por el tráfico rodado varían temporal y espacialmente debido a factores asociados con el tipo de vía y formas urbanas (Guedes et al., 2011; Maruyama et al., 2013; Romeu et al., 2011), con los eventos anómalos (Torija and Ruiz, 2012), el uso del suelo y las fuentes sonoras (Doygun and Kuşat Gurun, 2008; Oyedepo and Saadu, 2010), etc.; pero, actualmente, la Directiva no especifica cómo deben interpretarse algunas variaciones.

Además, aún no han sido desarrollados métodos óptimos para evaluar y predecir, a partir de medidas de ruido de corta duración, los valores “reales” de los índices acústicos con la precisión requerida (Can et al., 2011; Makarewicz and Gałuszka, 2012; Wolde, 2003). Sin embargo, diversos estudios han intentado analizar la variabilidad y estabilidad del ruido urbano a lo largo del “tiempo” y calcular el tiempo de estabilización y su incertidumbre cuando los muestreos de ruido son llevados a cabo en diferentes condiciones y configuraciones de medida (Alberola et al., 2005; Ng and Tang, 2008; Torija and Ruiz, 2012; Van Renterghem et al., 2012).

Debido al coste en tiempo y recursos necesarios para llevar a cabo medidas de larga duración a lo largo de un año completo, es práctica habitual obtener los datos de los niveles sonoros de la ciudad a partir de periodos que integren varios minutos u horas (Can et al., 2011; Da Paz and Zannin, 2010). Pocos son los estudios que miden durante un día completo (Kihlman and Abukhader, 2001; Onuu, 2000; Romeu et al., 2011; Skinner and Grimwood, 2005) y, raramente, se llevan a cabo medidas de ruido sobre periodos superiores al día (Alberola et al., 2005; Björk, 1994; Romeu et al., 2006). Este hecho demuestra que escasos autores han comparado los resultados con medidas de larga duración que realmente integren un periodo completo de medida del índice acústico en cuestión (Can et al., 2011; Jagniatinskis et al., 2011; Romeu et al., 2011) y, por lo tanto, se precisa de estudios que analicen la variabilidad y estructura del ruido ambiental, así como el tiempo de estabilización de los indicadores sonoros.

Por lo tanto y hasta ahora, a partir de estas medidas de corta duración, diferentes autores estiman y extrapolan los resultados a meses o años según lo requiere la Directiva (en su Anexo I) para el cálculo de los índices sonoros correspondientes a las horas (ecuaciones 2-3) y a los tres períodos de evaluación (día, tarde y noche) (ecuaciones 5-7) (Barrigón Morillas et al., 2005; Can et al., 2011; Chakrabarty et al., 1997; Da Paz and Zannin, 2010; To et al., 2002), a pesar de que no existen estudios que demuestren la validez de tales extrapolaciones o que contemplen la variabilidad de la estructura anual del ruido para conocer la variación o posible error que se comete.

Ten Wolde, arquitecto de la directiva de ruido, sugería que la estimación y la medida de las incertidumbres asociadas a los muestreos debían ser prioridades en futuras investigaciones (Wolde, 2003). Incluso, otros autores, como Craven y Kerry, recomendaban un método de incertidumbre para estimar las medidas de ruido ambiental en el que cada componente de la incertidumbre total debe estimarse basándose en juicios científicos o experiencias prácticas reales (Craven and Kerry, 2007).

Por todo ello, las cuestiones que se plantean en este trabajo, entre otras, son: ¿Cuánto tiempo de medida es necesario para caracterizar el ruido ambiental y asegurar que los resultados sean representativos de las condiciones anuales reales? ¿Durante cuánto tiempo se debería medir para conseguir una incertidumbre razonable? ¿Cuál es el margen de error ε que se comete cuando se extrapolan las medidas de corta duración? ¿Podríamos estimar los niveles equivalentes reales de las 24 horas del día a partir de un número consecutivo de minutos significativamente inferior? ¿Cómo son de representativas las medidas promediadas de varios niveles diarios? ¿Qué probabilidad existe de que el indicador L_{den} (o cualquier otro índice anual) evaluado durante días, semanas o meses se acerque al valor anual con un rango de precisión determinado (± 0,1 dBA, ± 0,5 dBA, ± 1 dBA, ± 2 dBA, etc.)? ¿Cuánto influyen los eventos anómalos o sucesos puntuales con niveles de presión sonora elevados sobre los promedios diarios, semanales, mensuales o, incluso, anuales? ¿Existen metodologías con enfoques analíticos para evaluar la estructura temporal del ruido urbano y estimar los niveles sonoros anuales de ruido de tráfico? ¿Qué relación estadística existe entre los diferentes tipos de vía de la ciudad y los indicadores acústicos de larga duración?...

Teniendo en cuenta todo lo anterior, y con el fin de poder predecir los niveles urbanos de presión sonora con márgenes de error determinados y analizar las actuales metodologías de evaluación, este trabajo busca y propone una serie de estrategias de medida, metodologías de trabajo y análisis, y procedimientos de evaluación para determinar los patrones espacio-temporales del ruido ambiental, estimar los indicadores acústicos de larga duración y responder a algunas de las preguntas indicadas anteriormente. Para ello, contamos con una gran base de datos sonoros con medidas de larga duración que integran, al menos, un año de muestreo en continuo.

El objetivo global será, por tanto, realizar un análisis detallado de la variabilidad espacial y temporal del ruido urbano, empleado diferentes técnicas estadísticas y analíticas, de forma que los resultados de este estudio permitan diseñar estrategias de estimación de los indicadores de larga duración recogidos en las normativas y legislaciones internacionales, que mejoren las estrategias actualmente existentes, tanto en una reducción del tiempo de medida como en una reducción de los errores cometidos en las estimaciones y que, finalmente, puedan tener una aplicación efectiva en el control del ruido a través del diseño urbanístico.

Por tanto, para resolver las preguntas mencionadas anteriormente y desarrollar el objetivo general antes indicado, han sido planteados una serie de objetivos y han sido realizados diferentes estudios mediante los enfoques estadístico y analítico y mediante el Método de Categorización, desembocando en siete publicaciones en revistas científicas de impacto recogidas en Journal Citations Reports Science Edition. A continuación se indican los objetivos esenciales perseguidos en cada una de ellas.

Objetivo 1: Buscar estrategias y procedimientos de análisis mediante programación en software de cálculo matricial para determinar la distribución de los patrones sonoros del ruido ambiental durante las 24 h del día, alcanzando un conocimiento preciso de la variabilidad temporal del ruido ambiental. El objetivo concreto es, por lo tanto, determinar cuantos minutos consecutivos son necesarios para aproximar el nivel sonoro equivalente de la hora $L_{Aeq,1h}$ (Ec. 3) con un error de ± x dB, en función de la correspondiente hora de muestreo.

Objetivo 2: Cuantificar las contribuciones de los eventos sonoros anómalos puntuales sobre los índices recomendados para la evaluación de los niveles sonoros urbanos anuales establecidos en las normativas y directivas europeas. El hecho de que eventos singulares puedan ocurrir y puedan afectar a indicadores anuales resulta de gran importancia en la estimación de la contaminación acústica en un punto determinado. Tanto si estos eventos anómalos ocurren o no durante el periodo de medida, los valores extrapolados obtenidos a partir de ellas pueden no ser representativos del índice anual bajo estimación. Si tales eventos anómalos ocurren y son medidos, entonces los índices de larga duración estimados a partir de estas medidas podrán sobreestimar los valores de ruido. Pero, si no lo son, entonces los índices de larga duración estimados puede que subestimen el ruido existente en el punto bajo estudio.

Objetivo 3: Evaluar propuestas existentes en la literatura de estimación de índices de larga duración y de los errores asociados a estas estimaciones y desarrollar una metodología matemática para estimar, mediante medidas, los índices acústicos de larga duración recogidos en las normativas y directivas europeas. Una vez que se conoce la estabilidad de las horas y podemos estimarlas con un número inferior de minutos, es de interés saber cuántas horas/días son necesarias para estimar los indicadores de larga duración. El fin último es estimar la capacidad predictiva de los análisis teóricos existentes, evaluando la incertidumbre asociada y proporcionando una comparación estadística de las medidas de ruido "reales" y estimadas.

Objetivo 4: Obtener metodologías que permitan incrementar la precisión y calidad de las predicciones evitando consumir recursos durante el muestreo espacial y temporal. Se propone una nueva metodología analítica en el estudio de la estructura temporal desarrollando un modelo matemático, basado en el análisis de Fourier, para estimar los indicadores anuales de ruido de tráfico.

Objetivo 5: Aplicar el Método de Categorización, desarrollado por el laboratorio de acústica de la Universidad de Extremadura, a los indicadores obtenidos a partir de medidas de continuo. Estratificar las calles de la ciudad de acuerdo al método de categorización, analizar la variabilidad de los niveles de ruido y extender el estudio de la aplicabilidad del Método de Categorización desde medidas de calle de corta duración a medidas de continuo, de forma que permitan evaluar los índices recomendados por la Directiva Europea.

Objetivo 6: Proponer modelos para la evaluación espacial de los niveles sonoros urbanos teniendo en cuenta el Método de Categorización y analizando medidas de ruido de larga duración en diferentes estaciones de medida. Estudiar los niveles sonoros anuales y la variabilidad temporal en las categorías propuestas por el método. La principal novedad de este trabajo es el estudio de la aplicabilidad del Método de Categorización no ya a la estructura espacial del ruido urbano, sino si la estructura temporal también posee una estratificación basada en el uso de la vía como medio de comunicación y si esta estratificación permite disminuir el tiempo de medida necesario para realizar una estimación de los índices sonoros de larga duración e incrementar la precisión de esta estimación.

Objetivo 7: Así mismo, como una parte más de este estudio del ruido urbano y de metodologías de evaluación, finalmente aplicables a diferentes estrategias de control del ruido urbano desde la fuente, mediante un planteamiento urbanístico, se ha considerado un último objetivo a desarrollar, en este caso, enfocado al desarrollo de estrategias de control del ruido actuando sobre la fuente y la propagación de la onda sonora. Contribuir al conocimiento existente sobre el comportamiento físico y técnico de las barreras acústicas desarrollando e implementando un conjunto de modelos (2.5D Boundary Element Method) que, aplicados al análisis de difusores acústicos, permitan un análisis preciso de su comportamiento y el desarrollo de una nueva propuesta de diseño de barreras con superficies difusoras del sonido.

RESULTADOS

Objetivo 1: Stabilisation patterns of hourly urban sound levels

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Trabajo publicado en

Environmental Monitoring and Assessment (2014), Vol. 187(1), Págs. 1-16

Environ Monit Assess (2015) 187:4072
DOI 10.1007/s10661-014-4072-3

Stabilisation patterns of hourly urban sound levels

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Received: 12 July 2013 / Accepted: 28 October 2014

Abstract In this paper, the stabilisation times for all 24 h of the day are analysed for 12 measurement stations located in the Spanish town of Malaga and throughout 5 years (2007–2011) of sampling environmental noise levels. For the results to be generalised to sound level measurements made in other streets or cities where there have been no long-term measurements, this study was developed for different road types and urban shapes. This distinction was made according to the types of roads indicated in other studies in which a statistically significant relationship was found between noise levels and the road type. The final objective of the study is to determine the capacity to estimate and approximate the real equivalent hourly noise level ($L_{\mathrm{Aeq,1h}}$) from the integration of a number of consecutive minutes (short-term measurements) less than 60 ($L_{\mathrm{Aeq,1h}} \approx L_{\mathrm{Aeq,T}}$ being $T \leq 60$ min). Clearly, this strategy would save time and resources by making measurements of reduced duration. In summary and according to this analysis, a short-time measurement of 15 min is adequate to work with 90 % confidence levels and errors of ±2 dB, with 80 % confidence levels and errors of ±1 dB, and 50 % confidence levels and errors of ±0.5 dB. However, it is necessary to consider the measurement hour period to achieve these levels of confidence due to the high variability throughout the day.

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Keywords Stabilisation time · Long-term sampling · Short-term sampling · Environmental noise

Introduction

The current growth of cities and the lifestyle evolution in the developed countries have been increasing recently the rates of air pollution. Generally, any substance that people introduce into the atmosphere that has damaging effects on living things and the environment is air pollution, such as acoustic contamination caused by noise. The effects of noise pollution on human health have been considered by the World Health Organization to be the third most dangerous type of pollution (Berglund et al. 1999) causing health effects, including psychophysiological problems (Öhrström 2004; Mohammadi 2009; Fyhri and Aasvang 2010; Birk et al. 2011; Chang et al. 2011; Marquis-Favre et al. 2005).

As a result, Directive 2002/49/EC has been developed (Council European Parliament 2002), which provides a series of measures and actions to be carried out by authorities of its member states to control the impact of this polluting agent.

Among these measures and actions used to monitor environmental noise pollution (generally caused by road traffic flow (Barrigón Morillas et al. 2005; To et al. 2002; Rey Gozalo et al. 2013)), the European Commission establishes the value of a parameter L_{den} (composed of L_{day}, L_{evening} and L_{night}), which should be based on estimates (de Noronha Castro Pinto and Moreno Mardones 2009) or measurements monitored over the

Published online: 19 November 2014

course of a full year (Council European Parliament 1988). While the recommendation that the indicators be representative of an annual period is clear, the Directive does not mention the practical difficulties of following this specification rigorously, i.e. taking measurements for long periods of time. On the other hand, failing to measure for a full year can cause erroneous estimates in the environmental sound level. This may ultimately affect the management and evaluation of noise action plans.

It has been shown that noise levels associated with road traffic vary in time and space due to factors associated with the road type and urban shape (Maruyama et al. 2013; Romeu et al. 2011; Guedes et al. 2011), weather (Kephalopoulos et al. 2007; Waddington and Kerry 2012; Wilson 2007), abnormal events (Torija et al. 2012), urban area (Doygun and Kuşat Gurun 2008; Oyedepo and Saadu 2010), plant zones (Ozer et al. 2008), etc., but currently, the Directive does not specify how variations in noise levels should be handled. Additionally, optimal methods have not been developed to assess, from short-term measurements, the real L_{den} and $L_{\mathrm{Aeq,1h}}$ with the precision required (Wolde 2003; Makarewicz and Gałuszka 2012; Can et al. 2011); however, several studies have tried to calculate a stabilisation time (ST) and its uncertainty when noise samplings are performed in different conditions and measurement configurations (Torija et al. 2012; Ng and Tang 2008; Alberola et al. 2005; Van Renterghem et al. 2012; Barrigón Morillas and Prieto Gajardo 2014; Torija et al. 2011; Brocolini et al. 2013).

Part of this problem is due to the cost in time and resources involved in making long-term measurements; therefore, using short-term measurements, different authors estimated the sound index values corresponding to individual hours ($L_{\mathrm{Aeq,1h}}$), and the three periods described in the Directive (day, evening and night) (Chakrabarty et al. 1997; To et al. 2002; Barrigón Morillas et al. 2005). A typical procedure is to take short-term measurements at different intervals of the day, with integration times ranging from 5 min to hour(s) (Can et al. 2011; Da Paz and Zannin 2010), but only a few authors have compared the results with those obtained with long-term measurements that actually integrate the whole period of the acoustic index in question (Romeu et al. 2011; Can et al. 2011; Jagniatinskis et al. 2011).

But, how much time is needed to characterise the environmental noise in order to ensure that the results are representative of actual conditions? To this end, some authors (Torija et al. 2012; González et al. 2007; De Donato 2007) establish that urban noise measurements should be extended for a sufficiently long period of time that the results are stable and reliable, but not excessively long, in order not to increase the costs associated with the fieldwork. But, what is the appropriate middle ground for measurement time? One parameter that describes the time required to obtain a representative sound pressure level of urban noise is the sound ST.

Therefore, the present study proposes a number of strategies and analysis procedures to determine the hourly ST patterns. This is accomplished by compiling a database with long-term measurements obtained during 5 years of continuous sampling (2007–2011) at 12 measurement stations distributed throughout the city of Malaga (Spain) with different urban characteristics. The objective, therefore, is to determine how many consecutive minutes are required to approximate the hour equivalent level $L_{\mathrm{Aeq,1h}}$ with an error of $\pm x$ dB, depending on the corresponding sampling hour (0:00–23:59).

In the following section, characterisation and location of the measurement stations are presented ("Characterisation and location of the measurement stations"). The next section is on "Experimental methodology" and also describes the analytical procedure used to obtain the results. Finally, in the section on "Analysis and discussion of the results," the results of the parameter "stabilisation time (ST) of the sound pressure level" are evaluated, discussed and analysed.

Characterisation and location of the measurement stations

Malaga is the capital of the province of the same name, in the south of the region of Andalucía (Spain), shown in Fig. 1. The city area is 395.13 km^2, and its total population is 568,305 inhabitants (Instituto Nacional de Estadística 2012), making it the second most populous city of Andalucía and the sixth largest in Spain. Malaga lies on Costa del Sol (Coast of the Sun) on the Mediterranean Sea, approximately 100 km east of the Strait of Gibraltar and approximately 130 km north of Africa.

To assess and manage environmental pollution related to noise, the city of Malaga has implemented a control system to supervise and monitor environmental noise, which consists of a series of fixed noise monitoring stations positioned according to the methodology

Fig. 1 Malaga zone map

described in ISO 1996-2 (ISO 2007) (at a height of 4 m and a distance of 1–2 m from building facades).

In this work, 12 monitoring stations were chosen from the total city control system. Stations with a greater number of measurement days between 2007 and 2011 were chosen. Additionally, to cover the six different urban road types, the streets were classified according to a categorisation method (Barrigón Morillas et al. 2011, 2002) in which city roads are classified according to their use as communication routes. The categorisation for the city of Malaga can be found elsewhere (Prieto Gajardo et al. 2013). The distribution of the fixed monitoring stations as a function of the road category was as follows: Cat. 1 (station 1), Cat. 2 (stations 2–3), Cat. 3 (stations 4–6), Cat. 4 (station 7), Cat. 5 (stations 8–10), and Cat. 6 (stations 11–12). Figure 1 shows a zone map of the city of Malaga, indicating the geographical location of the measuring stations.

Experimental methodology

Measurement instrumentation

Continuously running noise analysers (SDR-500, PD de Audio, S.L.) were selected as environmental sound monitoring equipment (class 1 sound level meter (IEC 2002)) by the Malaga city council. The parameter measured to evaluate the noise level was the continuous equivalent A-weighted level integrated every minute ($L_{Aeq,1min}$), in compliance with regulations (ISO 2003).

Analysis procedure

The method of analysis of the sampled data is summarised in the following five steps (schematised in Fig. 2).

1. After data had been recorded every minute during the years 2007–2011, a global matrix was generated to sort and identify each minute according to the procedure shown in Table 1. Those hours that failed to register the corresponding 60 min, as well as stations that, for technical reasons, did not store enough data, were eliminated from the analysis. Moreover, specific or anomalous events were not discarded in the analysis (defined as anomalous are those short time events that introduce a large amount of sound pressure. They include, in the urban context, ambulances, vehicles moving at high speeds, honking horns, banging or crashing sounds,

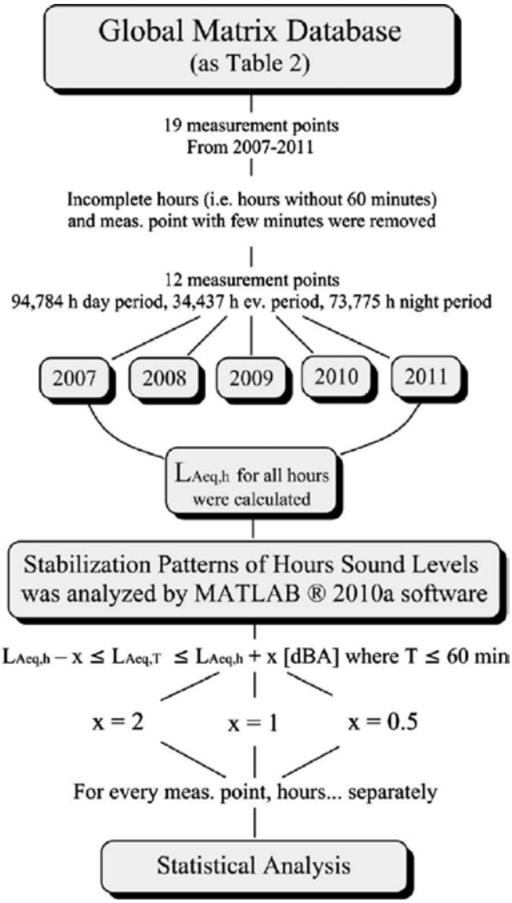

Fig. 2 Analysis procedure scheme

shouting voices, church bells, schools bells, etc.) (Torija et al. 2012).

2. Then, five different matrices were created, one for each year (2007–2011), so that each year of measurement could be assessed, although several researchers have demonstrated annual stability over the sound parameters (Romeu et al. 2006; Gaja et al. 2003; Brambilla et al. 2007).
3. For the stability analysis pursued in this study, the weighted A equivalent level for each hour ($L_{\mathrm{Aeq,1h}}$ averaged over 60 min) was calculated for all hours and days recorded.
4. Once all the measurement data* were processed and stored according to Table 1, a mathematical program developed for matrix manipulations (MATLAB ® R2010a) analysed the stabilisation patterns of hourly sound levels to determine how many consecutive minutes (starting from the first minute of the hour) are needed to approximate the real hour-long averaged value $L_{\mathrm{Aeq,1h}}$ with an error condition equal to ±xdB (being x=2, 1 and 0.5).

   The following condition was considered

$$L_{\mathrm{Aeq,1h}} - x \le L_{\mathrm{Aeq,T}} \le L_{\mathrm{Aeq,1h}} + x [\mathrm{dBA}] \text{ where } T \le 60\,\mathrm{min} \quad (1)$$

   If this inequality is not satisfied, the software increases and averages a minute (the next) to the value of "$L_{\mathrm{Aeq,T}}$" and returns to check the inequality. The process was complete when the inequality was satisfied. Then, the program shows the ST or number of consecutive minutes T ($T \le 60$) that was required to solve the condition.
5. Finally, a statistical analysis was performed

   *Impulsive sound events (outliers) were not discarded in the analysis because in real short-term noise measurements frequently $L_{\mathrm{Aeq,1h}}$ is unknown (as long as the period of time is less than 60 min). Therefore, there is no criteria to discard some sound events and neither it is possible to know the frequency and how it will affect the measurement. Only when a specific noise source would not be desired in the analysis would this criterion be clear. On other hand, it has already been treated in the reference Prieto Gajardo et al. (2014).

Table 1 Matrix generated to sort and identify every registered minute

Point	Hour	Minute	Day	M-S	Lab-Fes	Week	Month	Season	Year	L_{eq} (dB)
1	0	0	1	Monday	Labor	1	1	Winter	2007	58.62
13	23	59	31	Saturday	Festive	52	12	Winter	2011	61.23

Analysis and discussion of the results

Preliminary analysis

For the three error conditions considered in this study (±2, ±1 and ±0.5 dB) suggested by Wolde (2003) and already used in previous works (Gaja et al. 2003; Romeu et al. 2011; Ng and Tang 2008), the mean (μ) and standard deviation (σ) of the ST, for each hour of the day and for all 12 fixed monitoring stations indicated in Fig. 1 are shown in Table 2.

To visualise this information in a concise overview, Fig. 3 shows, for each measurement station, the mean ST for the three error conditions. Each circumference has been divided into 24 radii that correspond to each of the 24 h of the day. Thus, the figure easily shows the hourly variability for multiple error conditions and measurement stations simultaneously.

Note in Fig. 3 the important variability of the ST values over different hours of the day and the selected error conditions for any specific hour or measurement station. However, for a majority of the measurement stations, the temporal patterns of the L_{Aeq} index are similar, and even, in some cases, lack substantial variations in the values of ST obtained.

From the results shown (Table 2 and Fig. 3), it can be deduced that there is a period between approximately 1:00 and 8:59 that needs a longer measurement time to comply with the stabilisation condition given by Eq. 1. Furthermore, this period is also the most unstable according to the results obtained for the deviation parameter (Table 2). It should be noted that a large part of this period corresponds to night time, which indicates the difficulty of evaluating night noise levels (23:00 to 6:59) with short-term measurements. However, it is noteworthy that the 2 h that require longer ST correspond to the last hour of the night period (6:00 to 6:59) and the first hour of the day period (7:00 to 7:59).

If the average results of the ST (Table 2) are observed in detail, it can be verified that the maximum values of the average time required to stabilise $L_{\mathrm{Aeq,1h}}$ are 20, 27 and 36 min, respectively, for error conditions equal to ±2, ±1 and ±0.5 dB. These average values were obtained for the period 8:00–8:59 at station 12, 7:00–7:59 at station 7 and 6:00–6:59 at station 3, respectively.

If the error condition is established as ±2 dB, then 98.3 % of the 288 ST values (resulting from 24 h at each measurement station) are less than 15 min, and 88.9 % are less than 10 min. For the error range of ±1 dB, 94.1 % of the data are less than 20 min, and 84.7 % are less than 15 min. Finally, for the ±0.5 dB error condition, 96.5 % of the results are less than 30 min, and 81.9 % are less than 20 min. Thus, for mean values of the ST, if confidence levels equal to or greater than 95 % are required, 15, 20 and 30 min would be the appropriate measurement times to estimate the value of $L_{\mathrm{Aeq,1h}}$ for the error conditions ±2, ±1 and ±0.5 dB, respectively. This is the case for an average scenario of urban planning and shape conditions where the measurement stations are located and, on average, throughout the 24 h of the day.

Table 3 shows the mean values and standard deviations of the ST for each hour of the day, averaged over all measurement stations. In addition, there is an ample margin of hours with mean values of ST between 3 and 5 min for the error condition ±2 dB; this occurs between 9:00 and 2:59. ST values between 6 and 8 min for the error condition ±1 dB and 11–13 min for the error condition ±0.5 dB between 9:00 and 23:59 h are observed. Therefore, if only the mean ST values are taken into account, and measurements are taken at certain periods for less than 15 min, the calculated equivalent level would deviate less than 0.5 dB with respect to the hour value $L_{\mathrm{Aeq,1h}}$. Subsequently, the ST probability distribution will be analysed to know to what extent this result has a practical interest.

Later, Table 4 presents the mean values and deviations of the ST for each measurement station, averaging the obtained values for the different hours of the day. It can be seen that the variability of the ST and their deviations increases when the uncertainty in the estimation of the equivalent level rises. Note how, except for stations 10 to 12, the stabilisation average time is 5 min or lower for the error condition ±2 dB, less than 10 min for the error condition ±1 dB and less than 15 min for the error condition ±0.5 dB. Therefore, a measurement time of 15 min may be a suitable choice for a good estimation of the $L_{\mathrm{Aeq,1h}}$ index.

In Tables 2 and 4, it is noted that, in a large percentage of cases, the standard deviation of the ST mean values is similar to or greater than the average. This suggests that the probability distribution of the equivalent level $L_{\mathrm{Aeq,1h}}$ ST may not correspond to a normal distribution. If so, an analysis of the ST based on the mean and the standard deviation would be incomplete. Therefore, by using a matrix calculation program (MATLAB® R2010a), the statistical distribution of the ST values was analysed. To do this, the nonparametric

Table 2 Mean and deviation ($\mu \pm \sigma$) in minutes of the stabilisation time (ST) for each measurement station and hour of the day

St. no.	Cond [dB]	Hour of day by periods (night, day and evening)																							
		23	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	±2	2±4	1±2	1±3	1±1	1±1	1±1	2±4	4±7	4±8	5±9	4±8	4±8	2±5	2±5	2±5	2±5	3±6	2±5	2±5	2±3	2±4	2±6	3±7	2±4
	±1	3±7	2±4	3±6	3±4	3±4	3±4	6±11	17±17	15±16	10±15	8±14	6±12	4±10	4±10	4±9	4±10	5±10	4±9	3±8	3±8	4±9	5±11	5±11	3±8
	±0.5	6±10	7±11	12±15	9±12	6±9	6±10	14±18	30±21	26±20	17±19	12±17	10±16	7±14	8±13	7±12	8±14	8±14	7±13	6±12	6±11	7±13	9±14	8±14	6±12
2	±2	3±7	4±10	4±8	3±4	4±9	6±9	6±8	9±12	7±9	2±4	2±3	1±2	2±3	2±4	2±4	1±2	2±4	2±3	1±3	2±3	2±2	1±2	1±2	2±3
	±1	6±11	7±13	9±13	6±8	9±13	10±13	10±13	20±20	20±18	4±7	3±5	3±6	3±7	4±8	3±6	3±6	5±9	3±6	3±5	3±6	3±5	3±5	3±4	4±7
	±0.5	12±16	11±16	18±19	12±14	14±16	16±17	16±17	30±23	30±22	8±12	6±10	7±10	6±10	7±11	7±11	7±12	10±14	6±9	6±9	6±10	6±9	5±8	6±10	10±14
3	±2	3±6	3±5	3±6	4±6	4±6	5±8	6±8	14±15	5±7	2±5	2±5	2±4	2±4	2±4	2±4	2±4	3±5	2±4	2±4	2±4	2±4	2±3	2±2	2±4
	±1	7±10	6±10	8±11	8±11	8±11	8±11	11±14	26±20	13±15	5±8	5±8	6±9	5±9	5±9	5±8	4±8	6±10	5±9	5±8	5±9	6±9	4±7	4±7	5±8
	±0.5	13±16	11±15	15±17	14±16	15±16	14±15	17±18	36±21	23±20	9±12	10±13	11±14	10±13	10±13	10±13	9±13	11±15	10±13	10±13	10±14	11±14	8±11	8±12	11±14
4	±2	2±4	2±4	2±3	2±3	3±4	3±4	4±6	7±11	8±11	2±4	2±4	2±4	2±4	2±3	2±4	2±4	2±2	2±4	2±3	2±3	2±4	2±3	2±3	1±2
	±1	4±7	4±7	5±8	5±7	6±8	6±9	8±11	16±19	20±19	6±10	5±8	4±8	4±8	4±8	4±8	4±8	4±7	4±7	3±6	4±7	4±7	3±7	3±7	3±6
	±0.5	9±12	8±11	11±14	11±14	11±14	11±13	14±16	25±23	30±22	10±14	8±12	8±11	8±12	8±12	8±12	8±13	8±12	7±11	7±11	7±11	7±11	7±11	6±11	9±13
5	±2	4±10	3±8	3±5	3±5	6±9	5±9	5±7	7±10	9±12	5±10	3±7	4±10	5±10	4±9	4±9	4±9	4±10	3±7	3±8	3±8	4±8	3±8	4±9	3±8
	±1	7±12	6±10	6±9	8±10	11±14	11±14	11±13	14±16	21±19	10±14	6±11	8±14	10±14	8±13	7±12	7±12	8±14	7±11	7±11	7±12	7±12	7±12	7±12	6±11
	±0.5	12±16	11±13	12±15	14±15	17±17	17±17	17±18	22±21	30±22	16±16	11±15	13±17	16±18	13±16	12±16	11±16	12±17	12±15	11±15	12±16	12±15	11±15	13±16	11±16
6	±2	3±6	3±4	3±4	3±5	5±7	5±7	5±6	12±14	9±11	4±7	3±7	3±6	3±7	4±9	2±4	3±5	3±5	2±4	2±4	2±4	2±3	2±6	2±2	2±4
	±1	5±9	6±10	6±9	7±9	9±11	9±11	9±11	21±20	20±18	8±12	6±9	6±10	6±10	7±12	5±8	5±9	5±9	5±8	5±7	5±8	5±7	5±9	4±7	5±9
	±0.5	10±13	10±13	12±14	12±14	14±16	14±15	15±16	31±22	31±21	13±15	11±14	11±14	10±13	12±15	8±12	10±13	10±12	9±11	8±11	9±12	8±10	8±11	8±11	9±13
7	±2	3±6	4±6	3±5	5±7	6±7	8±10	8±11	12±15	17±16	4±7	4±8	4±8	6±11	4±8	4±8	4±9	3±7	5±10	4±9	5±10	4±10	3±7	2±6	3±6
	±1	7±11	8±11	8±11	11±13	12±12	13±13	13±14	19±19	27±19	8±12	7±11	6±10	10±14	8±11	7±12	7±12	6±10	8±13	7±12	8±12	7±12	6±11	5±10	5±10
	±0.5	12±16	13±15	15±17	19±18	18±17	19±17	19±17	27±21	35±20	13±16	12±15	11±14	15±18	15±17	13±16	11±15	10±14	14±16	12±15	13±15	12±15	11±14	10±14	10±14
8	±2	3±3	3±4	4±5	5±7	6±7	8±10	7±7	12±13	9±10	3±6	4±7	4±7	4±6	4±8	4±8	3±6	3±6	3±6	4±7	3±5	2±3	2±4	2±2	3±5
	±1	6±8	6±8	8±10	9±11	11±12	11±12	11±12	21±19	17±16	7±9	7±10	6±10	7±10	8±12	8±11	6±10	7±10	6±9	8±11	5±8	4±6	4±7	4±6	5±8
	±0.5	12±14	11±14	15±16	14±14	16±16	16±15	16±15	29±22	26±20	12±12	13±15	11±14	12±14	12±15	13±15	11±14	12±14	11±14	12±14	9±12	8±10	8±11	9±11	10±13
9	±2	6±8	8±11	7±10	9±11	10±12	13±15	12±13	12±13	9±10	6±10	5±7	6±9	6±8	5±7	5±8	5±7	6±10	5±7	4±6	5±7	6±10	4±7	4±7	4±6
	±1	11±13	13±15	13±15	16±16	17±16	20±18	17±16	19±16	16±17	12±14	9±11	11±14	10±12	9±11	10±13	9±12	11±15	9±11	8±11	8±10	11±14	9±12	9±12	8±10
	±0.5	18±18	18±18	21±19	22±19	23±19	27±21	24±18	26±19	24±20	18±18	15±16	16±17	16±16	14±15	16±16	15±17	18±18	14±15	15±16	14±15	18±18	15±17	14±16	13±15
10	±2	4±8	5±8	5±8	7±10	8±12	8±11	8±10	10±14	14±17	6±10	4±8	5±9	5±9	5±9	5±9	5±9	4±8	4±8	4±8	5±8	5±9	5±9	5±9	5±9
	±1	9±13	11±14	11±14	13±15	13±16	13±14	13±15	18±19	23±21	13±16	8±12	10±13	11±14	10±13	10±13	10±13	8±12	9±13	9±13	10±13	10±13	11±14	10±14	9±13
	±0.5	16±18	20±19	19±19	22±19	20±19	19±18	19±18	25±22	32±22	20±19	14±16	16±17	16±17	16±17	16±17	17±17	14±16	15±17	16±17	16±17	16±17	19±18	16±18	15±17
11	±2	5±11	11±15	12±15	11±14	14±16	14±15	12±13	13±16	16±16	16±17	10±13	8±12	7±10	6±9	5±9	5±9	6±11	6±10	5±8	6±9	5±9	4±8	4±8	4±7
	±1	10±15	17±18	19±18	18±18	20±18	21±18	20±18	20±19	23±19	21±19	16±17	14±16	12±15	12±14	10±13	10±13	11±15	11±14	10±13	11±14	12±14	9±12	9±13	9±12
	±0.5	17±18	23±20	25±20	24±20	25±20	27±20	28±21	26±21	29±21	27±20	23±20	21±19	18±18	18±17	17±17	15±17	16±18	17±17	16±17	18±18	19±18	16±17	15±17	15±17
12	±2	5±10	12±16	12±14	10±13	14±14	14±15	12±13	13±15	19±19	20±17	12±14	11±14	10±12	7±11	6±11	6±10	8±13	7±11	7±10	7±10	5±9	4±7	5±8	4±8
	±1	10±14	18±19	18±17	17±17	19±17	19±18	20±17	19±19	25±21	26±19	19±17	17±18	15±16	12±14	12±15	13±15	14±17	13±15	12±14	13±15	10±14	8±11	10±14	9±13
	±0.5	16±17	24±20	24±19	24±20	26±19	26±20	27±20	26±21	30±21	32±20	26±20	24±20	21±19	18±18	18±18	21±20	20±20	19±18	19±18	20±18	18±18	14±16	18±19	16±17

Anderson–Darling and Kolmogorov–Smirnov (Stephens 1974) tests were used for each hour of the day and the measurement station considered in this study to determine if the data distribution, which is organised by hour and measurement point (in total 288 data sets), is normal. In the test results, the *p* value index was equal to 0 in all cases and less than the confidence level α (0.05 by default). It is concluded as in Chang et al. (2011), therefore, that the data do not come from a normal distribution (null hypothesis is rejected).

The data distribution was unimodal and positively skewed. As an example, Fig. 4 shows a histogram distribution of the ST for a random sample taken at measurement station number 4 in the sampling period from 23:00 to 23:59. As seen, the ST values of all evaluated hours are generally concentrated in the first 5 min of the hour, but there is a very pronounced tail that continues beyond 40 min. This will mean that the average is greatly influenced by this tail of high values and will move away from the median value of the distribution.

These results led to the calculation of stabilisation time percentiles, which will be denoted by ST_x (where x=50, 80, 90, 95, 99 and 100), to supplement mean values. These percentiles will correspond to the confidence levels of achieving the stabilisation of $L_{Aeq,1h}$. With these parameters, it can be ensured that a certain percentage of hours (confidence level) has been stabilised with a chosen error (in this paper, ±2, ±1 and ±0.5 dB), fulfilling the condition given in Eq. 1. For example, ST_{90} means that 90 % of the hours have reached the specified stability error condition.

As a consequence of the high variability detected for the mean ST among different measurement stations, it is useful to conduct a comprehensive study of all stations together. Additionally, considering the fact that ST hourly distributions do not have a normal distribution, it follows that it is appropriate to use other parameters for the study to complement the conclusions that can be reached by analysing the average and deviation of the ST. Combining both results, it is necessary to know if the variability detected in the ST mean values for each measurement station extends to percentiles before proceeding with the study. As an example of this analysis, Fig. 5 shows a representation of ST_{90} for the error condition ±1 dB, for each measurement station (y axis) and hour of the day (x axis). Note the high variability of the generated surface. These results show the need for a global analysis including all stations simultaneously.

Global analysis

Next, an overall analysis of the data collected is shown. As already indicated, all measurement stations have been considered together (Fig. 1) to achieve results and conclusions that can be applicable, regardless of the street type or urban shape considered.

In the box-and-whisker plots depicted in Figs. 6–and 8, the ST distributions obtained from the average values for 24 h of the day are represented. The parameters ST_{50}, average value, ST_{80}, ST_{90}, ST_{95}, ST_{99} and ST_{100} are displayed. The value for every hour is calculated by arithmetically averaging the results for each measurement station for error conditions of ±2 dB (Fig. 6), ±1 dB (Fig. 7) and ±0.5 dB (Fig. 8). Each box, therefore, represents 24 values corresponding to the hours of the day.

First, the distribution of these parameters indicates the potential importance of an adequate selection of the hour or period of measurement. In a general overview, these three figures show that, as the uncertainty condition for the $L_{Aeq,1h}$ ST decreases, an increase in the percentile ST_{50}, the mean and ST_{80} appears. Instead, the dispersion of the ST_{90} percentile remains stable and ST_{95}, ST_{99} and ST_{100} decrease (see Fig. 9). The practical meaning of these results is that an appropriate selection of the hour of measurement can be very important in terms of the percentage of stabilised values (50, 80, 90, 95 and 100 %) and the desired uncertainty condition (±2, ±1 and ±0.5 dB) for the $L_{Aeq,1h}$ value estimation.

It can also be observed in the different box-and-whisker distributions that, regardless of the uncertainty margins in the $L_{Aeq,1h}$ estimation, outlier values appear, i.e. hours at which the ST is greater than the third quartile (Q3) value plus one and a half times the interquartile range (IQR). These values correspond to measurements taken between 6:00 and 7:59. Therefore, it is recommended that data collection at these hours be avoided in the measurement database. Note that, also, the error condition chosen for the $L_{Aeq,1h}$ estimation is influential in the presence and importance of the outliers due to traffic flow, labour working hours, commercial/leisure activities, construction works, etc. (Torija et al. 2011).

Consider now, specifically, the ST values that appear in these figures and their practical significance for assigning an error condition and confidence level to a measurement time. Those percentiles that may be of greater practical interest will be analysed in detail; these are ST_{50}, ST_{80}, ST_{90} and ST_{95}.

Table 3 Mean and deviation ($\mu \pm \sigma$) in minutes of the stabilisation time (ST) for each hour, averaging all measurement station values

	Cond [dB]	Hour of the day by periods (night, day and evening)																							
		23	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
μ	±2	4±7	13±15	5±7	5±7	7±9	8±10	7±9	10±13	10±12	6±9	5±7	5±8	4±8	4±7	4±7	3±7	4±7	4±7	3±6	3±6	3±6	3±6	3±6	3±6
	±1	7±11	9±11	10±12	10±12	11±13	2±13	13±14	19±19	20±18	11±13	8±11	8±11	8±12	8±12	7±11	7±11	7±11	7±10	7±10	7±10	7±10	6±10	6±10	6±10
	±0.5	13±15	14±15	16±17	6±10	17±16	18±16	19±18	28±21	29±21	16±16	13±15	13±15	13±15	13±15	12±15	12±15	12±15	12±15	12±14	12±14	12±14	11±14	11±14	11±15

First, the minimum value for the abovementioned percentiles is considered. For measurement times below the minimum values, no hour of the day will have the indicated proportion of hours by the considered percentile. Thus, for the error conditions ±2, ±1 and ±0.5 dB, a minimum collection time of 2, 3 and 5 min is required to reach a stabilisation time (ST_{50}) with a confidence of 50 %. Similarly, 3, 8 and 20 min would be required for stability to be achieved 80 % of the time (ST_{80}), and 6, 16 and 33 min would be required to achieve stability 90 % of the time (ST_{90}). Finally, for the same error condition, 12, 28 and 43 min would be required to achieve stability with a 95 % confidence (ST_{95}).

Subsequently, the maximum values have been analysed without considering the hours at which outliers are observed (6:00 to 7:59). The results indicate a measurement time value below which stabilisation will have been achieved at any measured hour with the corresponding condition error and confidence levels. It is observed that the percentiles ST_{50}, ST_{80}, ST_{90} and ST_{95} correspond with stabilisation times of 5, 13, 20 and 30 min (error condition equal to ±2 dB, Fig. 6); 7, 23, 35 and 43 min (error condition equal to ±1 dB, Fig. 7) and 13, 52, 55 and 53 min (±0.5 dB error condition, Fig. 8). These maximum values ensure that all hours of the day (excluding outliers) are stabilised, with confidence levels given by the percentile in question. Therefore, to reach a confidence level of 90 % with an error condition of ±2, ±1 and ±0.5 dB, 20, 35 and 55 min are required, respectively, at any measurement hour or arbitrary point.

In Figs. 6 and 8, the medians of the distributions indicate the ST values for which the 50 % of the hours of the day have been stabilised with a certain confidence level (ST_x) and error condition (±xdB). In this way, for an error condition of ±2 dB (Fig. 6), these values would be 2, 5, 10 and 18 min for ST_{50}, ST_{80}, ST_{90} and ST_{95}, respectively. Therefore, taking as an example a confidence level of 90 %, with ten measurement minutes, in 50 % of the hours of the day (for an arbitrary day and measurement station), the $L_{\mathrm{Aeq,1h}}$ value is stabilised to correspond with the $L_{\mathrm{Aeq,1h}}$ value calculated by integrating all 60 min in the hour. The same approach, with an error condition equal to ±1 dB (Fig. 7), shows that it is necessary to measure 12 min for a confidence level of 80 % and 23 min for a confidence level of 90 %. Finally, for an error condition of ±0.5 dB (Fig. 8), 25 min are required for 80 % and 39 min for 90 % confidence.

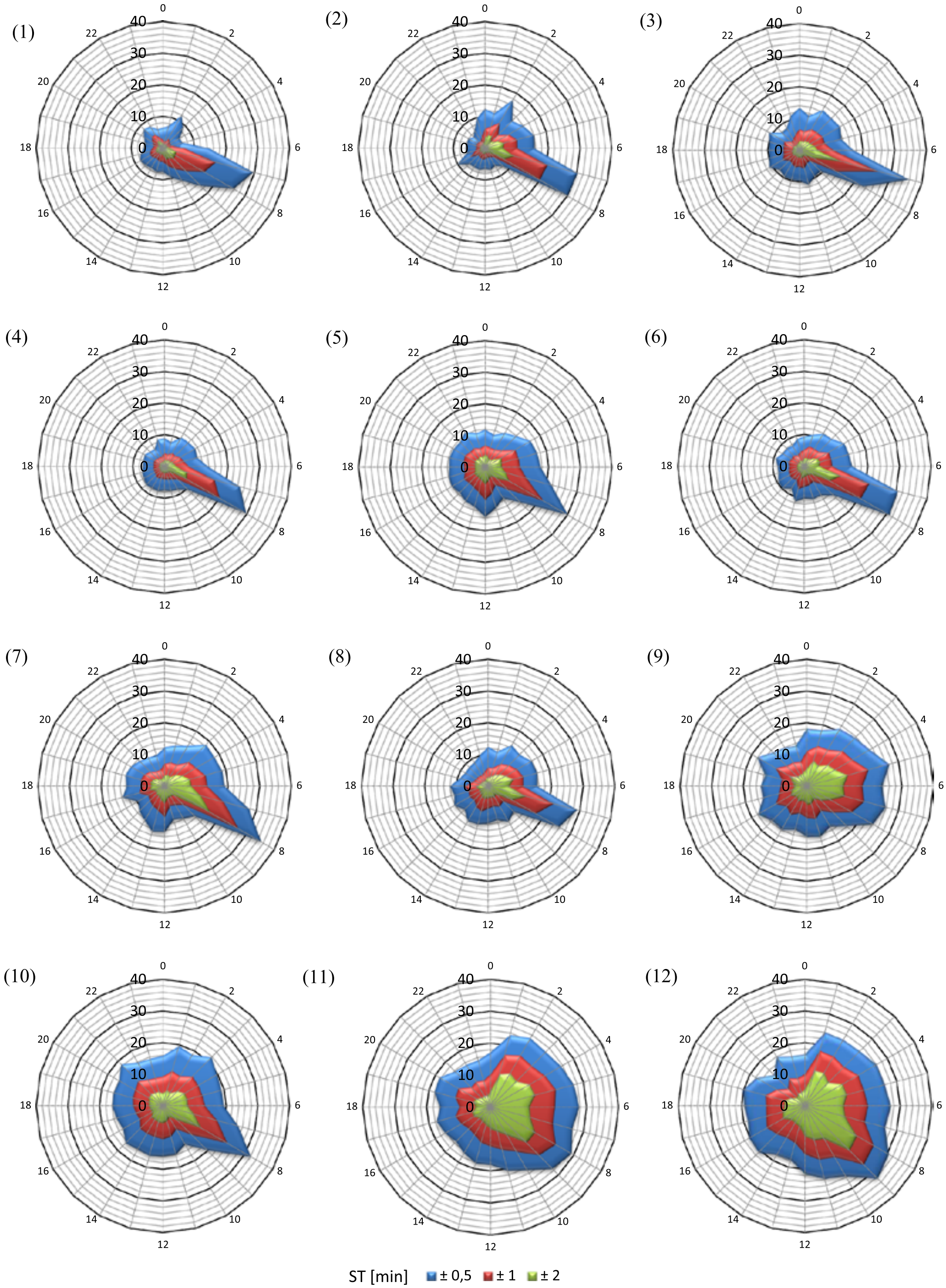

Fig. 3 Mean values of the ST [minutes] for an error of ±2 (*green*), ±1 (*red*) and ±0.5 dB (*blue*)

Table 4 Mean and deviation of *ST* ($\mu \pm \sigma$) in minutes for each measurement station

Measurement station number												
$\mu \pm \sigma$	1	2	3	4	5	6	7	8	9	10	11	12
±2 dB	2±5	3±5	3±5	3±4	4±8	4±6	5±9	4±6	4±6	6±10	9±12	10±12
±1 dB	5±9	6±9	7±10	6±9	9±13	7±10	9±12	8±10	8±10	11±14	14±16	15±16
±0.5 dB	10±14	11±13	13±15	10±13	14±16	12±14	15±16	13±14	13±14	18±18	21±19	22±19

In Figs. 6 and 8, the third quartile (Q3) values of the distributions give the ST values for which 75 % of the hours of the day have been stabilised with a certain confidence level (ST_x). Thus, for an error condition of ±2 dB (Fig. 6), these values would be 3, 9, 16 and 23 min with 50 %, 80 %, 90 % and 95 % confidence levels, respectively. However, with an error condition equal to ±1 dB (Fig. 7), measurements of 6, 19, 29 and 38 min will be required for 50 %, 80 %, 90 % and 95 % confidence levels, respectively. Finally, for the ±0.5 dB error condition (Fig. 8), it will be necessary to measure for 10, 33 and 44 min for confidence levels equal to 50 %, 80 % and 90 %.

Consider, according to these results, a 15 min measurement time. Remember that, in the previous section, it was concluded that this value could be well suited to measure and achieve, in most cases, an equivalent hour level stabilisation.

Note in this analysis that, effectively, with 15 min of measurement and for an error condition of ±2 dB, 75 % of the 24 h of the day are stabilised with a 90 % confidence level. All hours, except anomalous periods (6:00–7:59), have been stabilised with an 80 % confidence level. Only 25 % of the hours have been stabilised with a confidence level of 95 %.

Given an error condition equal to ±1 dB and a measurement period of 15 min at an arbitrary location and day, it would follow that more than 50 % of the hours of the day were stabilised with a confidence level of 80 %, and all hours (excluding outliers) were stabilised with a confidence level of 50 %. At no hour of the day would it be possible to measure for 15 min and ensure a confidence level equal to 90 %.

Finally, setting the error condition to ±0.5 dB, for 15 measured minutes at any hour, location and day, stability of the equivalent noise level is achieved with 50 % confidence. But, at no hour of the day will it be possible to measure for 15 min and ensure a confidence level equal or greater than 80 %.

In summary, according to this analysis, a short-time measurement of 15 min may be adequate to work with 90 % confidence levels and errors of ±2 dB, with 80 % confidence levels and errors of ±1 dB, or 50 % confidence levels and errors of ±0.5 dB. However, it is important to note that, in all cases, it is necessary to consider the measurement hour period used to achieve these levels of confidence.

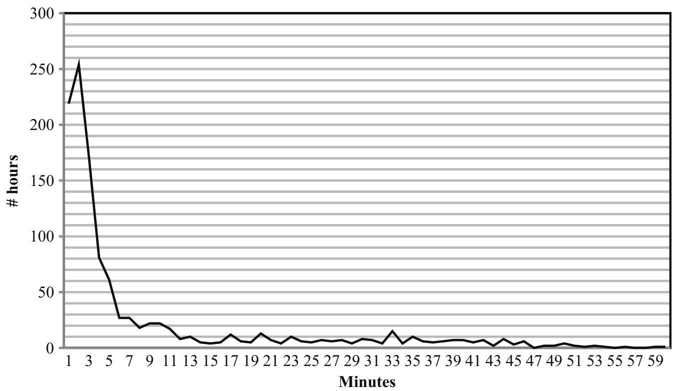

Fig. 4 Stabilisation time (ST) histogram (station #4, hour 23:00–23:59)

Stratified analysis by road use

Within this work, the variability in ST required to estimate $L_{Aeq,1h}$ with a predefined accuracy for the 12 measurement stations has been evaluated. In the literature (Barrigón Morillas et al. 2005; Romeu et al. 2011; Birk et al. 2011), an efficient means of analysis has been observed that can be seen as a proposal that it has shown the efficiency when environmental noise is stratified based on set of categories.

Therefore, it was considered important to rethink the study based on the stratification (Prieto Gajardo et al. 2013) of the city of Malaga and group measurement stations together according to street type and shape; traffic flow is related to the categorisation.

The stations mentioned in Fig. 1 have been grouped into four different strata (A, B, C and D) depending on the use of the streets as a communication routes within the city. Therefore, the category distribution would be defined as follows: Stratum A: Main access and mobility roads to the city (Sts. 1–3); Stratum B: Secondary roads to get around the city with functionality for all inhabitants (Sts. 4–6); Stratum C: Roads which involve neighbourhood mobility and have no clear functionality for all the inhabitants of the city (Sts. 7–10); and finally, Stratum D considers pedestrian roads in which traffic flow is nonexistent or regulated (Sts. 11–12).

For each of these strata and 24 h of the day, the ST results for 50, 80, 90 and 95 % percentiles and ±2, ±1, and ±0.5 dB error conditions are presented in Table 5.

Note that there is an increase in ST values when the error condition decreases or stratum increases.

Stratum A

For stratum A and according to Table 5, with the exception of 4:00 to 7:59, for an error condition of ±2 dB, 15 min of measurement is sufficient to achieve stabilisation with a 95 % confidence level. Including all hours, 11 min on average is sufficient to reach this level of confidence. If the error condition is established as ±1 dB, and omitting 6:00 to 7:59 h, less than 15 min of measurement is sufficient to achieve stabilisation with an 80 % confidence level. Including all hours, less than

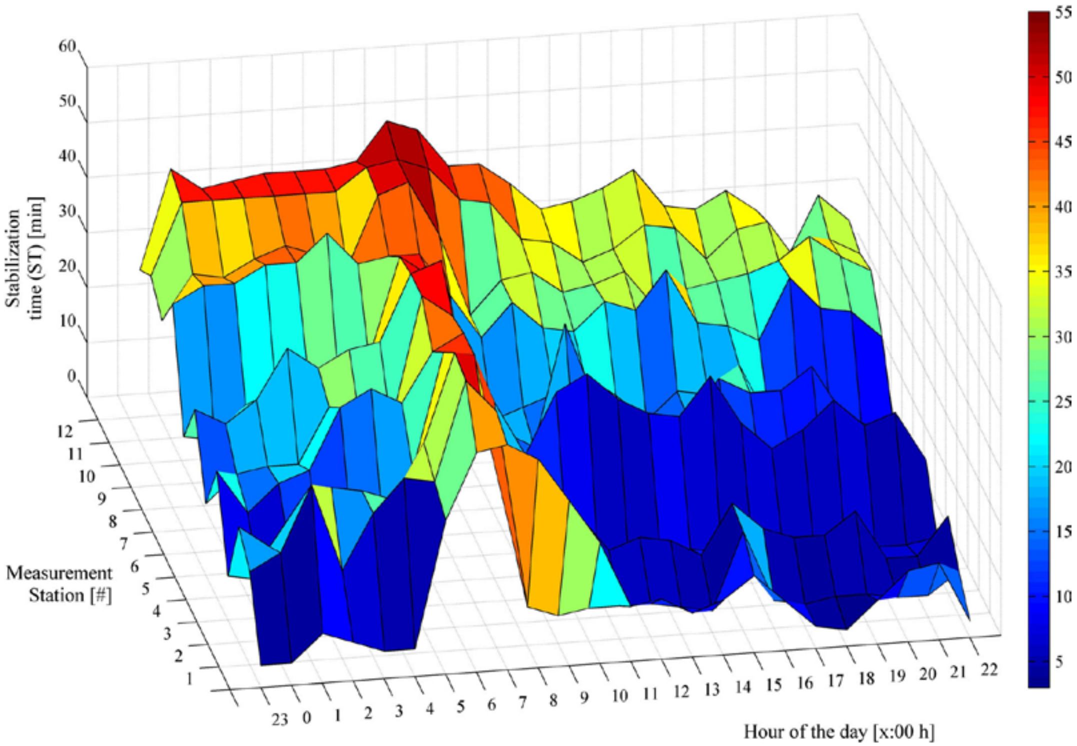

Fig. 5 ST_{90} (axis *z*) for each hour of the day (axis *x*) and station (axis *y*). Error condition ±1 dB

9 min on average is required to reach this confidence level. To achieve a 90 % confidence level with less than 15 min of measurement, sampling should occur between 11:00 and 0:59 (excepting 15:00–15:59). Finally, for the ±0.5 dB error condition and except for the range 6:00 to 7:59, 7 min is sufficient to achieve stabilisation with a 50 % confidence level. Including all hours, 6 min on average is required to reach this level.

Stratum B

For stratum B and according to Table 5, with the exception of 6:00 to 7:59, for an error condition of ±2 dB, 12 min of measurement is sufficient to achieve stabilisation with a 90 % confidence level. Including all hours, 8 min on average is sufficient to reach this level of confidence. Except for 6:00 to 7:59, for the ±1 dB error condition, 15 min of measurement is sufficient to reach stabilisation with an 80 % confidence level. Including all hours, less than 11 min on average is required to reach this level of confidence. To attain a 90 % confidence level required 20 min on average. Finally, with the exception of 6:00 to 7:59, for the error condition ±0.5 dB, 7 min is sufficient to achieve stabilisation with a 50 % confidence level. Including all hours, 7 min on average is required to reach this level of confidence.

Stratum C

For stratum C and according to Table 5, with the exception of 2:00 to 7:59, for the error condition ±2 dB, 14 min of measurement is sufficient to achieve stabilisation with a 90 % confidence level. Including all hours, 8 min on average is required to reach this level of confidence. For the ±1 dB error condition and except for 0:00 to 8:59, 15 min of measurement is sufficient to achieve stabilisation with an 80 % confidence level. Including all hours, less than 18 min on average is required to reach this level of confidence. Finally, for the error condition ±0.5 dB and except for 6:00 to 7:59, 15 min of measurement is sufficient to achieve stabilisation with a 50 % confidence level. Including all hours, less than 10 min is required to reach this level of confidence.

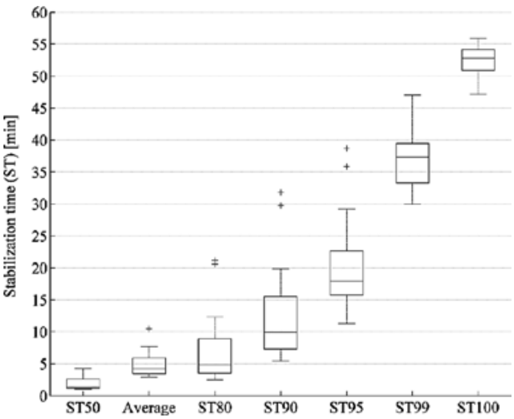

Fig. 6 *Box-and-whisker plot.* Error condition ±2 dB

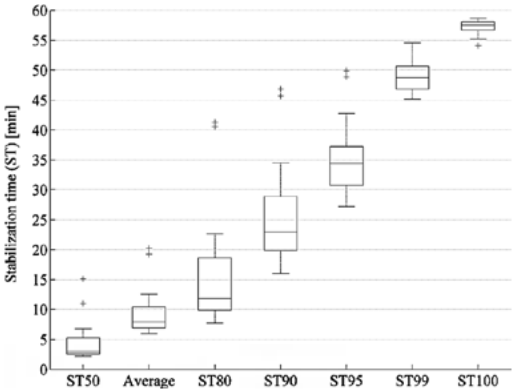

Fig. 7 *Box-and-whisker plot.* Error condition ±1 dB

Stratum D

For stratum D and according to Table 5, including all hours of the day and the ±2 dB error condition, 11 min of measurement is sufficient to achieve stabilisation with a 50 % confidence level. With the exception of

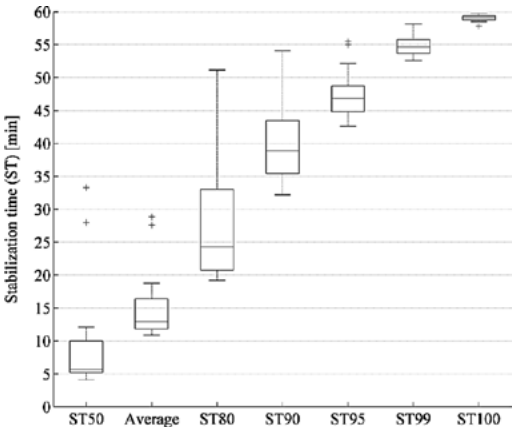

Fig. 8 *Box-and-whisker plot.* Error condition ±0.5 dB

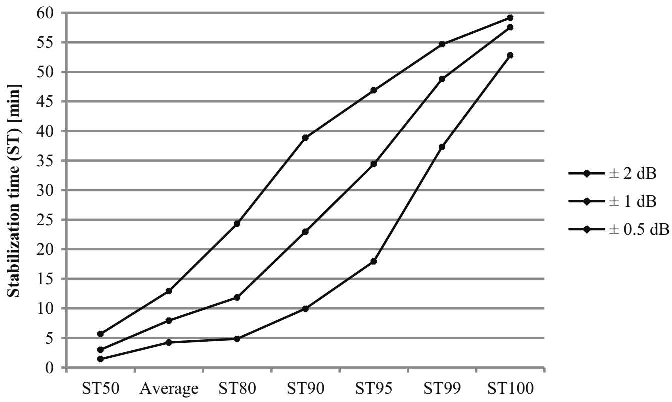

Fig. 9 ST mean values. Error condition ±2/1/0.5 dB

0:00 to 10:59, 14 min is sufficient to achieve stabilisation with an 80 % confidence level. Including all hours, less than 16 min on average is required to reach this level of confidence. For the ±1 dB error condition and except for 7:00 to 8:59, 15 min of measurement is sufficient to achieve stabilisation with a 50 % confidence level. Including all hours, less than 9 min on average is required to reach this level of confidence. Finally, for the ±0.5 dB error condition and except for 0:00 to 10:59, less than 15 min is sufficient to achieve stabilisation with a 50 % confidence level. Including all hours, just over 15 min on average is required to reach this level.

Overview resulting from stratified analysis

Thus, for an error condition of ±2 dB and 15 min of measurement time, the confidence level for achieving stabilisation in stratum A (major roads) is equal to 95 %. For strata B (secondary roads), C (district roads) and D (pedestrian), the confidence levels are 90 %, 80 % and 50 %, respectively.

For an error condition of ±1 dB for less than 15 min of measurement time, the confidence level to achieve stabilisation in stratum A (major roads) is equal to 80 %. For strata B (secondary roads) and C (district roads), more than 15 min is necessary to achieve the same confidence level. For D (pedestrian) with the same measurement time, the confidence level is 50 %.

Finally, for an error condition of ±0.5 dB in almost all hours, for less than 15 min of measurement time, the confidence level for achieving stabilisation in strata A (major roads), B (secondary roads) and C (district roads) is 50 %. This is not true for stratum D (pedestrian). Thus, it can be noted that, when road traffic intensity decreased (strata A to D), the stabilisation time increased.

Conclusions

The STs for all 24 h of the day have been studied at 12 fixed environmental noise stations located in a city with approximately 550000 inhabitants, using a sound-level database collected during five continuous sampling years. The measurement stations were located in different parts of the city in order to cover a wide variety of urban types, from main traffic roads to neighbourhood streets and pedestrian areas.

From the obtained results, it follows that there is a high variability in the ST values depending on the hour of the day, the measurement station in question and the error condition analysed. From a global analysis of all measurement stations and hours of the day, based on average ST values, it is deduced that 15 min of measurement is suitable for estimating the equivalent sound level even when uncertainty is equal to ±0.5 dB.

A statistical analysis of hourly distributions of the ST values leads to the conclusion that the distribution is not normal. Consequently, the study has been supplemented with the use of stabilisation time percentiles. Thus, the 1:00 to 8:59 period must integrate more minutes to attain stabilisation. The ST values required for the last hour of the night period (6:00 to 6:59) and the first of the day period (7:00 to 7:59) are very different from the rest of the hours, significantly higher. Thereby, an adequate selection of the measurement hour can be very important in terms of the percent of values stabilised (50 %,

Table 5 Stabilisation time (ST) when the error condition is established as ±2/±1/±0.5 dB

	Hours																								
	Perc.	23	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A	ST_{50}	1/2/3	1/2/3	1/2/4	2/2/5	2/2/5	2/3/6	2/3/7	3/16/43	2/8/30	1/2/4	1/2/3	1/2/3	1/1/2	1/1/2	1/1/2	1/1/2	1/2/3	1/2/3	1/2/2	1/2/2	1/2/2	1/2/2	1/2/2	1/2/3
	ST_{80}	2/5/22	2/5/17	2/10/35	3/8/25	3/9/21	5/10/21	6/14/34	18/43/52	8/35/49	2/11/22	2/6/17	2/5/15	2/3/11	2/4/11	1/3/11	1/3/9	2/5/19	2/3/11	2/3/9	1/3/9	2/4/12	1/2/9	2/3/9	2/4/14
	ST_{90}	3/14/35	4/14/35	6/22/43	5/17/37	6/19/35	10/20/35	11/31/47	28/46/53	18/40/51	9/19/34	5/15/31	5/16/32	2/9/27	3/10/27	2/9/26	2/8/28	3/17/35	3/9/26	2/7/21	2/7/20	2/10/25	2/8/23	2/8/27	2/8/31
	ST_{95}	10/26/42	15/28/44	12/31/46	9/25/43	12/29/43	19/31/44	18/40/52	34/48/55	26/43/52	12/26/42	10/25/41	13/26/40	8/24/40	5/24/41	5/19/39	5/22/44	11/30/43	6/22/37	5/17/37	3/16/39	5/22/38	5/19/36	7/20/40	4/19/42
B	ST_{50}	1/2/4	1/2/4	1/2/4	1/3/6	2/3/6	2/4/7	2/4/7	2/7/22	3/16/41	1/2/5	1/2/4	1/2/4	1/3/4	1/2/4	1/2/3	1/2/4	1/2/3	1/2/4	1/2/4	1/2/3	1/2/3	1/2/3	1/2/3	1/2/3
	ST_{80}	2/5/17	3/7/15	3/8/22	4/9/23	6/14/27	5/13/26	6/15/32	16/39/51	18/41/51	3/12/26	2/6/17	3/7/18	3/11/20	3/7/18	2/6/15	2/5/15	2/5/16	2/5/14	2/5/13	2/5/14	2/6/14	2/5/12	2/5/13	2/5/14
	ST_{90}	4/15/34	4/13/29	4/17/38	6/18/38	11/26/43	11/26/40	12/28/46	27/45/54	27/45/53	8/26/40	4/16/33	5/20/36	9/19/33	6/19/36	4/15/31	4/16/33	4/17/33	3/15/30	4/12/28	4/13/31	5/15/28	3/13/27	4/12/26	3/11/36
	ST_{95}	14/29/43	10/26/41	8/28/45	10/28/46	19/35/48	19/36/48	18/39/51	35/48/55	32/47/54	18/37/48	11/28/43	13/30/43	16/31/46	19/32/46	11/28/43	12/28/45	12/31/45	9/23/39	10/23/40	8/27/41	12/24/38	9/24/42	10/22/40	10/26/45
C	ST_{50}	2/3/6	2/4/8	2/4/9	3/6/12	4/7/12	5/9/15	4/8/13	4/10/25	5/18/32	2/4/9	2/3/6	2/3/6	2/4/7	2/4/7	1/3/7	1/3/6	1/3/6	1/3/6	2/3/6	1/3/6	1/3/7	1/3/6	1/3/5	1/3/6
	ST_{80}	4/13/31	7/16/31	6/18/37	10/24/39	13/25/39	16/27/39	14/25/36	24/41/51	24/41/51	6/17/31	4/12/25	5/13/26	6/15/29	5/14/28	5/14/28	4/11/24	4/13/25	5/13/25	4/11/26	4/12/23	5/14/27	4/12/26	3/10/23	4/9/22
	ST_{90}	9/28/44	14/29/43	13/32/49	19/36/48	22/36/49	25/37/48	23/36/48	35/47/55	32/47/54	13/29/42	9/22/42	11/25/40	14/30/44	11/26/43	11/25/41	9/23/41	9/25/41	10/25/40	8/25/42	9/22/38	11/26/40	9/23/38	7/21/38	7/19/39
	ST_{95}	16/36/49	21/36/49	21/39/51	26/42/51	28/43/52	37/45/53	32/45/52	42/51/56	38/51/56	23/39/49	16/36/48	20/36/49	26/40/50	24/39/50	21/39/49	22/38/49	16/37/49	21/37/49	21/40/49	19/32/46	23/35/45	15/35/46	13/30/46	13/31/47
D	ST_{50}	2/4/9	3/9/19	5/12/21	4/11/20	8/14/22	7/14/24	6/15/25	5/11/22	9/19/30	11/20/31	4/10/19	3/8/16	3/6/13	2/5/10	1/4/10	1/4/9	2/4/9	3/5/11	2/5/10	2/6/12	1/4/10	1/3/7	1/3/7	1/3/7
	ST_{80}	6/17/36	22/38/47	24/37/48	20/37/49	27/38/49	29/41/50	25/42/52	27/43/52	36/47/53	36/45/52	23/37/49	17/33/46	14/27/40	9/23/37	7/20/36	7/22/40	10/25/39	9/23/37	7/21/36	9/24/40	6/22/39	4/14/32	4/20/39	4/15/35
	ST_{90}	14/33/48	39/48/53	35/46/53	33/46/53	37/47/54	38/47/54	36/47/54	38/50/54	47/54/57	47/52/55	34/45/53	32/45/53	25/39/50	19/36/47	16/35/48	17/37/49	25/40/50	21/36/48	16/33/48	19/37/48	15/35/47	10/27/43	12/34/47	11/30/45
	ST_{95}	25/48/54	49/54/57	45/51/55	39/49/54	48/52/56	45/52/55	38/48/54	47/53/56	52/57/59	52/56/58	39/48/54	39/50/55	35/48/54	28/44/52	30/44/53	30/44/52	37/48/54	31/45/53	27/42/52	28/44/53	27/43/52	19/37/49	23/40/50	21/38/50

80 %, 90 %, 95 % and 100 %) and the required uncertainty (±2, ±1 and ±0.5 dB) for estimating $L_{Aeq,1h}$.

From the analysis by percentiles and considering all measurement stations together, it has been concluded that 15 min of integration time may be an appropriate time to achieve confidence levels of 90 % and ±2 dB uncertainties, confidence levels of 80 % and ±1 dB uncertainties, or 50 % confidence levels and uncertainties of ±0.5 dB.

A stratified analysis of the measuring points leads to the conclusion that, for an error condition of ±2 dB and 15 min of measurement time, the confidence level to achieve stabilisation in the stratum A (major roads) is equal to 95 %. For strata B (secondary roads), C (district roads) and D (pedestrian), the confidence levels are 90 %, 80 % and 50 %, respectively.

Acknowledgements The authors wish to thank the Government of Extremadura, the Regional Ministry of Economy, Trade and Innovation (GR10175) and the European Social Fund for funding the project. The European Regional Development Fund (ERDF) and the Ministry of Economy and Competitiveness (TRA2012-37117). This appreciation is extended to the municipality of Malaga (Dpt. of Environment and Sustainability) for so generously offering us the noise data corresponding to all of their measurement stations.

References

Alberola, J., Flindell, I. H., & Bullmore, A. J. (2005). Variability in road traffic noise levels. *Applied Acoustics, 66*(10), 1180–1195. doi:10.1016/j.apacoust.2005.03.001.

Barrigón Morillas, J. M., Gómez Escobar, V., Méndez Sierra, J. A., Vílchez-Gómez, R., & Trujillo Carmona, J. (2002). An environmental noise study in the city of Cáceres, Spain. *Applied Acoustics, 63*(10), 1061–1070. doi:10.1016/s0003-682x(02)00030-0.

Barrigón Morillas, J. M., Gómez Escobar, V., Méndez Sierra, J. A., Vílchez-Gómez, R., Vaquero, J. M., & Trujillo Carmona, J. (2005). A categorization method applied to the study of urban road traffic noise. *Journal of the Acoustical Society of America, 117*(5), 2844–2852. doi:10.1121/1.1889437.

Barrigón Morillas, J. M., Gómez Escobar, V., Trujillo Carmona, J., Méndez Sierra, J. A., Vílchez-Gómez, R., & Carmona Del Río, F. J. (2011). Analysis of the prediction capacity of a categorization method for urban noise assessment. *Applied Acoustics, 72*(10), 760–771. doi:10.1016/j.apacoust.2011.04.008.

Barrigón Morillas, J. M., & Prieto Gajardo, C. (2014). Uncertainty evaluation of continuous noise sampling. *Applied Acoustics, 75*, 27–36. doi:10.1016/j.apacoust.2013.07.005.

Berglund, B., Lindvall, T., & Schwela, D. H. (1999). *Guidelines for community noise*. Geneva: World Health Organization.

Birk, M., Ivina, O., Von Klot, S., Babisch, W., & Heinrich, J. (2011). Road traffic noise: self-reported noise annoyance versus GIS modelled road traffic noise exposure. *Journal of Environmental Monitoring, 13*(11), 3237–3245. doi:10.1039/c1em10347d.

Brambilla, G., Lo Castro, F., Cerniglia, A., & Verardi, P. (2007). *Accuracy of temporal samplings of environmental noise to estimate the long-term L_{den} value.* Paper presented at the INTER-NOISE 2007, Istanbul, Turkey, 28–31 August

Brocolini, L., Lavandier, C., Quoy, M., & Ribeiro, C. (2013). Measurements of acoustic environments for urban soundscapes: choice of homogeneous periods, optimization of durations, and selection of indicators. *Journal of the Acoustical Society of America, 134*(1), 813–821. doi:10.1121/1.4807809.

Can, A., Van Renterghem, T., Rademaker, M., Dauwe, S., Thomas, P., De Baets, B., et al. (2011). Sampling approaches to predict urban street noise levels using fixed and temporary microphones. *Journal of Environmental Monitoring, 13*(10), 2710–2719. doi:10.1039/c1em10292c.

Chakrabarty, D., Santra, S. C., Mukherjee, A., Roy, B., & Das, P. (1997). Status of road traffic noise in Calcutta metropolis, India. *Journal of the Acoustical Society of America, 101*(2), 943–949. doi:10.1121/1.418131.

Chang, T. Y., Liu, C. S., Bao, B. Y., Li, S. F., Chen, T. I., & Lin, Y. J. (2011). Characterization of road traffic noise exposure and prevalence of hypertension in central Taiwan. *Science of the Total Environment, 409*(6), 1053–1057. doi:10.1016/j.scitotenv.2010.11.039.

Da Paz, E. C., & Zannin, P. H. T. (2010). Urban daytime traffic noise prediction models. *Environmental Monitoring and Assessment, 163*(1–4), 515–529. doi:10.1007/s10661-009-0854-4.

De Donato, S. R. (2007). Estimation of the minimum integration time for determining the equivalent continuous sound level with a given level of uncertainty considering some statistical hypotheses for road traffic. *Noise Control Engineering Journal, 55*(6), 526–531.

de Noronha Castro Pinto, F. A., & Moreno Mardones, M. D. (2009). Noise mapping of densely populated neighborhoods—example of Copacabana, Rio de Janeiro—Brazil. *Environmental Monitoring and Assessment, 155*(1–4), 309–318. doi:10.1007/s10661-008-0437-9.

Doygun, H., & Kuşat Gurun, D. (2008). Analysing and mapping spatial and temporal dynamics of urban traffic noise pollution: a case study in Kahramanmaraş, Turkey. *Environmental Monitoring and Assessment, 142*(1–3), 65–72. doi:10.1007/s10661-007-9908-7.

European Parliament, C. (1988). Directive 89/106/EEC of 21 December 1988 on the approximation of laws, regulations and administrative provisions of the Member States relating to construction products. (Vol. L 40, pp. 12–26)

European Parliament, C. (2002). Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise. (Vol. L 189, pp. 12–25)

Fyhri, A., & Aasvang, G. M. (2010). Noise, sleep and poor health: modeling the relationship between road traffic noise and cardiovascular problems. *Science of the Total Environment, 408*(21), 4935–4942. doi:10.1016/j.scitotenv.2010.06.057.

Gaja, E., Giménez, A., Sancho, S., & Reig, A. (2003). Sampling techniques for the estimation of the annual equivalent noise level under urban traffic conditions. *Applied Acoustics, 64*(1), 43–53. doi:10.1016/s0003-682x(02)00050-6.

González, A. E., Cardozo, M. G., Rocamora, E. P., & Bracho, A. A. (2007). Urban noise: measurement duration and modelling of noise levels in three different cities. *Noise Control Engineering Journal, 55*(3), 367–372. doi:10.3397/1.2732992.

Guedes, I. C. M., Bertoli, S. R., & Zannin, P. H. T. (2011). Influence of urban shapes on environmental noise: a case study in Aracaju—Brazil. *Science of the Total Environment, 412–413*, 66–76. doi:10.1016/j.scitotenv.2011.10.018.

IEC 616721–1 (2002). Electroacoustics—sound level meters—part 1: specifications. Switzerland: International Standard IEC.

Instituto Nacional de Estadística (2012). Territorio. Población, superficie y densidad por municipios. www.ine.es. Accessed November, 2012.

ISO 1996–1 (2003). Acoustics. Description, measurement and assessment of environmental noise. Part 1: basic quantities and assessment procedures. Switzerland: International Organization for Standardization.

ISO 1996–2 (2007). Acoustics. Description, measurement and assessment of environmental noise. Part 2: determination of environmental noise levels. Switzerland: International Organization for Standardization.

Jagniatinskis, A., Fiks, B., & Mickaitis, M. (2011). Statistical assessment of environmental noise generated by road traffic. *Transport, 26*(1), 96–105. doi:10.3846/16484142.2011.568084.

Kephalopoulos, S., Paviotti, M., Knauss, D., & Bérengier, M. (2007). Uncertainties in long-term road noise monitoring including meteorological influences. *Noise Control Engineering Journal, 55*(1), 133–141. doi:10.3397/1.2709621.

Makarewicz, R., & Gałuszka, M. (2012). Nonlinear uncertainty of the long term average level calculated from short term average sound levels. *Noise Control Engineering Journal, 60*(6), 770–774. doi:10.3397/1.3701047.

Marquis-Favre, C., Premat, E., Aubrée, D., & Vallett, M. (2005). Noise and its effects—a review on qualitative aspects of sound. Part I: notions and acoustic ratings. *Acta Acustica united with Acustica, 91*(4), 613–625.

Maruyama, M., Kuno, K., & Sone, T. (2013). The minimum measurement time for estimating L_{AeqT} of road traffic noise from the number of vehicle pass-bys. *Applied Acoustics, 74*(3), 317–324. doi:10.1016/j.apacoust.2012.08.005.

Mohammadi, G. (2009). An investigation of community response to urban traffic noise. *Iranian Journal of Environmental Health Science and Engineering, 6*(2), 137–142.

Ng, C. H., & Tang, S. K. (2008). On monitoring community noise using arbitrarily chosen measurement periods. *Applied Acoustics, 69*(7), 649–661. doi:10.1016/j.apacoust.2007.01.003.

Öhrström, E. (2004). Longitudinal surveys on effects of changes in road traffic noise—annoyance, activity disturbances, and psycho-social well-being. *Journal of the Acoustical Society of America, 115*(2), 719–729. doi:10.1121/1.1639333.

Oyedepo, O. S., & Saadu, A. A. (2010). Evaluation and analysis of noise levels in Ilorin metropolis, Nigeria. *Environmental Monitoring and Assessment, 160*(1–4), 563–577. doi:10.1007/s10661-008-0719-2.

Ozer, S., Irmak, M. A., & Yilmaz, H. (2008). Determination of roadside noise reduction effectiveness of *Pinus sylvestris* L. and *Populus nigra* L. in Erzurum, Turkey. *Environmental Monitoring and Assessment, 144*(1–3), 191–197. doi:10.1007/s10661-007-9978-6.

Prieto Gajardo, C., Barrigón Morillas, J. M., Gómez Escobar, V., Rey Gozalo, G., Vílchez Gómez, R., Méndez Sierra, J. A., et al. (2013). *Categorization Method to Study Environmental Noise in Málaga.* Paper presented at the AIA-DAGA 2013 / EAA Euroregio, International Conference on Acoustics, Merano.

Prieto Gajardo, C., Barrigón Morillas, J. M., Gómez Escobar, V., Vílchez Gómez, R., & Rey Gozalo, G. (2014). Effects of singular noisy events on long-term environmental noise measurements. *Polish Journal of Environmental Studies, (In press).*

Rey Gozalo, G., Barrigón Morillas, J. M., & Gómez Escobar, V. (2013). Urban streets functionality as a tool for urban pollution management. *Science of the Total Environment, 461–462*, 453–461. doi:10.1016/j.scitotenv.2013.05.017.

Romeu, J., Genescà, M., Pàmies, T., & Jiménez, S. (2011). Street categorization for the estimation of day levels using short-term measurements. *Applied Acoustics, 72*(8), 569–577. doi:10.1016/j.apacoust.2010.09.012.

Romeu, J., Jiménez, S., Genescà, M., Pàmies, T., & Capdevila, R. (2006). Spatial sampling for night levels estimation in urban environments. *Journal of the Acoustical Society of America, 120*(2), 791–800. doi:10.1121/1.2215219.

Stephens, M. A. (1974). EDF statistics for goodness of fit and some comparisons. *Journal of the American Statistical Association, 69*(347), 730–737.

To, W. M., Ip, R. C. W., Lam, G. C. K., & Yau, C. T. H. (2002). A multiple regression model for urban traffic noise in Hong Kong. *Journal of the Acoustical Society of America, 112*(2), 551–556. doi:10.1121/1.1494803.

Torija, A. J., Ruiz, D. P., & Ramos-Ridao, A. (2011). Required stabilization time, short-term variability and impulsiveness of the sound pressure level to characterize the temporal composition of urban soundscapes. *Applied Acoustics, 72*(2–3), 89–99. doi:10.1016/j.apacoust.2010.09.011.

Torija, A. J., Ruiz, D. P., & Ramos-Ridao, A. (2012). Estimation procedure of the descriptor L_{Aeq}, T from the stabilization time of the sound pressure level value. *Noise and Vibration Worldwide, 43*(1), 11–18. doi:10.1260/0957-4565.43.1.11.

Van Renterghem, T., Botteldooren, D., & Dekoninck, L. (2012). Evolution of building façade road traffic noise levels in Flanders. *Journal of Environmental Monitoring, 14*(2), 677–686. doi:10.1039/c2em10705h.

Waddington, D., & Kerry, G. The effect of weather on the propagation and measurement of environmental noise. In *Proceedings of the Institute of Acoustics, London, 2012* (PART 1 ed., Vol. 34, pp. 3–15, Environmental Noise Propagation 2012: Definitions, Measuring and Control Aspects).

Wilson, D. K. Weather effects and outdoor noise exposure: where, when, and how often to measure? In *Reno, NV, 2007* (vol. 2, pp. 832–843, 22nd National Conference on Noise Control Engineering, NOISE-CON 2007)

Wolde, T. T. (2003). The EU noise policy and the related research needs. *Acta Acustica (Stuttgart), 89*(5), 735–742.

Objetivo 2: Effects of singular noisy events on long-term environmental noise measurements

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Trabajo publicado en

Polish Journal of Environmental Sciences (2014), Vol. 23(6), Págs. 2007-2017

Pol. J. Environ. Stud. Vol. 23, No. 6 (2014), 2007-2017

Original Research

Effects of Singular Noisy Events on Long-Term Environmental Noise Measurements

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Received: 20 February 2013
Accepted: 17 June 2014

Abstract

One important question to solve is if singular noisy events can affect noise levels in the short, medium, and long term. If the answer is yes and these singular noisy events are present or absent during the monitoring of a place, then long-term noise indices can be overestimating or underestimating, respectively, the noise impact. Therefore, it is necessary to observe and quantify the contribution of these singular noisy events to the annual indices established by the European directive [night level (L_n) and day-evening-night level (L_{den})]. As an example of this situation, for a whole year this study quantified in 24 measurement points how some representative sound indices were affected during the FIFA World Cup celebrated in South Africa during summer 2010 in three Spanish cities (Cáceres, Málaga, and Madrid). It is shown how very short singular events lasting only a few hours can alter appreciably the values of annual noise indices.

Keywords: long-term environmental noise monitoring, anomalous events, temporal variability, prediction models, FIFA World Cup

Introduction

The European Commission refers to environmental noise as one of the main environmental problems in Europe, and the Commission emphasizes the need for specific measures and initiatives to reduce environmental noise [1]. Indeed, considering the total exposure to road traffic noise, it can be calculated that approximately half of all Europeans live in areas of high noise pollution, and over 30% of the population is exposed to sound pressure levels exceeding 55 dBA (A-weighting, International Standard IEC 61672:2003) at night.

European Noise Directive 2002/49/EC introduces two key indices for environmental noise assessment, L_{den} (day, evening, and night) to assess noise annoyance and L_n (night) to assess sleep disturbance. According to this directive, it is recommended that noise assessments for the estimation of the community response to disturbances caused by noise pollution are made for a long-term time interval, usually one year. State members must use these indices to prepare and revise strategic noise maps.

Sound level measurements are required either to contrast the results of the strategic noise maps (obtained by prediction software) or to realize the noise map directly through position measurements[1)] (very rare). In both cases, due to the costs and time needed for long-term measurements it is common practice to obtain short-term data, vary-

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1) Working Group Assessment of Exposure to Noise recognizes that some noise measurement is essential to the development and validation of computation methods. It also has a role to play in other aspects of the implementation of the European Noise Directive.

ing from minutes to hours [2-6], to a whole day [7-10], longer periods of time are rarely used [11-14]. To obtain the long-term time indicated in the European Noise Directive 2002/49/EC, these results are extrapolated to longer periods (primarily months or years).

By considering the typical method of using an extrapolation of the measurements taken for periods of less than a month, the fact that singular events may occur during the measurement period can seriously affect the estimates, because extrapolated values can present a non-representative value; if these singular events are present and measured, then the long-term index will overestimate the noise, but if they are not, then the long-term index will underestimate the noise. Therefore, there is a need to observe and quantify the contributions of these singular events to the annual indices established by the European directive (L_{den} and L_n).

We have sought, in the time interval for which we have data from long-term measurements in a large number of sampling points, some kind of events that could potentially

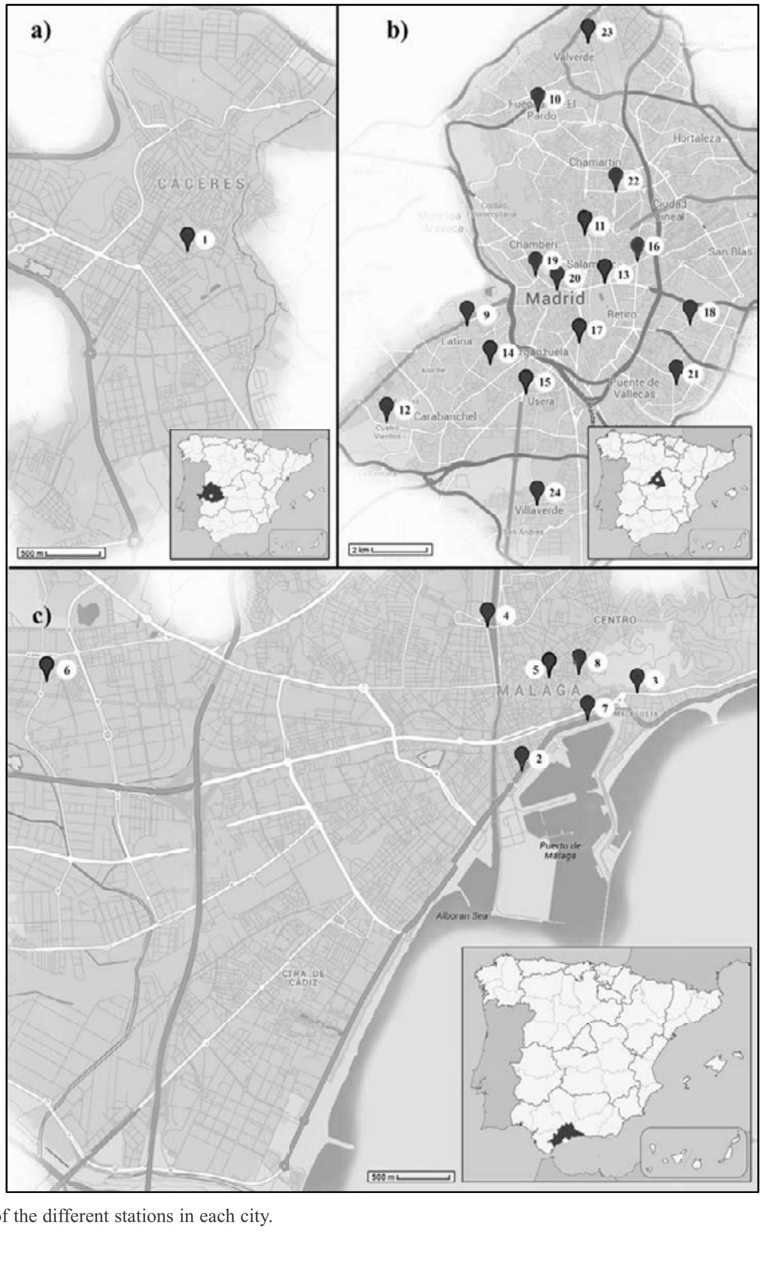

Fig. 1. Location of the different stations in each city.

Table 1. Main features of the environmental sound monitoring stations.

City Population Area Density	Measurement point	Street Category*	Coordinates GPS Latitude-Longitude	
CÁCERES (Cc) 93.131 inhabit. 1750.33 km^2 53.21 inhabit./km^2	Cáceres (1)	3	39.469633	-6.373886
MÁLAGA (Ma) 568.305 inhabit. 395.13 km^2 1438.26 inhabit./km^2	Agustín Heredia (2)	2	36.714328	-4.423072
	Alcazabilla (3)	4	36.722522	-4.416997
	Fátima/Martiricos (4)	3	36.726908	-4.427008
	Granada (5)	6	36.721814	-4.420633
	Hermes (6)	5	36.722064	-4.473908
	Paseo de los curas (7)	2	36.718453	-4.417339
	Uncibay (8)	5	36.722394	-4.420161
MADRID (M) 3.255.944 inhabit. 605.77 km^2 5374.86 inhabit./km^2	Alto de Extremadura (9)	3	40.406947	-3.742517
	Barrio del Pilar (10)	2	40.478228	-3.711542
	Castellana (11)	1	40.439722	-3.690278
	Cuatro Vientos (12)	3	40.376111	-3.776639
	Escuelas Aguirre (13)	1	40.421564	-3.682319
	Farolillo (14)	4	40.394778	-3.731833
	Plz. Fdez. Ladreda (15)	2	40.384722	-3.718611
	Manuel Becerra (16)	2	40.428753	-3.668833
	Méndez Álvaro (17)	4	40.398056	-3.686667
	Moratalaz (18)	3	40.407956	-3.645294
	Plaza de España (19)	2	40.423992	-3.712333
	Plaza del Carmen (20)	3	40.419208	-3.703172
	Puente de Vallecas (21)	3	40.388150	-3.651522
	Ramón y Cajal (22)	2	40.451472	-3.677353
	Tres olivos (23)	4	40.500556	-3.689722
	Villaverde (24)	3	40.347100	-3.713328

*Street categories go from 1 ‘Main city roads’ to 6 ‘pedestrian roads’. The definitions for the different categories can be found in [17, 18]

affect noise levels in the different measuring stations. We have found an example of a singular event that affects the sound levels in the 19th FIFA World Cup held in South Africa between 11 June and 11 July 2010.

This work analyzed the influence of this singular event on the L_{den} and L_n sound indices for hourly, monthly, and yearly time periods in three important Spanish cities (Madrid, Málaga, and Cáceres). The measurements were taken throughout 2010 at 24 different sampling points. That is, we have collected and analyzed as much data as possible from 24 measurement stations that collect a full year of noise levels at each station. The main objectives are the following:

- To analyze the levels obtained during the competition period and to evaluate its effect on the noise indices recommended in European Directive 2002/49/EC, L_{den} and L_n, with measurements taken for a full year.
- To separately evaluate (hourly, monthly, and yearly) increases in the L_{den} and L_n indices resulting from the celebrations of the three final matches of the Spanish team (quarter-finals, semi-finals, and final) in the World Cup.

Table 2. Calendar of the matches played by the Spanish team during 2010 FIFA World Cup in South Africa.

Round	Day	Month	Start time	End time	Match		Results
Group stage	Wednesday 16	June	16:00	17:50	Spain	Switzerland	0-1
Group stage	Monday 21	June	20:30	22:20	Spain	Honduras	2-0
Group stage	Friday 25	June	20:30	22:20	Chile	Spain	1-2
Round of 16	Tuesday 29	June	20:30	22:20	Spain	Portugal	1-0
Quarter-finals	**Saturday 3**	**July**	**20:30**	**22:20**	**Paraguay**	**Spain**	**0-1**
Semi-finals	**Wednesday 7**	**July**	**20:30**	**22:20**	**Germany**	**Spain**	**0-1**
Final	**Sunday 11**	**July**	**20:30**	**23:10**	**Netherlands**	**Spain**	**0-1**

The importance of our study was to assess the extent to which singular events can affect the sound levels obtained from measurements with duration clearly greater than the event itself. If this effect were detected, it could have important consequences on estimates of the appropriate extent of the noise measurements as well as for the preparation of noise maps using software.

Characterization and Location of Measurement Stations

For this study, three Spanish cities with different characteristics were chosen. Measurements were taken throughout 2010, with integration intervals of 1 minute, in 24 different locations (according to city inhabitants and size (Table 1)): one in Cáceres (small town), seven in Málaga (medium town), and 16 in Madrid (large town) (see Fig. 1 for the locations of the different stations). Table 1 contains the geographical locations of the sampling points and the street category.

Different authors consider that the values for the environmental noise from the streets may depend on different factors [10, 15], the type of road considered [16-19], social activities and socioeconomic factors [20], weather, and the intrinsic attributes of the street itself, such as the geometry, the presence of obstacles to the propagation of sound, the type of pavement [13, 21, 22], and the time of day [23]. For this reason, we have considered a wide variety of locations for the different measurement stations.

Temporary Location of Singular Events

To evaluate the noise contribution of a singular event, we must know which days and at what times it occurs. Table 2 shows the schedule of the latest qualifying rounds played by the Spanish team. After a preliminary analysis we found that the development and success of the Spanish team from the previous games did not result in the different stations used in this study, where such an increase could impact the annual or monthly noise levels. For this reason, only those events occurring after the last three matches in July (bolded rows in Table 2) were used in this study. As shown in Table 2, the sound levels that will be most affected due to the victory celebrations are those that incorporate the night period of the next day, i.e., L_n and L_{den}.

Fig. 2 shows the profile of the sound equivalent level in July for integration intervals of one hour together with the values of L_{den}, L_e, and L_n for each day of the month in three different locations. We should note that the index for the evening period, L_e, for all 24 stations considered in this study was mostly unaffected by the development of the matches. During this period (7-10:59 p.m.), matches took place and the fans were usually found indoors. However, in some locations (see Cáceres (Cc) and Méndez Álvaro (M) – Fig. 2), the evening level (L_e) was also affected notably, although the overall increase in noise pollution began when the fans of the Spanish team celebrated in the streets after a win. This is the peak event under study here.

Experimental Procedure

Statistical noise analyzers running continuously (Oper@ by 01dB-Metravid (Cáceres), SDR-500 by PD de Audio, S.L. (Málaga) and Noise Monitoring Terminal type 3639 by Brüel & Kjær (Madrid)) were used as the environmental sound monitoring equipment (class 0 and 1 sound level meter according to IEC 61672-1:2002). The parameter measured to evaluate the noise level was the continuous equivalent A-weighted level integrated every minute ($L_{Aeq,1min}$) for all of 2010. However, to calculate the noise indices that consider both the WHO [24] and the European Union [1], it is necessary to consider the parameter $L_{Aeq,1h}$, i.e., L_{Aeq} integrating within one hour. Once the hourly L_{Aeq} was estimated, the L_{den} and L_n indices were calculated and averaged.

Analysis and Discussion of Results

On the basis of the situation of the environmental sound monitoring stations (Table 1) and the specific times for the singular events mentioned above (Table 2), we proceeded to evaluate and analyze the noise level changes caused during the celebration of these peak events.

Increase over the Daily Average Noise Level

When evaluating and identifying the time slots when each single event developed, it is interesting to note that the increases in the sound indices (L_{den} and L_n) occurred only at night (from 11 p.m.-6:59 a.m.) after the days when victory celebrations occurred after the different matches in the final stages (Table 2), i.e., during the nights of the 4 (quarter-finals), 8 (semi-final), and 12 (final) of July 2010 (Fig. 2).

To understand and evaluate this impact, the values of L_{den} and L_n for all of the measurement stations for the day in July when the final celebration occurred are presented in Table 3, along with the monthly and annual averages. It can be observed that the percentage of stations measuring 5 dB above the annual average was approximately 96% for the night of 12 July (46% for 8 July and 30% for 4 July). Furthermore, 83% of the stations had values 10 dB above the L_n annual average for 12 July (25% of the stations were 10 dB above on 8 July; and approximately 9% of the stations were 10 dB above for 4 July).

Given the very significant effect observed on the sound levels on the days of celebration, especially on 12 July, we decided to perform a more detailed analysis of what happened that night. Table 4 shows a comparison of the equivalent levels for the first hours (11 p.m.-2:59 a.m.) of the night of 12 July together with the average value of the night period for the remaining days of 2010. Differences at or above 10 dB for the 24 measurement stations are shaded in Table 4. Empty fields indicate that during that time the station failed to capture more than 45 minutes and, therefore, as noted above, this hour was omitted. Clearly there is an important increase in the noise level at that time for the vast majority of the stations studied. The duration of these events was estimated to be at least three hours; however, some stations had events lasting throughout the night (11 p.m.-6:59 a.m.). We can see that the hourly noise difference for most of the 24 stations remained very close to or above 10 dB for four hours in some locations, and this difference was greater than 20 dB for three hours. This difference was greater than or approximately equal to 5 dB for six hours.

Increase over the Monthly Average Noise Level

As established in the Introduction of the present paper, it is necessary to know the noise increase percentage during the month in which the World Cup celebration occurred to better assess the impact of this event on the main acoustic indices collected in European Directive 2002/49/EC.

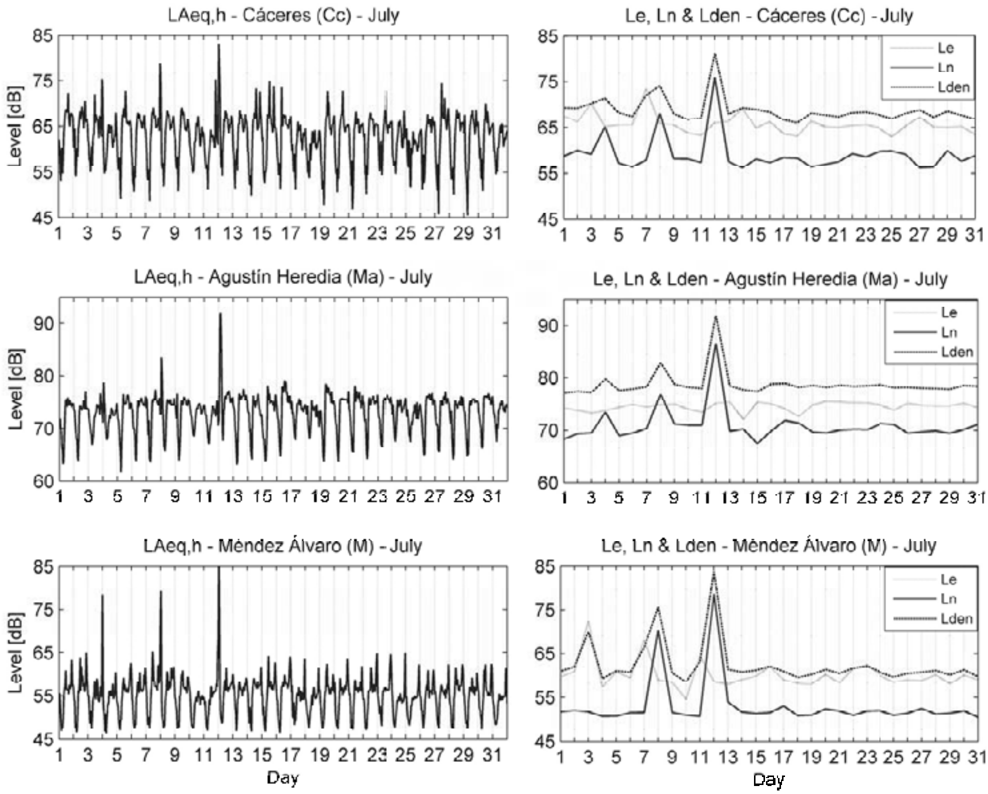

Fig. 2. $L_{Aeq,h}$, L_e, L_n, and L_{den} measurements for July in Cáceres and at one of the Málaga and Madrid stations.

Table 3. Annual, monthly, and daily averages for the different stations.

Measurement points	Annual average		July average		July 12	
	Ln	LDEN	Ln	LDEN	Ln	LDEN
Cáceres (Cc)	59.4	68.9	63.3	70.7	75.9	81.2
Agustín Heredia (Ma)	70.6	78.6	74.2	80.7	86.6	91.9
Alcazabilla (Ma)	69.1	76.4	73.4	79.5	84.4	89.7
Fátima/Martiricos (Ma)	67.8	76.2	70.1	77.2	80.9	86.3
Granada (Ma)	70.6	77.1	77.2	82.6	90.4	95.7
Hermes (Ma)	60.1	66.4	66.9	68.1	79.3	---
Paseo de los curas (Ma)	69.4	77.7	71.5	78.8	82.2	87.6
Uncibay (Ma)	71.8	76.0	77.6	74.6	90.5	---
Alto de Extremadura (M)	58.4	66.2	59.4	66.8	68.1	73.7
Barrio del Pilar (M)	58.5	66.6	61.0	68.0	72.8	78.2
Castellana (M)	61.3	68.3	62.8	69.3	72.7	78.1
Cuatro Vientos (M)	61.4	69.7	61.5	69.4	71.8	77.3
Escuelas Aguirre (M)	66.3	73.7	67.5	74.2	77.7	83.1
Farolillo (M)	60.1	66.1	60.2	66.4	72.1	77.4
Plz. Fdez. Ladreda (M)	62.2	69.8	64.3	70.9	75.8	81.1
Manuel Becerra (M)	61.6	69.4	63.7	70.4	75.9	81.2
Méndez Álvaro (M)	55.7	63.0	64.4	70.2	78.5	83.7
Moratalaz (M)	58.4	66.9	62.9	69.4	75.7	81.0
Plaza de España (M)	66.9	74.0	73.2	79.1	78.5	84.2
Plaza del Carmen (M)	62.3	68.7	62.8	69.7	71.5	77.5
Puente de Vallecas (M)	63.8	70.7	73.4	79.4	68.8	74.2
Ramón y Cajal (M)	64.4	72.7	65.4	72.9	75.7	81.3
Tres olivos (M)	52.0	61.1	55.7	62.9	65.1	70.6
Villaverde (M)	61.6	67.8	60.6	67.2	69.4	74.8
% of Measurements points exceeding 5/10 [dB]			25/0	18.2/0	95.8/83.3	95.5/54.5

Cc – Cáceres, Ma – Málaga, and M – Madrid

The first two columns of Table 5 show the monthly noise increases (in dB and per cent) caused from the development and subsequent celebration of the World Cup matches played by the Spanish team. That is, the differences in the L_{den} and L_n between the average monthly value and the averaged value we would have obtained if we had averaged July without the days corresponding to the matches and the celebrations (3, 4, 7, 8, 11, and 12 July) are shown in these two columns. In the next two columns, the increases due solely to the celebrations (days 4, 8, and 12 July) are shown. Finally, in the last two columns the increases due solely to the celebration of the final victory of the Spanish team are shown.

For the first two columns the events discarded (days 3, 4, 7, 8, 11, and 12, July 2010) would imply a 15% maximum increase in the L_{den}. In the case of the L_n, the maximum percentage increase is greater than 24%. These two maxima were measured at the Méndez Álvaro station (Madrid). In the next columns, from which 4, 8, and 12 July were omitted, we can see how the magnitude of the increases is very similar to those obtained in the previous case for both indicators. This corroborates our claim that the noise effects of the World Cup are mainly due to the celebration of victories. For this reason, in the last two columns we studied the effects of the celebration on 12 July instead of the match day, because the final match ended after 11 p.m. on 11 July (Table 2). Comparing the last two columns to the previous two in Table 5, we can deduce that although the most important effect is concentrated from the celebration after the final, the effects of the quarter and semi-finals are

Table 4. Hourly equivalent levels at night for all of 2010 and for 12 July 2010, together with the differences between them.

Meas. points	23:00			00:00			01:00			02:00		
	July 11	Annual	Dif.	July 12	Annual	Dif.	July 12	Annual	Dif.	July 12	Annual	Dif.
Cáceres (Cc)	83.0	62.6	**20.5**	79.1	60.1	**19.1**	73.3	57.2	**16.2**	60.7	56.0	4.7
Agustín Heredia (Ma)	77.2	72.5	4.7	91.6	71.6	**20.1**	91.9	70.5	**21.4**	86.9	69.1	**17.8**
Alcazabilla (Ma)	78.6	70.0	8.6	88.9	69.7	**19.2**	88.9	68.9	**20.1**	85.4	68.1	**17.3**
Fátima/Martiricos (Ma)	74.9	71.0	3.8	87.1	69.6	**17.6**	84.5	68.0	**16.5**	80.9	66.4	**14.6**
Granada (Ma)	---	---	---	92.9	68.8	**24.2**	93.9	69.9	**24.0**	91.7	68.9	**22.9**
Hermes (Ma)	76.1	62.6	**13.6**	86.9	61.8	**25.1**	80.4	59.6	**20.8**	75.9	56.8	**19.1**
Paseo de los curas (Ma)	74.5	72.1	2.4	87.4	71.1	**16.3**	87.3	69.6	**17.6**	82.9	67.8	**15.1**
Uncibay (Ma)	79.3	70.2	9.2	92.4	70.6	**21.8**	94.6	70.9	**23.6**	94.2	70.5	**23.7**
Alto de Ext. (M)	74.2	60.1	**14.1**	72.9	59.5	**13.4**	62.7	58.0	4.7	61.4	57.9	3.5
Barrio del Pilar (M)	78.4	60.5	**17.9**	76.5	60.7	**15.8**	72.0	59.1	**12.9**	69.1	56.9	**12.2**
Castellana (M)	73.8	62.0	**11.8**	75.9	62.2	**13.7**	75.4	61.7	**13.7**	74.7	61.4	**13.3**
Cuatro Vientos (M)	79.6	63.0	**16.6**	73.3	64.2	9.1	64.1	58.8	5.3	58.2	57.2	1.0
Escuelas Aguirre (M)	80.9	67.6	**13.3**	82.8	67.5	**15.3**	79.6	66.5	**13.1**	76.3	65.7	**10.6**
Farolillo (M)	81.0	54.2	**26.8**	63.8	67.6	-3.8	63.5	58.9	4.6	50.1	52.8	-2.7
Pl. Fdez. Ladreda (M)	80.9	64.2	**16.7**	80.8	63.0	**17.8**	77.0	61.4	**15.6**	65.8	60.4	5.4
Manuel Becerra (M)	80.4	62.3	**18.1**	82.4	63.9	**18.5**	71.9	63.4	8.5	68.0	59.9	8.1
Méndez Álvaro (M)	87.5	54.0	**33.5**	66.0	53.3	**12.7**	51.8	50.9	0.9	50.0	49.1	0.9
Moratalaz (M)	82.6	60.5	**22.1**	79.7	58.8	**20.9**	72.0	57.0	**15.0**	65.2	55.7	9.5
Plaza de España (M)	77.0	67.9	9.1	83.0	67.4	**15.6**	80.0	66.8	**13.2**	78.8	65.5	**13.3**
Plaza del Carmen (M)	77.4	61.7	**15.7**	72.5	64.8	7.7	71.3	63.1	8.2	71.5	62.9	8.6
Puente de Vallecas (M)	76.7	68.4	8.3	68.9	68.4	0.5	67.0	66.8	0.2	53.7	56.8	-3.1
Ramón y Cajal (M)	78.6	66.6	**12.0**	81.7	65.9	**15.8**	75.8	64.3	**11.5**	72.5	63.0	9.5
Tres olivos (M)	73.2	54.2	**19.0**	63.5	55.4	8.1	62.4	49.7	**12.7**	52.8	48.0	4.8
Villaverde (M)	77.3	59.8	**17.5**	70.4	69.8	0.6	64.9	55.0	9.9	53.5	50.1	3.4
Mean [dB]	79.7	66.7	14.6	85.6	67.0	14.4	85.7	65.5	12.9	83.6	64.1	9.7
Standard Deviation [dB]	3.4	5.6	7.3	8.9	5.1	7.4	11.1	6.1	6.7	13.2	6.6	7.5

Bold numbers indicate differences above 10 dB in relation with the annual average for that hour.

not negligible. Therefore, we can assume the existence of similar effects in countries where the football team won these matches and went on to the next phase of qualifying.

In Table 5 we note the existence of a station where no effect is detected from the celebrations of the World Cup: the “Puente de Vallecas” station in Madrid. The cause was not that the celebration of the World Cup poses no important increase over the normal noise values measured at this station, but rather during that month, there was another singular event whose impact masked the World Cup celebration. Fig. 3 shows that between 16 and 19 July there was a very important variation in the “Puente de Vallecas” station coinciding with another celebration in the neighborhood (“Fiestas del Carmen”). Additionally, it can be observed that there are other months in this location when other noisy events seem to have occurred and led to significant increases in the L_{den} and L_n compared to the baseline values. Table 6 shows the increases in the July and yearly values of the L_{den} and L_n due to the “Fiestas del Carmen” celebration that took place from 16 to 19 July, with and without considering the World Cup final. The inclusion or exclusion of the World Cup only affects the July values.

Table 5. Monthly noise increases due to the development of the World Cup.

Measurement points	July 3, 4, 7, 8, 11, and 12		July 4, 8, and 12		July 12	
	ΔL_n (dB/%)	ΔL_{den} (dB/%)	ΔL_n (dB/%)	ΔL_{den} (dB/%)	ΔL_n (dB/%)	ΔL_{den} (dB/%)
Cáceres (Cc)	5.1/8.8	2.7/3.9	5.1/8.8	2.4/3.5	3.6/6.0	1.9/2.7
Agustín Heredia (Ma)	4.1/5.8	2.5/3.2	4.1/5.8	2.6/3.3	3.4/4.8	2.2/2.9
Alcazabilla (Ma)	5.2/7.7	4.0/5.3	5.2/7.6	3.9/5.2	2.2/3.1	1.8/2.3
Fátima/Martiricos (Ma)	2.7/4	1.4/1.9	2.8/4.2	1.6/2.1	2.0/2.9	1.2/1.6
Granada (Ma)	10.5/15.8	9.6/13.1	10.5/15.7	9.4/12.9	4.7/6.5	4.4/5.7
Hermes (Ma)	5.8/9.5	0.1/0.1	5.8/9.6	--/--	4.7/7.5	--/--
Paseo de los curas (Ma)	2.2/3.2	1.2/1.5	2.3/3.3	1.2/1.6	2.0/2.9	1.1/1.5
Uncibay (Ma)	9.2/13.4	--/--	8.9/12.9	--/--	4.3/5.9	--/--
Alto de Ext. (M)	1.4/2.5	1.0/1.5	1.5/2.5	0.9/1.3	1.0/1.8	0.6/0.9
Barrio del Pilar (M)	3.8/6.6	2.2/3.4	3.8/6.6	2.1/3.2	2.8/4.8	1.6/2.4
Castellana (M)	2.5/4.1	1.8/2.6	2.4/4.0	1.7/2.5	1.5/2.4	1.1/1.6
Cuatro Vientos (M)	2.0/3.4	1.0/1.5	1.9/3.3	0.9/1.4	1.7/2.8	0.8/1.2
Escuelas Aguirre (M)	2.0/3.1	1.3/1.8	1.9/2.9	1.3/1.7	1.6/2.5	1.1/1.5
Farolillo (M)	7.9/15.2	5.5/9.0	7.7/14.8	4.6/7.4	2.9/5.1	2.1/3.3
Plz. Fdez. Ladreda (M)	3.0/5.0	2.0/3.0	3.0/4.9	2.0/2.9	2.5/4.0	1.6/2.4
Manuel Becerra (M)	3.5/5.9	2.3/3.4	3.5/5.9	2.2/3.2	3.2/5.3	2.0/2.9
Méndez Álvaro (M)	12.7/24.5	9.3/15.2	12.7/24.6	7.9/12.7	7.4/13.0	5.7/8.8
Moratalaz (M)	6.3/11.1	3.8/5.8	6.1/10.8	3.5/5.3	4.1/7.0	2.6/3.9
Plaza de España (M)	5.7/8.4	4.3/5.8	2.9/4.2	2.3/3.0	0.4/0.5	0.3/0.4
Plaza del Carmen (M)	1.6/2.5	1.9/2.8	1.4/2.3	1.0/1.4	1.0/1.7	0.8/1.1
Puente de Vallecas (M)	-0.9/-1.2	-0.8/-1.0	-0.4/-0.5	-0.4/-0.5	-0.1/-0.1	-0.1/-0.1
Ramón y Cajal (M)	2.3/3.6	1.3/1.7	2.1/3.4	1.1/1.6	1.7/2.7	0.9/1.3
Tres olivos (M)	5.1/10.1	2.7/4.5	5.0/9.8	2.7/4.4	3.4/6.5	2.0/3.3
Villaverde (M)	1.5/2.5	1.3/1.9	1.4/2.4	1.0/1.5	1.0/1.8	0.7/1.1
% Increase [dB] > 2.5	66.7%	37.5%	62.5%	29.2%	50.0%	12.5%

Therefore, the possibility of localized noise events at specific points, or spread over significant areas, in a city that can cause important variations in the long-term noise indices collected in the European Directive 2002/49/EC reinforces the interest of the present work.

Increase over the Annual Average Noise Level

During the 19th World Cup, the singular event under study, there were notable increases in the $L_{Aeq,1h}$ value collected by the monitoring stations due mainly to the celebration of the victory of the Spanish team. We compared the annual levels of all measurement stations (for 365 days of 2010) with the average annual levels after discarding the days when these singular events occurred, i.e., 3 and 4 July 2010 (quarter-finals), 7 and 8 July 2010 (semi-finals), and 11 and 12 July 2010 (final). The study was performed independently for each of the events to provide a reference for what might have happened in those countries that reached different classification levels throughout the occurrence of the World Cup. Table 7 shows the noise increase in the acoustic indices L_{den} and L_n (in dBA) over the annual period caused by the development and subsequent conclusion of the final match. The cells of the stations with annual increases in the L_{den} and L_n equal to or greater than 0.5 dB are shaded.

The singular events of 4, 8, and 12 July (3 days × 24 hours = 72 h), constituting less than 1% of the total hours in a year, represent an increase, in the worst case, of 4.4 dB, which is more than 8.5% over the reference value (in the case of L_n, this occurred at the Méndez Álvaro station in

Table 6. Variations in Lden and Ln due to "Fiestas del Carmen" (FC) at the "Puente de Vallecas" station.

Puente de Vallecas	Including FC – Excluding FC ΔL_n	Including FC – Excluding FC ΔL_{den}
Year 2010 with World Cup	6.1	4.1
July 2010 with World Cup	15.2	12.8
Year 2010 without World Cup	6.1	4.2
July 2010 without World Cup	16.1	13.6

Madrid). At this station, if the World Cup had not occurred, the L_n value averaged for 2010 would have been 51.3 dBA instead of the actual 55.7 dBA.

It is even more interesting to observe how only the celebration event related to the Spanish victory generated increments of 0.5 dBA or greater for the L_n levels averaged over 2010 for almost 30% of the monitoring stations: a period of only 8 hours (less than 0.3% of the number of hours in a year) for the celebration night after the Spanish team triumph, from 11 p.m.-6:59 a.m. on 12 July 2010, is able to modify the indices on an annual basis (with a night period of 2,920 hours and a combined 8,760 hours for the day, evening, and night periods) by 3.5 dB for the L_n and 1.8 dB for the L_{den} in the extreme case (the Méndez Álvaro station in Madrid).

Conclusions

In this study we analyzed the impact that specific sound events can have on standard sound indicators contained in international laws and regulations. The results obtained in this study could be extrapolated, in similar circumstances, to many countries around the world. The analyzed data proceed in 24 measurement stations located in three cities of different size, very far apart, with very different planning, over a full year.

- We detected the existence of a measurable effect on the average annual indices, L_{den} and L_n. There was only one station where no effect was detected due to the existence of another event with abnormal sound that was even greater than the event studied in this work. This is very important as it indicates that the relative importance on the year of the event under study may be affected in other stations by events that happened in them but they have not been studied. It further indicates that this event is not unique. The relationship of the importance of the event on the month and year can give us an idea of the existence of non-studied events in other months. The detailed study of the month at those stations where their relevance is smaller can make us detect anomalous sound events. In virtually all of the monitoring stations for environmental noise we measured a very important impact on the average daily and monthly noise levels after the celebrations corresponding to the quarterfinals onwards.
- The effect of the World Cup on the average annual indices was greater than 0.5 dB for the L_n indicator for nearly 40% of the measuring points, with a maximum increase of 4.4 dB. It was also greater than 0.5 dB for the L_{den} in more than 20% of the locations, with a maximum increase of 2.2 dB.

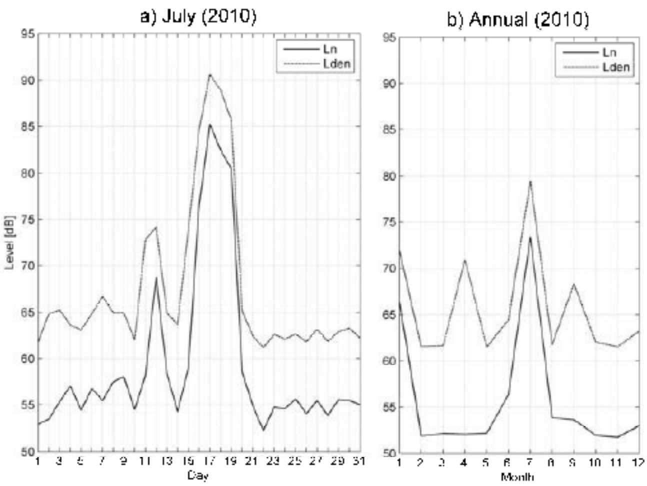

Fig. 3. July (a) and annual (b) L_{den} and L_n variations in the vicinity of the "Puente de Vallecas" station in Madrid.

Table 7. 2010 annual increases due to the development of the World Cup.

Measurement points	Including-Excluding 4, 8, and 12 July		Including-Excluding 12 July	
	ΔL_n	ΔL_{den}	ΔL_n	ΔL_{den}
Cáceres (Cc)	**0.7**	0.2	**0.6**	0.2
Agustín Heredia (Ma)	**0.6**	**0.5**	**0.5**	0.4
Alcazabilla (Ma)	**0.7**	**0.5**	0.4	0.3
Fátima/Martiricos (Ma)	0.3	0.1	0.2	0.1
Granada (Ma)	**2.0**	**1.5**	**1.4**	**1.0**
Hermes (Ma)	**1.3**	0.0	**1.2**	0.0
Paseo de los curas (Ma)	0.2	0.2	0.2	0.2
Uncibay (Ma)	**1.7**	0.0	**1.2**	0.0
Alto de Extremadura (M)	0.1	0.1	0.1	0.1
Barrio del Pilar (M)	0.4	0.2	0.3	0.2
Castellana (M)	0.3	0.2	0.2	0.2
Cuatro Vientos (M)	0.1	0.1	0.1	0.1
Escuelas Aguirre (M)	0.2	0.1	0.2	0.1
Farolillo (M)	0.3	0.2	0.2	0.2
Plz. Fdez. Ladreda (M)	0.3	0.2	0.3	0.2
Manuel Becerra (M)	0.3	0.2	0.3	0.2
Méndez Álvaro (M)	**4.4**	**2.2**	**3.5**	**1.8**
Moratalaz (M)	**0.8**	0.4	**0.7**	0.3
Plaza de España (M)	**0.9**	**0.6**	0.2	0.1
Plaza del Carmen (M)	0.1	0.1	0.1	0.1
Puente de Vallecas (M)	0.0	0.0	0.0	0.0
Ramón y Cajal (M)	0.2	0.1	0.2	0.1
Tres olivos (M)	0.4	0.1	0.3	0.1
Villaverde (M)	0.1	0.1	0.1	0.1
% increase [dB] > 0.5	37.5%	20.8%	29.2%	8.3%

Bolded cells show increases equal to or greater than 0.5 dB.

- The individual effect of the quarterfinals has been measured in more than 20% of the measurement stations for the L_n index, with a maximum increase of 0.7 dB, and 17% for the L_{den} index, with an increase up to 0.4 dB.
- The individual effect of the semi-finals has been measured at nearly 40% of the measurement stations for the L_n index, with a maximum increase of 0.4 dB, and 17% for the L_{den} index, with a maximum increase of 0.3 dB.
- The individual effect of the final has been measured at almost 100% of the measurement stations for both indices L_{den} and L_n, with a maximum increase of 3.5 dB for the first index and 1.8 dB for the second one.
- Therefore, this study suggests that there are singular noisy events that may have an appreciable effect on the mean daily, monthly, and even annual noise indices, implying that would not be adequately addressed in the noise maps that are being developed, both by measurements and by sound field propagation models. Given the type of event studied, the results can be used to remember similar situations.

Acknowledgements

The authors wish to thank the Government of Extremadura, the Regional Ministry of Economy, Trade and Innovation, and the European Social Fund for funding our project. This appreciation is extended to the municipalities of Madrid and Málaga (Department of Environment and Sustainability) for so selflessly offering us the noise data corresponding to all of their measurement stations.

Acknowledgements

The authors wish to thank the Government of Extremadura, the Regional Ministry of Economy, Trade and Innovation (GR10175), European Social Fund, European Regional Development Fund (ERDF) and the Ministry of Economy and Competitiveness (TRA2012-37117) for partially funding the project. This appreciation is extended to the municipalities of Madrid and Malaga (Department of Environment and Sustainability) for so selflessly offering us the noise data corresponding to all of their measurement stations.

References

1. EUROPEAN PARLIAMENT C. Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise. **2002**.
2. BENDTSEN H. The Nordic prediction method for road traffic noise. Sci. Total Environ., **235**, 331, **1999**.
3. LI B., TAO S., DAWSON R. W. Evaluation and analysis of traffic noise from the main urban roads in Beijing. Appl. Acoust., **63**, 1137, **2002**.
4. REY GOZALO G., BARRIGÓN MORILLAS J. M., GÓMEZ ESCOBAR V. Urban Streets Functionality As A Tool For Urban Pollution Management. Sci. Total Environ., **461-462**, 453, **2013**.
5. TO W. M., IP R. C. W., LAM G. C. K., YAU C. T. H. A multiple regression model for urban traffic noise in Hong Kong. J. Acoust. Soc. Am., **112**, 551, **2002**.
6. ZANNIN P. H. T., DINIZ F. B., BARBOSA W. A. Environmental noise pollution in the city of Curitiba, Brazil. Appl. Acoust., **63**, 351, **2002**.
7. KIHLMAN T., ABUKHADER S. Long-term noise abatement planning-case studies in Göteborg, Sweden. Internoise. The Hague, Holland. **2001**.
8. ONUU M. U. Road traffic noise in Nigeria: Measurements, analysis and evaluation of nuisance. J. Sound Vib., **233**, 391, **2000**.
9. SKINNER C. J., GRIMWOOD C. J. The UK noise climate 1990-2001: Population exposure and attitudes to environmental noise. Appl. Acoust., **66**, 231, **2005**.
10. VAN RENTERGHEM T., BOTTELDOOREN D., DEKONINCK L. Evolution of building façade road traffic noise levels in Flanders. J. Environ. Monitor., **14**, 677, **2012**.
11. ALBEROLA J., FLINDELL I. H., BULLMORE A. J. Variability in road traffic noise levels. Appl. Acoust., **66**, 1180, **2005**.
12. BJÖRK E. A. Community noise in different seasons in Kuopio, Finland. Appl. Acoust., **42**, 137, **1994**.
13. ROMEU J., JIMÉNEZ S., GENESCÀ M., PÀMIES T., CAPDEVILA R. Spatial sampling for night levels estimation in urban environments. J. Acoust. Soc. Am., **120**, 791, **2006**.
14. CAN A., VAN RENTERGHEM T., RADEMAKER M., DAUWE S., THOMAS P., DE BAETS B., BOTTELDOOREN D. Sampling approaches to predict urban street noise levels using fixed and temporary microphones. J. Environ. Monitor., **13**, 2710, **2011**.
15. GUEDES I. C. M., BERTOLI S. R., ZANNIN P. H. T. Influence of urban shapes on environmental noise: A case study in Aracaju – Brazil. Sci. Total Environ., **412-413**, 66, **2011**.
16. BARRIGÓN MORILLAS J. M., GÓMEZ ESCOBAR V., REY GOZALO G., VÍLCHEZ-GÓMEZ R. Possible relation of noise levels in streets to the population of the municipalities in which they are located. J. Acoust. Soc. Am., **128**, EL86, **2010**.
17. BARRIGÓN MORILLAS J. M., GÓMEZ ESCOBAR V., TRUJILLO CARMONA J., MÉNDEZ SIERRA J. A., VÍLCHEZ-GÓMEZ R., CARMONA DEL RÍO F. J. Analysis of the prediction capacity of a categorization method for urban noise assessment. Appl. Acoust., **72**, 760, **2011**.
18. CARMONA DEL RÍO F. J., GÓMEZ ESCOBAR V., TRUJILLO CARMONA J., VÍLCHEZ-GÓMEZ R., MÉNDEZ SIERRA J. A., REY GOZALO G., BARRIGÓN MORILLAS J. M. A Street categorization method to study urban noise: The valladolid (Spain) study. Environ. Eng. Sci., **28**, 811, **2011**.
19. REY GOZALO G., BARRIGÓN MORILLAS J. M., GÓMEZ ESCOBAR V. Analyzing nocturnal noise stratification. Sci. Total Environ., **479-480**, 39, **2014**.
20. DOYGUN H., KUŞAT GURUN D. Analysing and mapping spatial and temporal dynamics of urban traffic noise pollution: A case study in Kahramanmaraş, Turkey. Environ. Monit. Assess., **142**, 65, **2008**.
21. BRAMBILLA G., LO CASTRO F., CERNIGLIA A., VERARDI P. Accuracy of temporal samplings of environmental noise to estimate the long-term L_{den} value. Inter-noise 2007. Istanbul, Turkey. **2007**.
22. MONZÓN A., GUERRERO M. J. Valuation of social and health effects of transport-related air pollution in Madrid (Spain). Sci. Total Environ., **334-335**, 427, **2004**.
23. BARRIGÓN MORILLAS J. M., PRIETO GAJARDO C. Uncertainty evaluation of continuous noise sampling. Appl. Acoust., **75**, 27, **2014**.
24. BERGLUND B., LINDVALL T., SCHWELA D. H. Guidelines for community noise. Geneva: World Health Organization. **1999**.

Objetivo 3: Uncertainty evaluation of continuous noise sampling

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Trabajo publicado en

Polish Applied Acoustics (2013), Vol. 75, Págs. 27-36

Applied Acoustics 75 (2014) 27–36

Contents lists available at SciVerse ScienceDirect

Applied Acoustics

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

Uncertainty evaluation of continuous noise sampling

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ARTICLE INFO

Article history:
Received 11 June 2012
Received in revised form 8 April 2013
Accepted 3 July 2013
Available online 30 July 2013

Keywords:
Noise mapping
Long-term sampling
Uncertainty
Environmental noise

ABSTRACT

An area of current interest and topic of multiple publications is the assessment of uncertainty in estimating long-term indicators from measurements made for periods of time of less than 1 year. In this work, these prior investigations have been used as a starting point.

Based on measurements made during one whole year at 26 sampling points with variables of urban and traffic characteristics, it was considered two aims related to uncertainty in the estimation of the annual L_{den}. The strength of this study is the large amount of data, which allows to simulate real measurements by sampling data from random days. Thus, it was studied in detail the predictive ability of the expressions proposed in the literature. Associated with this objective, then it was sought to evaluate the uncertainty associated with the estimation of annual L_{den} when random days of sampling were much lower than a full year.

The results indicate the need for further progress in the theoretical determination of uncertainty. Second, the results made it able to estimate the uncertainty for the L_{den} indicator based on the number days sampled randomly.

1. Introduction

Noise pollution poses serious risks to health and quality of life for large parts of the world population [1–5]. Many studies have been conducted over the last few decades on various aspects of noise pollution, including sources [6–8], sampling strategies [9–13], noise pollution levels [14–17], strategic noise map uncertainty [18–21], exposure levels [22,23], and physiological and psychological effects [24,25].

The European Community [26] suggests the use of noise maps as a major tool for assessing noise levels and their effects on humans. Such evaluations are required for devising noise pollution improvements or solutions.

European Directive 2002/49/EC recommends that noise assessments and an evaluation of noise pollution effects on the community be made over a long time interval, such as 1 year. This recommendation suggests that noise mapping measurements and sound field propagation models should use annual averages or other techniques with time periods on the order of 1 year. Naturally, the predictions should be compared with measurements representative of the entire year if it were possible.

Sound level measurements are therefore required either to confirm model predictions or to directly generate a noise map. Because of the costs and time needed for long-term measurements, it is common practice to obtain noise data over periods of minutes to hours [27–31], with some studies measuring noise over a whole day [32–35]. Noise measurements over periods longer than a day are rarely performed [36–38]. Generally, short-term noise measurements are extrapolated to the months or years required by the European Noise Directive 2002/49/EC. Therefore, studies that analyse the variability of sound indicators based on sound measurements that have been taken continuously for a year or more are required.

Several authors [39–41] have worked to find measurement strategies that would provide estimated average values of the L_{den} index that provide acceptable values for $L_{den}^{(map)}$ (see Eq. (5)).

A research area related to noise measurements involves understanding the uncertainties associated with long-term noise estimates when they are generated based on short- or medium-term measurements. A recent theoretical paper [19] gives a mathematical expression to estimate the $L_{den}^{(map)}$ when the number of sampling days is much less than the 365 days of the year used for the L_{den} index.

The goal of this paper is to confirm the theoretical analysis by providing a statistical comparison of estimated and "real" noise measurements. This comparison was conducted using a wide range of measurements over an entire year to obtain estimated annual values [19]; those estimates were then compared with actual long-term measurements which were taken at 26 points that had a variety of noise conditions on randomly selected days throughout the year.

In this paper, Section 2 describes the characterisation and location of measurement stations, Section 3 presents the experimental

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0003-682X/$ - see front matter
http://dx.doi.org/10.1016/j.apacoust.2013.07.005

methodology, materials and methods, Section 4 presents the assessments of the results, and Section 5 contains the conclusions.

2. Characterisation and location of measurement stations

Environmental noise in cities is primarily derived from road traffic. Past research has shown that street noise depends on a number of factors, including land use [42], road type [43], social activities and socioeconomic factors [9], weather and the intrinsic attributes of the street itself, such as its geometry, the presence of obstacles to sound propagation and the type of pavement [37,44,45]. A wide variety of locations were considered for the measurement stations so as to ensure differing characteristics of urban and architectural environment, traffic flow and other factors.

Measurements were taken throughout 2006, at 26 different locations in Madrid. Table 1 and Fig. 2 contains relevant geographic characteristics for the measurement stations, while Table 2 summarises relevant meteorological characteristics for the stations. The data were obtained from the Spanish Meteorological Agency website [46]. All measurements had an integration interval of 1 min.

Stations that had lost more than 5% of the measurement days during the analysed year were discarded to avoid introducing uncertainties associated with the total time of measurement when calculating L_{den}.

3. Methodology

Twenty-six statistical noise analysers from *Brüel & Kjær* models *4441* and *4435* were used for environmental sound monitoring. The analysers were operated continuously during the year 2006. The measured parameter was the continuous equivalent A-weighted noise level integrated every hour ($L_{Aeq,1h}$) for all months of 2006. The L_{den} indices were calculated and averaged from the hourly L_{Aeq} results, as shown in Fig. 1.

Acoustic parameter L_{den} is calculated using Eq. (1) [26]:

$$L_{den} = 10\log\frac{1}{24}\left\{12\times 10^{\frac{L_{day}}{10}} + 4\times 10^{\frac{L_{evening}+5}{10}} + 8\times 10^{\frac{L_{night}+10}{10}}\right\} \quad (1)$$

Because L_{den} should be based on all the days of a year, the calculation of L_{day}, $L_{evining}$ and L_{night}, as performed using Eqs. (2)–(4), should use n to represent every day in the year.

$$L_{day} = 10\log\left\{\frac{1}{n}\sum_{i=1}^{n}10^{\frac{L_{day}^{(i)}}{10}}\right\} \quad (2)$$

$$L_{evening} = 10\log\left\{\frac{1}{n}\sum_{i=1}^{n}10^{\frac{L_{evening}^{(i)}}{10}}\right\} \quad (3)$$

Table 2
Meteorological characteristics of the city where the stations were located.

City	Annual minimum mean maximum (°C)	July minimum mean maximum (°C)	Precip. annual: total–max. July: (total–max.) (mm)	Weather averages
Madrid	9.37 14.34 19.29	17.96 24.52 31.06	37.10–13.35 (11.41–7.44)	1920–2011

Table 1
Main features of the environmental sound monitoring stations.

City population area density	Measurement station number	Geographical location	Traffic	Street category[a] [31,47]	Coordinates GPS latitude–longitude	
Madrid 3,255,944 inhab. 605,77 km^2 5,374,86 inhab./km^2	1	*Plaza del Carmen – Tres Cruces*	Medium	3	40.419208	−3.703172
	2	*c/Princesa – Plaza de España*	Intense	2	40.423992	−3.712333
	3	*Avda. Betanzos – c/Monforte de Lemos*	Intense	2	40.478228	−3.711542
	4	*Plaza Dr. Marañón – c/Miguel Ángel*	Intense	1	40.442500	−3.689444
	5	*Plaza Marqués de Salamanca*	Intense	2	40.430833	−3.679167
	6	*c/Alcalá – c/O'Donell*	Intense	1	40.421564	−3.682319
	7	*Paseo de las Delicias – c/Canarias*	Intense	1	40.425556	−3.681111
	8	*Avda. de Pablo Iglesias – P. de S. Francisco de Sales*	Medium	3	40.445542	−3.707128
	9	*Avda. Ramón y Cajal – c/Príncipe de Vergara*	Intense	2	40.451472	−3.677353
	10	*Dr. Gómez Ulla – Jardines Eva Duarte de Perón*	Intense	2	40.428753	−3.668833
	11	*c/Arroyo del Olivar – c/Río Grande*	Medium	3	40.388150	−3.651522
	12	*Plaza Fernández Ladreda – c/Marcelo Usera*	Intense	1	40.389444	−3.716111
	13	*Plaza de Castilla – c/Agustín de Foxá*	Intense	2	40.465556	−3.688611
	14	*c/Vizconde de los Asilos – c/Arturo Soria*	Light	4	40.440047	−3.639233
	15	*Glorieta Marqués de Vadillo – c/ Antonio Leiva*	Light	4	40.394778	−3.731833
	16	*Paseo de Extremadura – c/Francisco Brizuela*	Medium	3	40.399167	−3.714444
	17	*Avda. de Moratalaz – c/Camino de Vinateros*	Medium	3	40.407956	−3.645294
	18	*Plaza de Cristo Rey – c/Isaac Peral*	Intense	2	40.439722	−3.716389
	19	*Puerta de Toledo – Paseo Pontones*	Medium	3	40.407500	−3.709444
	20	End of *c/Alcalá* (*Canillejas*)	Intense	2	40.449167	−3.608333
	21	*Casa de Campo* (Near the cable bar)	Pedestrian	6	40.419356	−3.747344
	22	*c/Riaño*	Light	4	40.462500	−3.580556
	23	*c/Júpiter*	Light	4	40.476928	−3.580028
	24	*Avda. de la Aviación*	Medium	3	40.376111	−3.776639
	25	*Avda. de la Guardia*	Light	4	40.518056	−3.774611
	26	*Ribera del Sena s/n*	Intense	2	40.461667	−3.615250

[a] Streets categories go from 1 'Main city roads' to 6 'pedestrian roads'. The definitions for the different categories can be found in [25,40].

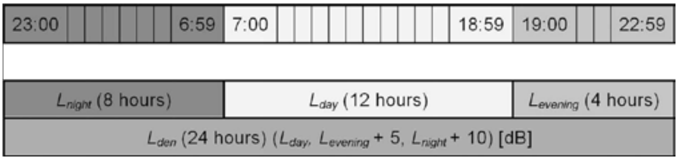

Fig. 1. Periods of the sound indexes.

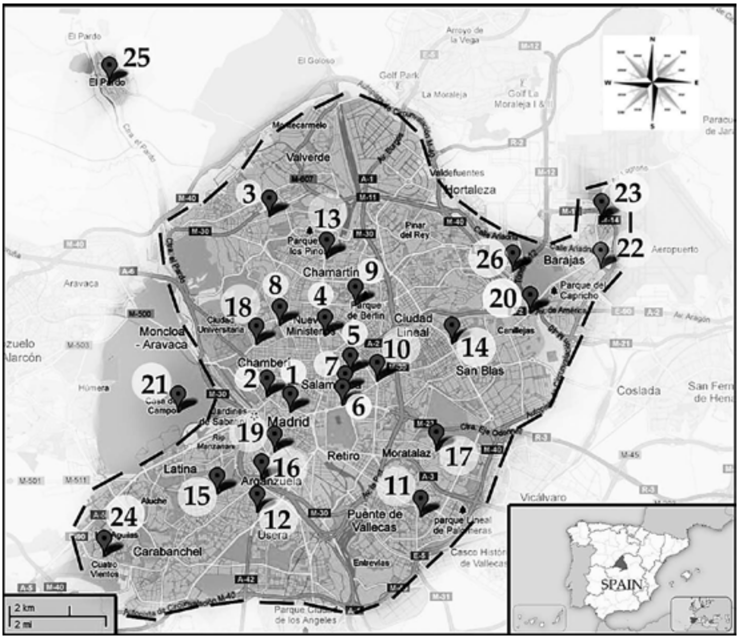

Fig. 2. Madrid zone map.

$$L_{night} = 10\log\left\{\frac{1}{n}\sum_{i=1}^{n}10^{\frac{L_{night}^{(i)}}{10}}\right\} \quad (4)$$

The index n runs through all the days of a year. The uncertainty associated with estimating L_{den} using measurements conducted on m randomly selected days during the year was evaluated by calculating L_{den} as m varied between 3 and 60 days.

The parameter $L_{den}^{(map)}$ characterises the noise situation at an arbitrary point [19]. Per the European Noise Directive, $L_{den}^{(map)}$ is calculated using measurements taken over an entire year, as shown in following equation:

$$L_{den}^{(map)} = 10\log\left\{\frac{1}{n}\sum_{i=1}^{n}10^{\frac{L_{den}^{(i)}}{10}}\right\} \quad (5)$$

The standard deviation in $L_{den}^{(map)}$ is given by:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(L_{den}^{(i)} - \overline{L_{DEN}}\right)^2}{n-1}} \quad (6)$$

The index $\overline{L_{DEN}}$ is the arithmetic mean of the values of $L_{den}^{(i)}$. Per the European Noise Directive, $L_{den}^{(i)}$ is given by:

$$L_{den}^{(i)} = 10\log\frac{1}{24}\left\{12 \times 10^{\frac{L_{day}^{(i)}}{10}} + 4 \times 10^{\frac{L_{evening}^{(i)}+5}{10}} + 8 \times 10^{\frac{L_{night}^{(i)}+10}{10}}\right\} \quad (7)$$

Gaps in the collected noise data may have been caused by a number of temporary technical challenges. Such gaps were identified by "missing" hours in the noise measurements. Gaps were handled in the following manner. If no more than 2 h were missing from the daytime data, the value of L_{day} for that day was considered valid. Similarly, if no more than 1 h was missing from evening or night-time data, the respective values of L_{even} and L_{night} were considered valid. To avoid introducing further uncertainties in the calculation of L_{den}, stations in which more than 5% of the measurement days for the analysed year were considered invalid were discarded. Therefore, all evaluation points considered valid for this study had the number of days n equal to or higher than 347 days.

Eq. (8) defines an index value $\langle L_{den}\rangle^{(k)}$ that represents the real value of the estimator $L_{den}^{(map)}$ for a package k containing m sampling days randomly selected from a year's worth of measurements:

$$\langle L_{den}\rangle^{(k)} = 10\log\left\{\frac{1}{m}\sum_{i=1}^{m}10^{\frac{L_{den}^{(i)}}{10}}\right\} \quad (8)$$

The value of this parameter $\langle L_{den}\rangle^{(k)}$ depends on the group of randomly selected days.

To estimate the expected value of this indicator $\langle L_{den}\rangle^{(k)}$ and its variability, one thousand sample packages ($k = 1,\ldots,1000$) were set, each containing m randomly selected days. Values of $\langle L_{den}\rangle^{(k)}$ were calculated; then, a mean (Eq. (9)) and standard deviation (Eq. (10)) were calculated:

$$\langle\overline{L_{den}}\rangle = \sum_{k=1}^{1000}\frac{\langle L_{den}\rangle^{(k)}}{1000} \qquad (9)$$

$$\sigma_{\langle\overline{L_{den}}\rangle} = \sqrt{\frac{\sum_{k=1}^{1000}\left(\langle L_{den}\rangle^{(k)} - \langle\overline{L_{den}}\rangle\right)^2}{1000-1}} \qquad (10)$$

For a given measurement station, the standard deviation defined in Eq. (10) represents the expected variability if the $L_{den}^{(map)}$ indicator is estimated (Eq. (5)) based on the $\langle L_{den}\rangle^{(k)}$ indicator (Eq. (8)). The standard deviation can only be estimated if there are a large number of m sample days.

In a real measurement situation, a single sampling of m days will be used to obtain the value of $\langle L_{den}\rangle^{(k)}$. In that case, the only known variability will be over those m days, so the standard deviation will be in the form shown in following equation:

$$\sigma_{\langle L_{den}\rangle}^{(k)} = \sqrt{\frac{\sum_{i=1}^{m}\left(L_{den}^{(i)} - \overline{L_{den}^{(k)}}\right)^2}{m-1}} \qquad (11)$$

where $\overline{L_{den}^{(k)}}$ represents the arithmetic mean of a specified sampling k of m L_{den} values used to calculate the $\langle L_{den}\rangle^{(k)}$ parameter (Eq. (8)).

The standard deviation value, (Eq. (11)), depends on sampling considered. Therefore, assuming one thousand random samples, the expected value of this standard deviation can be estimated using the mean value calculated with Eq. (12), and a measure of its variability can be estimated using Eq. (13). These two quantities can be evaluated because one complete year of measurement data is available for each station.

$$\langle\sigma_{\langle L_{den}\rangle}\rangle = \frac{1}{1000}\sum_{k=1}^{1000}\sigma_{\langle L_{den}\rangle}^{(k)} \qquad (12)$$

$$\sigma_{\langle\sigma_{\langle L_{den}\rangle}\rangle} = \sqrt{\frac{\sum_{k=1}^{1000}\left(\sigma_{\langle L_{den}\rangle}^{(k)} - \langle\sigma_{\langle L_{den}\rangle}\rangle\right)^2}{1000-1}} \qquad (13)$$

In previous work [19], a proposal was made for obtaining the uncertainty associated with the estimation of $L_{den}^{(map)}$ using m sampling random days. This method used Eq. (14), which is assumed to be verified:

$$\eta_k^{(i)} = \frac{|\widetilde{\langle E\rangle}_k - \langle E\rangle|}{\langle E\rangle} \ll 1 \qquad (14)$$

It can be mathematically proven that the annual real average $L_{den}^{(map)}$ will be within the range given by Eq. (15). In this equation, $\langle L_{den}\rangle^{(k)}$, represents the value of L_{den} obtained from a m sampling days, where m is much less than 365 days and the standard deviation, $\sigma_L^{(k)}$, is determined using Eq. (16). Eqs. (14)–(16) can be evaluated from measured values of L_{den} using m sampling days. A prior study [19] provides the calculation details.

$$\langle L_{den}\rangle^{(k)} - K\sigma_L^{(k)} \leqslant L_{den}^{(map)} \leqslant \langle L_{den}\rangle^{(k)} + K * \sigma_L^{(k)} \qquad (15)$$

$$\sigma_L^{(k)} \approx \frac{10}{\ln 10}\frac{10^{\frac{\langle L_{den}\rangle^{(k)}}{10}}}{\sqrt{m}}\sqrt{\frac{1}{4}\sigma_{d(k)}^2 + \frac{5}{18}\sigma_{e(k)}^2 + \frac{100}{9}\sigma_{n(k)}^2 + \frac{10}{6}C_{de(k)} + \frac{10}{3}C_{dn(k)} + \frac{10\sqrt{10}}{9}C_{en(k)}} \qquad (16)$$

The standard deviation given in Eq. (16) is not immediately comparable to the standard deviations given in Eq. (6), Eq. (10) or Eq. (12). The latter three standard deviations can be known only if measurements have been performed over an entire year. The standard deviation in Eq. (6) represents the variability of L_{den} during a complete year, the standard deviation in Eq. (10) represents the L_{den} variability when it is obtained using a sample of m days, and the standard deviation in Eq. (12) represents the average internal variability of groups of m days used to estimate L_{den}.

To study Eqs. (15) and (16) in a similar manner as described above, a mean and standard deviation were defined as shown in following equations:

$$\langle\sigma_L\rangle = \frac{1}{1000}\sum_{k=1}^{1000}\sigma_L^{(k)} \qquad (17)$$

$$\sigma_{\langle\sigma_L\rangle} = \sqrt{\frac{\sum_{k=1}^{1000}\left(\sigma_L^{(k)} - \langle\sigma_L\rangle\right)^2}{1000-1}} \qquad (18)$$

4. Analysis of the results

Tables 3–6 present results for m = 5, 10, 20 and 40 days, respectively. The format and added information in these tables are similar.

In each table, the first column (station) shows a reference number for a measurement station. The second column (days), gives the number of measurement days for the station during 2006. Because of the decision to not include stations that were missing more than 5% of the year's data, no listed station was missing more than 19 days of data.

The third column shows the value of the L_{den} index ($L_{den}^{(map)}$ (Eq. (5))) obtained using all available data. This value therefore is the same as in the mentioned four tables (Tables 3–6), and it will serve as reference for comparing the estimations that are made using a lower number of days. The fourth column shows the standard deviation, σ (Eq. (6)), of the $L_{den}^{(map)}$ index. This standard deviation gives an indication of the variability in L_{den} over the entire year's data set for each measurement station.

The values of $L_{den}^{(map)}$ vary from a minimum of 56.5 dBA (station 21) to 74.7 dBA (station 4). There is thus a wide range of variation among the stations. The smallest standard deviation is 0.8 dB (station 13), which indicates low variation in $L_{den}^{(map)}$ at that station throughout the year. The largest standard deviation is 3.7 dB (station 11), which indicates a large variability in $L_{den}^{(map)}$ throughout the year. These results suggest that there could be substantial differences in urban noise levels on the basis of both location and time throughout the year.

The fifth column in Tables 3–6 presents the average value $\langle\overline{L_{den}}\rangle$ (Eq. (9)) of the 1000 process repetitions over $\langle L_{den}\rangle^{(k)}$ index (Eq. (8)), taking each (k) as a random sampling of m days. The standard deviation in $\langle\overline{L_{den}}\rangle$, $\sigma_{\langle\overline{L_{den}}\rangle}$, is given in the sixth column (Eq. (10)). Column five thus gives the expected value of L_{den} at a station based on m days of a year, while column six indicates that parameter's variability.

The average value, $\langle\overline{L_{den}}\rangle$, of the estimator $\langle L_{den}\rangle^{(k)}$, is generally similar to the real value, $L_{den}^{(map)}$. Furthermore, the average value generally changes very little as the number of sampling days changes, although there are cases where the differences are substantial. These results show important differences in the internal structure of L_{den} over the different stations throughout the year. The standard deviation for the estimator is generally lower than the standard deviation for the "real" value, and the standard deviation of the estimator decreases slowly as the number of sampling days increases. The change in the standard deviation with the number of days is expected because it is based on an average.

Tables 3–6 show that stations 3, 7, 11, 15, 16 and 25 have values for $\sigma_{\langle\overline{L_{den}}\rangle}$ that are clearly higher than the values for the other

Table 3
Year 2006. Random packages for 5 complete days ($m = 5$).

Station	Days	$L_{den}^{(map)}$	σ	$\langle\overline{L_{den}}\rangle$	$\sigma_{\langle\overline{L_{den}}\rangle}$	$\langle\sigma_{\langle L_{den}\rangle}\rangle$	$\sigma_{\langle\sigma_{\langle L_{den}\rangle}\rangle}$	% K = 1	% K = 2	$\langle\sigma_L\rangle$	$\sigma_{\langle\sigma_L\rangle}$	% K = 1	% K = 2
1	365	67.4	1.3	67.2	0.9	1.1	0.7	82.6	96.3	0.5	0.4	51.4	77.7
2	365	70.3	1.2	70.3	0.9	1.1	0.7	82.9	97.2	0.5	0.4	50.5	79.3
3	365	68.1	2.5	67.0	2.4	1.8	1.8	28.6	49.1	0.8	0.9	14.5	27.1
4	365	74.7	1.2	74.7	0.6	1.1	0.5	87.7	98.5	0.5	0.2	56.3	87.6
5	360	68.7	1.2	68.7	0.5	1.1	0.5	93.1	99.5	0.5	0.2	66.7	93.3
6	365	73.7	1.3	73.7	0.6	1.3	0.5	88.7	98.0	0.6	0.2	59.8	87.1
7	362	72.4	1.4	71.9	1.7	0.9	1.2	29.9	72.8	0.4	0.6	12.2	22.4
8	357	70.6	2.0	70.4	1.1	1.8	0.9	92.0	98.8	0.8	0.4	54.4	89.1
9	364	73.7	1.1	73.6	0.5	1.0	0.4	91.0	99.1	0.5	0.1	65.9	91.4
10	365	70.0	1.9	69.7	1.4	1.5	1.1	62.1	84.7	0.7	0.6	33.5	58.5
11	365	74.4	3.7	64.4	5.2	2.1	3.0	7.4	12.3	0.9	1.1	3.0	7.0
12	358	72.4	0.9	72.3	0.5	0.8	0.4	88.1	98.2	0.4	0.2	61.1	87.9
13	365	74.1	0.8	74.1	0.4	0.8	0.4	90.7	98.4	0.4	0.2	57.4	88.1
14	360	66.4	1.2	66.3	0.8	1.1	0.6	88.5	97.9	0.5	0.3	56.4	85.2
15	363	65.7	3.1	61.2	3.6	2.0	2.2	16.5	25.1	0.9	1.0	10.0	18.1
16	365	67.6	1.5	66.6	1.7	1.1	1.1	26.7	63.1	0.5	0.5	12.6	23.4
17	365	67.5	1.4	67.2	1.2	1.0	0.9	67.2	94.3	0.5	0.5	36.5	69.6
18	361	69.9	1.2	69.8	0.5	1.1	0.4	91.5	99.4	0.5	0.2	67.6	91.3
19	361	69.9	1.6	69.6	1.2	1.2	0.9	74.4	93.2	0.6	0.4	39.6	71.3
20	363	68.4	1.2	68.3	0.6	1.1	0.5	86.0	96.2	0.5	0.3	57.1	82.9
21	355	56.5	1.9	56.3	1.0	1.6	0.8	81.1	94.9	0.7	0.4	48.7	76.6
22	347	68.3	1.1	68.3	0.6	1.0	0.5	87.5	96.9	0.5	0.3	58.4	85.2
23	365	66.4	1.5	66.2	1.3	1.2	0.9	76.0	95.9	0.6	0.5	49.1	75.2
24	365	69.5	2.3	69.4	1.2	2.1	0.9	89.6	97.9	0.8	0.4	54.1	85.2
25	361	63.5	1.7	62.7	1.9	1.2	1.3	30.5	75.7	0.5	0.6	9.4	24.0
26	364	64.6	1.8	64.5	0.9	1.6	0.8	91.3	99.5	0.7	0.4	58.2	89.2
26	362	70.4	1.6	69.9	1.3	1.3	0.9	70.4	85.9	0.6	0.4	44.0	68.2

Table 4
Year 2006. Random packages for 10 complete days ($m = 10$).

Station	Days	$L_{den}^{(map)}$	σ	$\langle\overline{L_{den}}\rangle$	$\sigma_{\langle\overline{L_{den}}\rangle}$	$\langle\sigma_{\langle L_{den}\rangle}\rangle$	$\sigma_{\langle\sigma_{\langle L_{den}\rangle}\rangle}$	% K = 1	% K = 2	$\langle\sigma_L\rangle$	$\sigma_{\langle\sigma_L\rangle}$	% K = 1	% K = 2
1	365	67.4	1.3	67.3	0.7	1.1	0.6	95.9	99.8	0.4	0.4	51.7	83.2
2	365	70.3	1.2	70.3	0.6	1.1	0.5	94.5	99.6	0.4	0.3	56.4	84.8
3	365	68.1	2.5	67.3	2.4	2.1	1.5	39.3	63.1	1.0	1.0	22.4	35.9
4	365	74.7	1.2	74.7	0.5	1.1	0.4	97.4	99.9	0.4	0.1	61.5	89.4
5	360	68.7	1.2	68.7	0.4	1.2	0.3	99.2	100.0	0.4	0.1	70.6	96.6
6	365	73.7	1.3	73.7	0.5	1.3	0.3	97.7	99.8	0.4	0.1	64.8	92.5
7	362	72.4	1.4	72.0	1.7	1.0	1.1	34.2	87.5	0.4	0.7	12.1	19.6
8	357	70.6	2.0	70.5	0.8	1.9	0.6	98.2	100.0	0.6	0.3	60.5	91.0
9	364	73.7	1.1	73.7	0.3	1.0	0.2	98.6	100.0	0.4	0.1	69.6	94.2
10	365	70.0	1.9	69.8	1.2	1.6	0.9	79.2	95.7	0.7	0.6	35.1	64.0
11	365	74.4	3.7	65.4	5.9	2.5	2.7	12.5	18.2	1.2	1.3	4.6	10.1
12	358	72.4	0.9	72.3	0.4	0.8	0.3	98.1	100.0	0.3	0.2	65.2	91.9
13	365	74.1	0.8	74.1	0.3	0.8	0.3	96.7	100.0	0.3	0.1	63.4	90.5
14	360	66.4	1.2	66.4	0.6	1.2	0.5	97.7	99.9	0.4	0.3	63.1	91.5
15	363	65.7	3.1	62.1	4.2	2.5	2.1	18.7	40.8	1.2	1.1	12.1	20.4
16	365	67.6	1.5	66.9	2.1	1.2	1.2	30.2	77.3	0.5	0.7	10.8	19.4
17	365	67.5	1.4	67.4	1.1	1.2	0.8	81.6	99.4	0.5	0.5	36.4	72.6
18	361	69.9	1.2	69.8	0.4	1.2	0.3	99.2	99.9	0.4	0.1	75.0	96.0
19	361	69.9	1.6	69.8	1.1	1.4	0.8	84.4	99.0	0.6	0.5	39.0	70.6
20	363	68.4	1.2	68.3	0.5	1.2	0.4	95.7	99.8	0.4	0.2	60.2	89.6
21	355	56.5	1.9	56.4	1.0	1.8	0.7	92.2	99.2	0.7	0.4	53.4	82.3
22	347	68.3	1.1	68.3	0.4	1.1	0.4	98.0	100.0	0.4	0.2	65.3	92.2
23	365	66.4	1.5	66.2	0.9	1.3	0.7	89.1	99.8	0.5	0.4	46.5	78.2
24	365	69.5	2.3	69.4	0.9	2.2	0.6	98.9	100.0	0.7	0.3	53.3	89.6
25	361	63.5	1.7	62.8	1.8	1.2	1.1	30.9	86.2	0.5	0.7	8.0	18.5
26	364	64.6	1.8	64.5	0.8	1.7	0.6	98.3	100.0	0.6	0.3	57.8	92.5
26	362	70.4	1.6	69.9	1.2	1.4	0.8	79.1	91.0	0.6	0.4	46.9	71.4

stations. The differences between $L_{den}^{(map)}$ and the $\langle\overline{L_{den}}\rangle$ average estimator are also higher for these stations than for the others. However, this does not happen with "true" standard deviations (column 4) where other stations (8, 10, 19, 21, 24 and 26) presents higher values than obtained for some measurements stations mentioned before. This result suggests that the $\sigma_{\langle\overline{L_{den}}\rangle}$ and the σ parameters provide different information about the temporal behaviour of urban noise at a given measurement station.

The seventh column presents the mean standard deviation, $\langle\sigma_{\langle L_{den}\rangle}\rangle$ (Eq. (12)), as a mean of the standard deviations obtained in each calculation of $\langle L_{den}\rangle^{(k)}$ (Eq. (8)). The eighth column shows the standard deviation of this parameter, $\sigma_{\langle\sigma_{\langle L_{den}\rangle}\rangle}$ (Eq. (13)).

The seventh column thus presents the expected mean standard deviation of $\langle L_{den}\rangle^{(k)}$ for each group of m sampling days, while the eighth column informs about its variability. In consequence, the value of $\langle\sigma_{\langle L_{den}\rangle}\rangle$ for each measurement station is always less that

Table 5
Year 2006. Random packages for 20 complete days ($m = 20$).

Station	Days	$L_{den}^{(map)}$	σ	$\langle\overline{L_{den}}\rangle$	$\sigma_{\langle\overline{L_{den}}\rangle}$	$\langle\sigma_{\langle L_{den}\rangle}\rangle$	$\sigma_{\langle\sigma_{\langle L_{den}\rangle}\rangle}$	% $K = 1$	% $K = 2$	$\langle\sigma_L\rangle$	$\sigma_{\langle\sigma_L\rangle}$	% $K = 1$	% $K = 2$
1	365	67.4	1.3	67.3	0.6	1.2	0.5	99.5	100.0	0.4	0.3	52.6	83.2
2	365	70.3	1.2	70.3	0.5	1.2	0.4	99.2	100.0	0.3	0.3	54.5	85.8
3	365	68.1	2.5	67.5	2.0	2.2	1.2	56.1	78.5	1.0	0.9	32.4	51.9
4	365	74.7	1.2	74.7	0.3	1.2	0.2	99.8	100.0	0.3	0.1	67.2	93.9
5	360	68.7	1.2	68.7	0.3	1.2	0.2	100.0	100.0	0.3	0.1	71.4	95.9
6	365	73.7	1.3	73.7	0.3	1.3	0.2	99.9	100.0	0.3	0.1	69.6	94.2
7	362	72.4	1.4	72.1	1.5	1.1	0.9	40.6	95.4	0.4	0.7	13.8	27.5
8	357	70.6	2.0	70.5	0.5	1.9	0.5	99.9	100.0	0.5	0.2	63.2	93.0
9	364	73.7	1.1	73.7	0.2	1.1	0.2	99.9	100.0	0.3	0.0	72.1	96.3
10	365	70.0	1.9	69.9	1.0	1.8	0.7	89.4	99.5	0.6	0.5	42.0	68.3
11	365	74.4	3.7	66.8	6.7	2.9	2.3	14.0	26.8	1.5	1.5	6.8	20.6
12	358	72.4	0.9	72.3	0.3	0.8	0.3	99.7	100.0	0.2	0.2	66.4	93.6
13	365	74.1	0.8	74.1	0.2	0.8	0.2	99.9	100.0	0.2	0.1	68.2	94.2
14	360	66.4	1.2	66.4	0.4	1.2	0.3	100.0	100.0	0.3	0.2	66.1	92.8
15	363	65.7	3.1	62.6	4.0	2.7	1.6	21.0	50.7	1.3	1.1	13.5	25.8
16	365	67.6	1.5	66.8	1.8	1.2	0.9	33.8	88.5	0.5	0.7	10.9	20.3
17	365	67.5	1.4	67.4	1.0	1.2	0.7	92.3	100.0	0.4	0.5	27.0	63.6
18	361	69.9	1.2	69.9	0.3	1.2	0.2	100.0	100.0	0.3	0.0	77.6	96.7
19	361	69.9	1.6	69.8	0.9	1.4	0.7	95.8	100.0	0.5	0.5	31.8	64.5
20	363	68.4	1.2	68.4	0.3	1.2	0.3	99.3	100.0	0.3	0.1	65.2	90.6
21	355	56.5	1.9	56.5	0.7	1.8	0.5	98.5	100.0	0.5	0.3	58.0	86.5
22	347	68.3	1.1	68.3	0.3	1.1	0.3	100.0	100.0	0.3	0.1	68.0	94.5
23	365	66.4	1.5	66.2	0.8	1.3	0.6	99.0	100.0	0.5	0.5	44.5	78.2
24	365	69.5	2.3	69.4	0.7	2.2	0.4	99.8	100.0	0.5	0.3	54.8	89.1
25	361	63.5	1.7	63.0	1.6	1.4	0.9	36.8	95.6	0.6	0.8	11.7	24.2
26	364	64.6	1.8	64.5	0.5	1.7	0.4	99.9	100.0	0.5	0.2	59.5	91.1
26	362	70.4	1.6	70.0	1.1	1.5	0.6	83.6	93.7	0.5	0.4	48.8	73.7

Table 6
Year 2006. Random packages for 40 complete days ($m = 40$).

Station	Days	$L_{den}^{(map)}$	σ	$\langle\overline{L_{den}}\rangle$	$\sigma_{\langle\overline{L_{den}}\rangle}$	$\langle\sigma_{\langle L_{den}\rangle}\rangle$	$\sigma_{\langle\sigma_{\langle L_{den}\rangle}\rangle}$	% $K = 1$	% $K = 2$	$\langle\sigma_L\rangle$	$\sigma_{\langle\sigma_L\rangle}$	% $K = 1$	% $K = 2$
1	365	67.4	1.3	67.4	0.4	1.2	0.4	99.9	100.0	0.3	0.3	52.8	82.9
2	365	70.3	1.2	70.3	0.4	1.2	0.3	100.0	100.0	0.3	0.2	56.0	88.2
3	365	68.1	2.5	67.7	1.5	2.3	0.9	74.5	92.7	1.0	0.7	41.6	64.9
4	365	74.7	1.2	74.7	0.2	1.2	0.2	100.0	100.0	0.2	0.0	69.3	93.6
5	360	68.7	1.2	68.7	0.2	1.2	0.2	100.0	100.0	0.2	0.0	75.5	98.0
6	365	73.7	1.3	73.7	0.2	1.3	0.1	100.0	100.0	0.2	0.0	69.5	95.6
7	362	72.4	1.4	72.2	1.3	1.2	0.7	48.3	99.4	0.5	0.8	16.8	32.1
8	357	70.6	2.0	70.5	0.4	2.0	0.3	100.0	100.0	0.4	0.1	65.4	91.6
9	364	73.7	1.1	73.7	0.2	1.1	0.1	100.0	100.0	0.2	0.0	75.7	98.0
10	365	70.0	1.9	69.9	0.7	1.8	0.5	97.4	100.0	0.5	0.3	46.9	73.4
11	365	74.4	3.7	68.6	6.8	3.2	1.9	20.3	38.7	2.0	1.5	16.2	30.7
12	358	72.4	0.9	72.3	0.2	0.9	0.2	100.0	100.0	0.2	0.1	67.3	93.9
13	365	74.1	0.8	74.1	0.2	0.8	0.1	100.0	100.0	0.2	0.0	66.5	95.3
14	360	66.4	1.2	66.4	0.3	1.2	0.3	100.0	100.0	0.3	0.2	62.0	93.8
15	363	65.7	3.1	63.3	3.9	2.8	1.2	25.0	62.3	1.5	1.2	4.0	31.8
16	365	67.6	1.5	67.1	1.8	1.4	0.8	35.7	97.2	0.6	0.9	2.4	25.6
17	365	67.5	1.4	67.5	0.8	1.3	0.6	99.2	100.0	0.4	0.5	22.8	54.9
18	361	69.9	1.2	69.9	0.2	1.2	0.1	100.0	100.0	0.2	0.0	79.4	98.3
19	361	69.9	1.6	69.9	0.7	1.5	0.5	99.4	100.0	0.5	0.4	33.4	62.6
20	363	68.4	1.2	68.4	0.2	1.2	0.2	100.0	100.0	0.2	0.1	67.3	93.9
21	355	56.5	1.9	56.5	0.5	1.8	0.4	100.0	100.0	0.4	0.2	55.6	85.9
22	347	68.3	1.1	68.3	0.2	1.1	0.2	100.0	100.0	0.2	0.1	67.5	95.8
23	365	66.4	1.5	66.3	0.7	1.4	0.5	99.9	100.0	0.4	0.4	41.0	74.8
24	365	69.5	2.3	69.5	0.5	2.2	0.3	100.0	100.0	0.4	0.2	59.9	91.6
25	361	63.5	1.7	63.1	1.5	1.5	0.8	42.5	99.8	0.6	0.8	18.6	29.5
26	364	64.6	1.8	64.6	0.4	1.7	0.3	100.0	100.0	0.4	0.1	63.3	93.6
26	362	70.4	1.6	70.0	0.9	1.5	0.5	86.2	95.8	0.5	0.4	49.9	75.8

the value of the standard deviation, σ (Eq. (6)), presented in the fourth column, but it can approach σ for a larger number of sampling days.

The value presented in the eighth column (Eq. (13)), which is the deviation of the average standard deviation, should decrease from Table 3 to 6 for each station because it is obtained using a different number of sampling days m. Table 7 makes this trend clear by showing the average results for each station for varying numbers of sampling days. Despite this decline, even for $m = 40$ days of sampling, this deviation remains very high for stations 11 and 15 (Table 6). This result indicates a great variability in the sound level measured at those stations on different days. It can see in these tables that, for the same stations with higher values of $\sigma_{\langle\overline{L_{den}}\rangle}$ (column 6), higher deviations are obtained (column 8). Therefore, $\sigma_{\langle\sigma_{\langle L_{den}\rangle}\rangle}$ may be an indicator of significant differences between the values shown in columns five and three.

Columns 9 and 10 show the percentage of times from 1000 samplings that the value of $L_{den}^{(map)}$ (thereby the real measurement in that point) is in the following interval:

$$\langle L_{den}\rangle^{(k)} - K\sigma^{(k)}_{\langle L_{den}\rangle} \leqslant L_{den}^{(map)} \leqslant \langle L_{den}\rangle^{(k)} + K\sigma^{(k)}_{\langle L_{den}\rangle} \quad (19)$$

with $K = 1$ and $K = 2$. Eq. (19) is equivalent to Eq. (15) shown above. Columns 9 and 10 thus show the probability of successfully estimating $L_{den}^{(map)}$ from $\langle L_{den}\rangle^{(k)}$ using Eq. (8), with a given set of m data using a criterion of one or two standard deviations, as calculated using Eq. (11).

For 5 days of sampling ($m = 5$), there are stations where the probability of success is very low. For $K = 1$, none of the stations had a probability of success equal to or greater than 95%; however, for $K = 2$, this rate of success occurs in 16 of the 26 stations (Table 3). It is interesting that this rate of success occurs at those stations in which the value in column 8 is around or below 0.9 dB, whereas the value in column 7 does not appear to be indicative of this fact.

For 10 sampling days (Table 4) and $K = 1$, 14 of 26 stations (54%) had $L_{den}^{(map)}$ within a confidence interval greater than 95%, whereas, for $K = 2$, 77% of the stations had $L_{den}^{(map)}$ a confidence interval greater than 95%. In the $K = 2$ case, 62% of the stations (16 of 26) met a 100% probability goal. These were the same stations that had a high probability of success with 5 sampling days. The average probability of success for all stations studied with $K = 1$ was 79%, and the probability of success with $K = 2$ was approximately 91%.

These probabilities rise with the increase of sampling days, m. For 20 days (Table 5) with $K = 1$, 70% of the stations had a 95% confidence interval, with an average success rate of 83%, and 14 stations had probability of success of 100%. For $K = 2$ and 20 sampling days, 85% of the stations (22 of the 26) had a probability of success 95% or higher; the average probability of success was 94% and there were 77% of stations (20) in which the probability of success was near 100%.

For 40 sampling days (Table 6) with $K = 1$, 77% of the stations have a probability of success above 95% with an average value for all the stations of 86%, and there are 57% of the stations with a success probability is 100%. The number of stations with a probability of success of 95% did not increase compared to 20 sampling days, where the fraction of stations was also 77%. For 40 days and $K = 2$, the average value increased to 96%, and 85% of stations had a probability of error less than 1%; 77% of the stations had a 100% probability.

These results suggest that, for any group of 40 sampling days, the probability that the calculated L_{den} index is an estimate of the true value of $L_{den}^{(map)}$, is 96% if $K = 2$. If only one standard deviation is allowed ($K = 1$), this probability is 86%, with 65% of stations in which the probability is 100%. For $K = 2$, 88% of the stations have a probability of success of 95%, and 81% of the stations have a probability of success of 100%. At only two stations (11 and 15) is the probability of success with 40 days of sampling less than 90%, which are also the stations with $\sigma_{\langle\sigma_{\langle L_{den}\rangle}\rangle}$ is greater than 1 dB.

Table 7 shows that the average probability of success with $K = 1$ over all 26 stations never reached a value of 90%; in contrast, with $K = 2$, this probability of success was reached after only 9 days of sampling, and a 95% probability of success was achieved with 30–35 days of sampling. Given the large number of stations, these results are useful in the implementation of noise maps using in situ measurements.

From analysing the real predictive capacity that a sampling of a m number random days can provide, the degree to which the method proposed by Makarewicz and Galuszka [19] allows good estimates of the $L_{den}^{(map)}$ indicator can be assessed.

Columns 11 and 12 show the expected average standard deviation, $\langle\sigma_L\rangle$, as calculated using Eq. (16), based on the values of the mean deviation for each group obtained with m days, as determined using Eq. (17), and its standard deviation $\sigma_{\langle\sigma_L\rangle}$, as defined in Eq. (18).

The values shown in columns 11 and 12 are less than the value indicated in column 7, which corresponds to the real average value of the deviation that would be obtained for the amount of data used in the calculation of L_{den} shown in the fifth column.

The last two columns show the percentage of times over 1000 assays in where the value of $L_{den}^{(map)}$ was in the range defined by Eq. (15). These data give the probability of success if it makes an estimation of $L_{den}^{(map)}$ from the L_{den} index obtained from a group of m days, using a confidence criterion of one or two ($K = 1$ or $K = 2$)

Table 7
Random packages 3–60 complete days.

n	Points	⟨Days⟩	$L_{den}^{(map)}$	σ	$\langle\overline{L_{den}}\rangle$	$\sigma_{\langle\overline{L_{den}}\rangle}$	$\langle\sigma_{\langle L_{den}\rangle}\rangle$	$\sigma_{\langle\sigma_{\langle L_{den}\rangle}\rangle}$	% $K = 1$	% $K = 2$	$\langle\sigma_L\rangle$	$\sigma_{\langle\sigma_L\rangle}$	% $K = 1$	% $K = 2$
3	26	362	70.4	1.6	69.8	1.4	1.2	1.1	60.4	78.0	0.6	0.5	40.2	62.6
4	26	362	70.4	1.6	69.8	1.3	1.3	0.9	67.0	83.0	0.6	0.4	42.8	66.1
5	26	362	70.4	1.6	69.9	1.3	1.3	0.9	70.4	85.9	0.6	0.4	44.0	68.2
6	26	362	70.4	1.6	69.9	1.2	1.3	0.8	73.5	87.4	0.6	0.4	44.9	69.6
7	26	362	70.4	1.6	69.9	1.2	1.4	0.8	75.3	88.6	0.6	0.4	46.0	70.6
8	26	362	70.4	1.6	69.9	1.2	1.4	0.8	77.2	89.5	0.6	0.4	46.3	71.3
9	26	362	70.4	1.6	69.9	1.2	1.4	0.8	78.5	90.2	0.6	0.4	47.0	71.4
10	26	362	70.4	1.6	69.9	1.2	1.4	0.8	79.1	91.0	0.6	0.4	46.9	71.4
11	26	362	70.4	1.6	69.9	1.1	1.4	0.7	79.9	91.1	0.5	0.4	46.8	71.5
12	26	362	70.4	1.6	69.9	1.1	1.4	0.7	80.3	91.4	0.5	0.4	47.3	71.7
13	26	362	70.4	1.6	69.9	1.1	1.4	0.7	81.1	92.0	0.5	0.4	47.0	71.8
14	26	362	70.4	1.6	69.9	1.1	1.4	0.7	81.4	92.3	0.5	0.4	47.7	72.5
15	26	362	70.4	1.6	69.9	1.1	1.4	0.7	81.8	92.3	0.5	0.4	47.6	72.8
16	26	362	70.4	1.6	69.9	1.1	1.4	0.6	82.1	92.7	0.5	0.4	48.3	73.5
17	26	362	70.4	1.6	70.0	1.1	1.5	0.6	82.8	93.2	0.5	0.4	49.0	74.0
18	26	362	70.4	1.6	70.0	1.1	1.5	0.6	82.9	93.1	0.5	0.4	48.2	73.5
19	26	362	70.4	1.6	70.0	1.1	1.5	0.6	83.1	93.6	0.5	0.4	48.6	73.8
20	26	362	70.4	1.6	70.0	1.1	1.5	0.6	83.6	93.7	0.5	0.4	48.8	73.7
25	26	362	70.4	1.6	70.0	1.0	1.5	0.5	84.5	94.5	0.5	0.4	49.4	74.7
30	26	362	70.4	1.6	70.0	1.0	1.5	0.5	85.4	94.9	0.5	0.4	49.0	75.3
35	26	362	70.4	1.6	70.0	1.0	1.5	0.5	85.9	95.4	0.5	0.4	49.5	75.5
40	26	362	70.4	1.6	70.0	0.9	1.5	0.5	86.2	95.8	0.5	0.4	49.9	75.8
45	26	362	70.4	1.6	70.1	0.9	1.5	0.5	86.7	96.1	0.5	0.3	50.9	76.0
50	26	362	70.4	1.6	70.1	0.9	1.5	0.4	87.4	96.4	0.5	0.3	50.8	75.8
55	26	362	70.4	1.6	70.1	0.9	1.6	0.4	88.4	96.6	0.5	0.3	51.6	76.6
60	26	362	70.4	1.6	70.1	0.9	1.6	0.4	88.7	96.7	0.5	0.3	52.4	77.2

standard deviations $\langle\sigma_L\rangle$ obtained by Eq. (16), as provided in reference [19].

The estimation of the uncertainty of the value of L_{den} obtained from a group of m data using the equation proposed in Ref. [19] present very different values compared to the experimental values presented in column 8 (Tables 3–7). Columns 14 and 15 show that, for $m = 10$ days, only for $K = 2$ at 2 stations is there a confidence interval of 95%. For 20 sampling days, there are three stations, and for 40 sampling days, there are only six stations with a confidence interval of 95%. Table 7 shows that even for 60 days

Table 8
1000 Method repetitions. $\eta_k < 0.1$.

	3	5	7	10	15	20	30	40	60	Mean
Station number										
1	38.1	8.0	33.1	15.7	54.6	21.3	39.8	77.8	87.8	41.8
2	51.1	58.8	57.5	30.4	74.1	73.2	76.0	88.6	74.7	64.9
3	1.3	25.9	11.7	39.8	48.4	23.9	45.7	25.7	21.7	27.1
4	25.8	52.3	42.5	64.1	44.6	79.7	93.3	91.9	98.9	65.9
5	31.0	38.7	16.0	58.6	47.8	64.4	80.2	75.7	79.7	54.7
6	33.1	28.0	4.3	58.6	43.8	62.6	3.9	76.6	81.5	43.6
7	60.8	67.9	49.9	81.8	84.5	87.0	74.0	83.6	79.8	74.4
8	31.4	35.6	15.9	53.4	63.2	52.5	10.5	68.1	18.3	38.8
9	43.5	52.0	49.6	73.2	77.5	83.2	91.4	96.1	98.8	73.9
10	6.3	23.0	27.5	29.7	33.0	34.9	10.3	42.5	51.8	28.8
11	13.0	5.1	41.2	3.2	13.0	32.3	12.8	4.3	14.7	15.5
12	55.9	63.7	0.3	81.5	85.0	91.8	94.4	97.6	100.0	74.5
13	25.4	62.8	66.8	82.7	77.7	8.7	88.5	97.2	6.4	57.4
14	42.1	43.4	55.0	69.1	80.0	79.3	76.4	86.1	99.0	70.0
15	31.3	10.4	13.8	32.7	31.2	20.3	22.7	10.1	9.7	20.2
16	45.1	47.0	63.8	66.0	74.6	80.0	63.3	78.4	76.1	66.0
17	19.3	45.1	41.2	53.4	64.6	69.6	70.2	32.0	12.7	45.3
18	23.3	36.1	34.2	52.7	21.8	44.1	81.0	86.8	81.3	51.3
19	29.4	37.6	23.3	3.4	68.9	72.1	6.1	9.2	5.4	28.4
20	30.2	13.9	35.4	26.2	27.4	56.5	65.3	69.2	72.2	44.0
21	16.2	11.4	42.8	38.4	38.6	56.9	62.2	70.2	41.1	42.0
22	37.7	10.1	48.4	11.2	64.2	50.1	83.0	59.4	42.9	45.2
23	15.8	27.0	35.9	10.7	43.2	55.0	56.0	48.8	83.4	41.8
24	17.7	28.0	22.9	7.4	48.6	39.7	56.3	29.6	64.2	34.9
25	37.0	28.3	16.8	2.6	75.0	78.3	78.0	79.0	80.6	52.8
26	14.9	41.3	45.6	42.3	46.7	47.7	38.1	63.1	37.9	42.0
Mean	29.9	34.7	34.4	41.9	55.1	56.4	56.9	63.4	58.5	
St. dev.	14.8	18.4	18.1	26.5	20.5	23.1	29.7	28.9	33.0	

Table 9
η_k Values – 1000 method repetitions. $\eta_k < 0.2$.

	3	5	7	10	15	20	30	40	60	Mean
Station number										
1	70.3	21.0	69.5	43.9	81.7	57.5	90.1	97.2	99.9	70.1
2	81.7	87.8	89.1	83.1	91.8	89.8	95.5	99.2	98.3	90.7
3	4.0	49.1	24.4	59.3	71.7	47.2	78.7	49.1	49.7	48.1
4	56.9	84.8	81.9	92.6	91.7	99.6	99.9	100.0	100.0	89.7
5	60.6	74.1	37.8	90.2	80.9	95.2	97.5	99.7	98.2	81.6
6	60.5	53.7	10.8	86.8	76.2	95.3	28.9	99.5	98.0	67.7
7	89.2	90.4	84.4	94.0	90.1	89.7	85.3	92.3	94.7	90.0
8	59.0	60.1	32.4	86.5	90.4	86.0	60.0	94.6	80.7	72.2
9	73.8	87.5	84.5	98.2	99.0	99.8	99.9	100.0	100.0	93.6
10	12.4	39.3	52.1	55.3	60.9	62.6	23.3	66.0	80.1	50.2
11	35.4	9.6	57.1	7.7	32.2	45.7	27.3	7.5	30.0	28.1
12	87.2	93.4	5.3	98.4	99.0	99.9	100.0	100.0	100.0	87.0
13	63.8	93.2	96.8	96.8	98.5	82.1	100.0	99.9	98.4	92.2
14	70.3	70.0	90.1	95.6	98.9	99.0	100.0	99.7	100.0	91.5
15	59.6	0.0	32.8	56.2	49.9	48.3	40.9	18.6	17.2	35.9
16	78.3	27.3	90.4	91.5	92.1	90.2	92.3	88.7	93.3	82.7
17	38.1	77.3	69.2	86.1	84.8	87.8	85.2	77.1	14.7	68.9
18	43.8	71.5	59.4	87.0	66.1	81.5	99.5	99.8	100.0	78.7
19	54.2	63.6	49.6	3.4	89.2	88.2	9.4	10.5	17.1	42.8
20	60.3	64.7	60.2	60.6	66.1	91.2	93.9	97.6	94.6	76.6
21	37.4	33.7	72.5	61.0	74.9	83.3	94.5	94.9	82.4	70.5
22	69.2	26.2	80.1	48.2	93.2	85.7	96.9	99.5	89.6	76.5
23	33.3	0.0	71.1	32.7	84.3	92.7	95.7	82.1	98.0	65.5
24	36.8	37.4	49.9	13.6	77.2	78.5	83.4	72.4	90.3	59.9
25	71.7	53.1	59.7	11.6	89.8	88.7	88.0	87.6	83.5	70.4
26	30.2	52.8	74.8	72.7	76.7	82.0	81.2	84.3	69.8	69.4
Mean	55.3	70.4	61.0	65.9	81.1	82.6	78.7	81.5	79.9	
St. dev.	21.8	72.0	25.1	30.9	16.1	16.5	28.1	28.5	28.7	

of sampling, the probability that the real value of $L_{den}^{(map)}$ is in the range proposed in [19] is much lower than 90%. This finding suggests a need to conduct additional studies.

These results may be based on the inequality in Eq. (14), which led to the development of Eq. (16). Tables 8 and 9 show the real behaviour of the η_k index, as calculated using Eq. (14).

In Table 8, given that the condition $\eta_k \ll 1$ [19] holds for $\eta_k < 0.1$, for 3 sampling days ($m = 3$), this condition is fulfilled in a range from 1% (station 3) to 60% (station 13), with a mean value of overall compliance in the stations under study of 30%. Even for 60 sampling days, the average of this condition is 58%. Considering that the condition $\eta_k \ll 1$ [19] holds for $\eta_k < 0.2$, Table 9 shows that for 3 sampling days, this condition is fulfilled in a range from 4% (station 3) to 89% (station 7), with a mean value of overall compliance in the stations under study of 55%. Even for 60 sampling days, the average of this condition is 80%. Thus, it is necessary to considerer another condition for the mathematical development of confidence intervals to evaluate the annual real average $L_{den}^{(map)}$.

5. Conclusions

It conducted a systematic study of the capacity to estimate the indicator $L_{den}^{(map)}$ from continuous measurements carried out during an arbitrary number of days randomly selected in the range from 3 to 60 days. It has analysed this capacity of estimation based on the use of two methods for obtaining the standard deviation, the value obtained from measurement data and a relation proposed in the literature.

It was used continuous measurements performed at 26 different stations that were subject to different sound level conditions and variability throughout the days studied, using at least 95% of the days of the year. On average, if it requires to obtain an estimate of $L_{den}^{(map)}$ with a probability of success within a 90% confidence interval, it needs to take measurements for 9 days spread randomly throughout the year and it should use two standard deviations of the mean ($K = 2$) as an interval. If it requires a probability of 95%, the number of sampling days should be increased to 30–35.

The mathematical relationship proposed in the literature for the estimation of $L_{den}^{(map)}$, contrasted with real data from our 26 measurement stations, suggests that it possible to achieve a probability of success of 90%. For 25–30 days and two standard deviations, the probability of success reaches 75%.

It would be necessary to carry out new mathematical developments that allow a better estimate of the range of variability to make a more precise estimation of $L_{den}^{(map)}$ from measurements made over a relatively small number of days.

Acknowledgements

The authors wish to thank the Government of Extremadura, the Regional Ministry of Economy, Trade and Innovation, the Regional Ministry of Business, Innovation and Employment (GR10175), the European Social Fund and the European Regional Development Fund (ERDF) for funding the project. This appreciation is extended to the municipality of Madrid (Department of Environment and Sustainability) for so selflessly offering us the noise data corresponding to all of their measurement stations.

References

[1] OECD. Noise abatement: present situation and future outlook. Paris: Organization for Economic Cooperation and Development; 1985.
[2] WHO. El Ruido. Criterios de salud ambiental, vol. 454. Ginebra: World Health Organization, OPS/WHO; 1983.
[3] Guidelines for community noise; 1999.
[4] WHO. Night noise guidelines for Europe. Copenhagen (Denmark): World Health Organization; 2009.
[5] WHO. Burden of disease from environmental noise. Quantification of healthy life years lost in Europe. Copenhagen (Denmark): World Health Organization; 2011.
[6] Zeng X, Zhan Y. Development of a noise sources classification system based on new method for feature selection. Appl Acoust 2005;66:1196–205.
[7] Yang D, Wang Z, Li B, Luo Y, Lian X. Quantitative measurement of pass-by noise radiated by vehicles running at high speeds. J Sound Vib 2011;330:1352–64.
[8] Pinto FA de Noronha Castro, Mardones MD Moreno. Noise mapping of densely populated neighborhoods – example of Copacabana, Rio de Janeiro – Brazil. Environ Monit Assess 2009;155:309–18.
[9] Doygun H, Kuşat Gurun D. Analysing and mapping spatial and temporal dynamics of urban traffic noise pollution: a case study in Kahramanmaraş, Turkey. Environ Monit Assess 2008;142:65–72.
[10] Barrigón Morillas JM, Escobar VG, Carmona JT, Sierra JAM, Vílchez-Gómez R, Río FJCD. Analysis of the prediction capacity of a categorization method for urban noise assessment. Appl Acoust 2011;72:760–71.
[11] Romeu J, Genescà M, Pmies T, Jiménez S. Street categorization for the estimation of day levels using short-term measurements. Appl Acoust 2011;72:569–77.
[12] Gómez Escobar V, Barrigón Morillas JM, Rey Gozalo G, Vaquero JM, Méndez Sierra JA, Vílchez-Gómez R, et al. Acoustical environment of the medieval centre of Cáceres (Spain). Appl Acoust 2012;73:673–85.
[13] Cho DS, Kim JH, Manvell D. Noise mapping using measured noise and GPS data. Appl Acoust 2007;68:1054–61.
[14] Arana M. Are urban noise pollution levels decreasing? (L). J Acoust Soc Am 2010;127:2107–9.
[15] Ko JH, Chang SI, Lee BC. Noise impact assessment by utilizing noise map and GIS: a case study in the city of Chungju, Republic of Korea. Appl Acoust 2011;72:544–50.
[16] Zannin PHT, Sant'Ana DQ. Noise mapping at different stages of a freeway redevelopment project – a case study in Brazil. Appl Acoust 2011;72:479–86.
[17] Diniz FB, Zannin PHT. Noise impact caused by electrical energy substations in the city of Curitiba, Brazil. Sci Total Environ 2004;328:23–31.
[18] Ausejo M, Recuero M, Asensio C, Pavón I, López JM. Study of precision, deviations and uncertainty in the design of the strategic noise map of the macrocenter of the city of Buenos Aires, Argentina. Environ Model Assess 2010;15:125–35.
[19] Makarewicz R, Galuszka M. Empirical revision of noise mapping. Appl Acoust 2011;72:578–81.
[20] Randrianoelina A, Salomons E. Traffic noise in shielded urban areas: comparison of experimental data with model results. In: Forum acoustics, Paris, 2008, 5795–9.
[21] Licitra G, Memoli G. Limits and advantages of good practice guide to noise mapping. In: Forum acoustics, Paris, 2008, 771–6.
[22] Brown AL, Van Kamp I. Response to a change in transport noise exposure: competing explanations of change effects. J Acoust Soc Am 2009;125:905–14.
[23] Hong J, Kim J, Lim C, Kim K, Lee S. The effects of long-term exposure to railway and road traffic noise on subjective sleep disturbance. J Acoust Soc Am 2010;128:2829–35.
[24] Morillas JMB, Escobar VG, Sierra JAM, Vílchez G, Vílchez-Gómez R, Vaquero JM, et al. Effects of leisure activity related noise in residential zones. Build Acoust 2005;12:265–76.
[25] Öhrström E. Longitudinal surveys on effects of changes in road traffic noise – annoyance, activity disturbances, and psycho-social well-being. J Acoust Soc Am 2004;115:719–29.
[26] European Parliament C. Directive 2002/49/EC of the European parliament and of the council of 25 June 2002 relating to the assessment and management of environmental noise, vol. L 189 ed., 2002. p. 12–25.
[27] Bendtsen H. The Nordic prediction method for road traffic noise. Sci Total Environ 1999;235:331–8.
[28] Li B, Tao S, Dawson RW. Evaluation and analysis of traffic noise from the main urban roads in Beijing. Appl Acoust 2002;63:1137–42.
[29] Zannin PHT, Diniz FB, Barbosa WA. Environmental noise pollution in the city of Curitiba, Brazil. Appl Acoust 2002;63:351–8.
[30] To WM, Ip RCW, Lam GCK, Yau CTH. A multiple regression model for urban traffic noise in Hong Kong. J Acoust Soc Am 2002;112:551–6.
[31] Barrigón Morillas JM, Gómez Escobar V, Méndez Sierra JA, Vílchez-Gómez R, Vaquero JM, Trujillo Carmona J. A categorization method applied to the study of urban road traffic noise. J Acoust Soc Am 2005;117:2844–52.
[32] Onuu MU. Road traffic noise in Nigeria: measurements, analysis and evaluation of nuisance. J Sound Vib 2000;233:391–405.
[33] Skinner CJ, Grimwood CJ. The UK noise climate 1990–2001: population exposure and attitudes to environmental noise. Appl Acoust 2005;66: 231–43.
[34] Kihlman T, Abukhader S. Long-term noise abatement planning-case studies in Göteborg, Sweden. In: Presented at the inter-noise, The Hague, Holland, 2001.
[35] Romeu J, Genescà M, Pàmies T, Jiménez S. Street categorization for the estimation of day levels using short-term measurements. Appl Acoust 2011;72:569–77.
[36] Alberola J, Flindell IH, Bullmore AJ. Variability in road traffic noise levels. Appl Acoust 2005;66:1180–95.
[37] Romeu J, Jiménez S, Genescà M, Pàmies T, Capdevila R. Spatial sampling for night levels estimation in urban environments. J Acoust Soc Am 2006;120:791–800.
[38] Björk EA. Community noise in different seasons in Kuopio, Finland. Appl Acoust 1994;42:137–50.

[39] Gaja E, Gimenez A, Sancho S, Reig A. Sampling techniques for the estimation of the annual equivalent noise level under urban traffic conditions. Appl Acoust 2003;64:43–53.
[40] Can A, Van Renterghem T, Rademaker M, Dauwe S, Thomas P, De Baets B, et al. Sampling approaches to predict urban street noise levels using fixed and temporary microphones. J Environ Monit 2011;13:2710–9.
[41] Larsson C. A method for determining the long-term aircraft noise level from short-time measurements. In: Presented at the international congress on acoustics, Trondheim, Norway, 1995.
[42] Guedes ICM, Bertoli SR, Zannin PHT. Influence of urban shapes on environmental noise: a case study in Aracaju – Brazil. Sci Total Environ 2011;412–413:66–76.
[43] Barrigón Morillas JM, Gómez-Escobar V, Vaquero JM, Méndez-Sierra JA, Vílchez-Gómez R. Measurement of noise pollution in Badajoz city, Spain. Acta Acust Unit Acust 2005;91:797–801.
[44] Monzón A, Guerrero MJ. Valuation of social and health effects of transport-related air pollution in Madrid (Spain). Sci Total Environ 2004;334–335:427–34.
[45] Brambilla G, Lo Castro F, Cerniglia A, Verardi P. Accuracy of temporal samplings of environmental noise to estimate the long-term L_{den} value. In: Presented at the inter-noise 2007, Istanbul, Turkey, 2007.
[46] AEMET (2012, March 6). Agencia Estatal de Meteorología, 2012.
[47] Barrigón Morillas JM, Gómez Escobar V, Rey Gozalo G, Vílchez-Gómez R. Possible relation of noise levels in streets to the population of the municipalities in which they are located. J Acoust Soc Am 2010;128:EL86–92.

Objetivo 4: The temporal structure of pollution levels in developed cities

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Trabajo publicado en

Science of the Total Environment (2015), Vol. 517, Págs. 31-37

Science of the Total Environment 517 (2015) 31–37

Contents lists available at ScienceDirect

Science of the Total Environment

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

Short Communication

The temporal structure of pollution levels in developed cities

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HIGHLIGHTS

- New analytical methodology in the temporal structure of urban noise was proposed
- Average errors less than one decibel in all acoustics indicators were found
- General purpose could be found for the study of pollution related with road traffic

ARTICLE INFO

Article history:
Received 15 October 2014
Received in revised form 23 January 2015
Accepted 16 February 2015
Available online 21 February 2015

Editor: P. Kassomenos

Keywords:
Environmental pollution
Road traffic noise
Long-term measurements
Temporal variability

ABSTRACT

Currently, the need for mobility can cause significant pollution levels in cities, with important effects on health and quality of life. Any approach to the study of urban pollution and its effects requires an analysis of spatial distribution and temporal variability.
It is a crucial dilemma to obtain proven methodologies that allow an increase in the quality of the prediction and the saving of resources in the spatial and temporal sampling.
This work proposes a new analytical methodology in the study of temporal structure. As a result, a model for estimating annual levels of urban traffic noise was proposed. The average errors are less than one decibel in all acoustics indicators.
A new working methodology of urban noise has begun. Additionally, a general application can be found for the study of the impacts of pollution associated with traffic, with implications for urban design and possibly in economic and sociological aspects.

1. Introduction and background

The effects of noise pollution on human health have been considered by the WHO (World Health Organization) to be the third most dangerous type of pollution (Berglund et al., 1999) causing health effects, including psycho-physiological problems (Birk et al., 2011; Chang et al., 2011; Fyhri and Aasvang, 2010; Marquis-Favre et al., 2005; Mohammadi, 2009; Öhrström, 2004).

The European Noise Directive 2002/49/EC introduces two key indices for environmental noise assessment, L_{den} (day, evening and night) to assess noise annoyance and L_n (night) to assess sleep disturbance. According to this directive, it is recommended that noise assessments for the estimation of the community response to disturbances caused by noise pollution are made for a long-term time interval, usually one year. State members must use these indices to prepare and revise strategic noise maps.

Urban noise is composed of a set of sources with different sound characteristics, both temporal and spatial. Any approach to the study of urban noise and its effects requires an analysis of both spatial distribution and temporal variability (Alberola et al., 2005; Banerjee et al., 2009; Gaja et al., 2003; Mehdi et al., 2011; Rey Gozalo et al., 2014; Torija et al., 2010). Multiple factors have been described that cause this variability: the type of traffic and urban forms (Guedes et al., 2011; Maruyama et al., 2013; Romeu et al., 2011), the metropolitan area (Doygun and Kuşat Gurun, 2008; Oyedepo and Saadu, 2010), the acoustic zone (Ozer et al., 2008), weather conditions (Kephalopoulos et al., 2007), anomalous events (Torija and Ruiz, 2012), etc.

For many years, studies using measures of the impact of urban noise on populations have been based on the grid method for spatial sampling (Brown and Lam, 1987; ISO, 1996-1, 2003; ISO, 1996-2, 1987, 2007). During the past decade, the categorization method was proposed. This raises a new strategy for spatial sampling planning (Barrigón Morillas et al., 2002), based on the concept of street functionality. The results achieved have demonstrated the existence of a significant stratification into five categories (Barrigón Morillas et al., 2005; Rey Gozalo et al., 2013, 2014) of a noise level dependent on categories relative to the size of the city (Barrigón Morillas et al., 2010) and with overall predictive capabilities of more than 90% (Rey Gozalo et al., 2013). Therefore, it may be an alternative methodology for urban noise assessment and

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http://dx.doi.org/10.1016/j.scitotenv.2015.02.057
0048-9697/

management. In fact, this idea has been used, and different authors have followed it with some variations (Ausejo et al., 2011; Romeu et al., 2011, 2006; Suárez and Barros, 2014).

The second aspect of interest in the sampling planning is the temporal variability. To assess environmental noise pollution, usually caused by road traffic (Butler, 2004), it is indicated that the sampling of noise should be performed over a one year interval (ANSI s12.9-1993, 2008; European Parliament, 2002; ISO, 1996-1, 2003; ISO, 1996-2, 2007).

In contrast to spatial sampling, the aspects related to temporal sampling have been studied in the scientific literature regularly for many years, requiring the efforts of many researchers. For the large majority, the studies have been oriented by a statistical approach (Attenborough et al., 1976; Barrigón Morillas and Prieto Gajardo, 2014; Botteldooren et al., 2006; Can et al., 2011; Mehdi et al., 2011; Omiya et al., 1997; Schomer and DeVor, 1981; To et al., 2002; Zuo et al., 2014).

Planning for adequate sampling is essential to any study approach of the impact of urban noise on population. Considering the prediction models, it is equally essential to know the spatial variability of traffic depending on the periods evaluated in the streets of the city (Butler, 2004; Romeu et al., 2006). This involves a development of a spatial and temporal sampling planning of traffic flows, possibly as complex as sampling the noise levels. Indeed, some authors have demonstrated that the use of road stratification for the estimation of the traffic flows significantly improves the quality of the prediction results (Ausejo et al., 2011; Suárez and Barros, 2014).

To advance the knowledge of the spatial-temporal structure of urban noise, this work proposes a new methodology based on the Discrete Fourier Analysis. First, by an analytical approach, using the Fast Fourier Transform (FFT) (Walker, 1996), a wide database of noise measurements has been analyzed for the purpose of searching the fundamental and main harmonic components. Subsequently, the predictive ability of these components when long-term parameters of a series of measurements are estimated has been studied. Finally, a model will be proposed that measures the behavior of the daily noise levels throughout the year for the streets whose primary source is traffic noise. In addition, whether the model has dependencies according to the stratification given by the categorization method will be analyzed. An advance of the results is presented. They are promising and open a new method for further research regarding the selection of a spatial and temporal sampling strategy in the study of the noise pollution associated with traffic, with implications for urban design (Vlachokostas et al., 2012, 2014).

2. Material and methods

Twenty-one noise analyzers (Brüel & Kjær models 4441 and 4435) in Madrid (3,255,944 inhabit. and 605.77 km^2) and six (SDR-500, PD de Audio) in Malaga (568,305 inhabit. and 395.13 km^2) with traffic as the fundamental noise source were selected. A wide variety of locations have been chosen to ensure different urban and architectural environments (residential, commercial, cultural or industrial), traffic flows, building's height range, number of lanes, with of road and other factors. The definitions for the different categories are:

Type 1 comprises those preferential streets whose function is to form a connection with other Spanish towns (national roads for the five towns studied) and to interconnect those preferential streets (in general, the indication of this latter type of street is its system of road signs).

Type 2 comprises those streets that provide access to the major distribution nodes of the town. For the purpose of this study, a distribution node is considered to exist when at least four major streets meet. This definition does not include any possible nodes of preferential streets as defined in Type 1 above. This category also includes the streets normally used as an alternative to Type 1 in case of traffic saturation.

Type 3 comprises the streets that lead to regional roads, streets that provide access from those of Types 1 and 2 to centers of interest in the town (hospitals, shopping malls, etc.), and streets that clearly allow communication between streets of Types 1 and 2.

Type 4 comprises all other streets that clearly allow communication between the three previously defined types of street, and the principal streets of the different districts of the town that were not included in the previously defined categories.

Type 5 comprises the rest of the streets of the town except pedestrian-only streets.

The measured parameter was the continuous equivalent A-weighted noise level integrated every hour ($L_{Aeq,1h}$) for all days of the year and the L_d, L_e, L_n, L_{dn} and L_{den} rating levels were calculated and averaged from the hourly $L_{Aeq,1h}$ results (all measurement starting from 23:00 h). The measurements were performed for a full year from 2006 to 2011. Fig. 1 and Table 1 shows the zone map and main features of the measurement stations.

The formulas for calculating the rating levels listed above and specified in the regulations (ISO, 1996-1, 2003) are:

$$L_{den}^{i,k} = 10\log\frac{1}{24}\left\{12*10^{\frac{L_d^{i,k}}{10}} + 4*10^{\frac{L_e^{i,k}+5}{10}} + 8*10^{\frac{L_n^{i,k}+10}{10}}\right\}\ [\mathrm{dB}] \quad (1)$$

$$L_{dn}^{i,k} = 10\log\frac{1}{24}\left\{16*10^{\frac{L_{d16h}^{i,k}}{10}} + 8*10^{\frac{L_n^{i,k}+10}{10}}\right\}\ [\mathrm{dB}] \quad (2)$$

$$L_d^{i,k} = 10\log\left\{\frac{1}{N}\sum_{j=1}^{N}10^{\frac{L_d^{i,k,j}}{10}}\right\}\ [\mathrm{dB}] \quad (3)$$

$$L_e^{i,k} = 10\log\left\{\frac{1}{N}\sum_{j=1}^{N}10^{\frac{L_e^{i,k,j}}{10}}\right\}\ [\mathrm{dB}] \quad (4)$$

$$L_n^{i,k} = 10\log\left\{\frac{1}{N}\sum_{j=1}^{N}10^{\frac{L_n^{i,k,j}}{10}}\right\}\ [\mathrm{dB}] \quad (5)$$

where,

- i is the station identification number (see Table 1)
- k is the category number according to the road type (see Table 1)
- N number of measured days (365 for a complete year)

in which,

- L_d is the A-weighted long-term average sound level as defined in ISO, 1996-2: 1987, determined over all the day periods (7:00-19:00) of a year,
- L_e is the A-weighted long-term average sound level as defined in ISO, 1996-2: 1987, determined over all the evening periods (19:00-23:00) of a year,
- L_n is the A-weighted long-term average sound level as defined in ISO, 1996-2: 1987, determined over all the night periods (23:00-7:00) of a year,
- L_{dn} is the A-weighted long-term average sound level as defined in ISO, 1996-1: 2003, determined during a 24-hour period with a penalty of 10 dB added for the night hours,

Fig. 1. Measurement stations (*i* index) zone map (Madrid left side, Malaga right side).

L_{den} is the A-weighted long-term average sound level as defined in ISO, 1996-1: 2003, determined during a 24-hour period with a penalty of 5 dB added for the evening hours, and a penalty of 10 dB added for the nighttime hours.

3. Methodology based on Fourier Analysis (FFT)

According to Fourier analysis, any continuous and periodic signal x(t) can be represented or approximated by sums of a series of suitable chosen trigonometric functions with the corresponding amplitudes (Walker, 1996). Thereby, any sound signal along a time *T* (e.g., annual SPL) will be able to decompose into a sum of sinusoidal functions in the following way:

$$x(t) = A_0^{i,k} + A_1^{i,k} \sin(2\pi f_1 t + \varphi_1) + \ldots + A_n^{i,k} \sin(2\pi f_n t + \varphi_n) \quad (6)$$

where,

$x(t)$ is the noise annual signal integrated hour by hour
A_0 is the continuous component and represents the linear average of the annual values
$A_{1-n}^{i,k}$ are the amplitudes of the Fourier series
f_1 is the fundamental frequency of the function and $f_{2\text{-}n}$ are the harmonic components
$\varphi_{1\text{-}n}$ represents the phase of the function.

Table 1
Main features of the environmental sound monitoring stations.

City/population/area	*i*	Year	Name	*k*[a]	Latitude	Longitude	# lanes	# floors
Madrid 3,255,944 inhab. 605.77 km^2	1	2006	Plz. De España	1	40.424139	−3.712215	4	7
	2	2006	Plz. Doctor Marañón	1	40.437551	−3.690902	7	7
	3	2009	Plz. Marqués de Salamanca	2	40.429793	−3.680176	4	6
	4	2009	Escuelas Aguirre	1	40.421654	−3.682373	6	0
	5	2006	Plz. Luca de Tena	2	40.402053	−3.693405	4	7
	6	2010	Cuatro Caminos	3	40.445596	−3.707248	4	7
	7	2010	Ramón y Cajal	2	40.451633	−3.677526	8	9
	8	2009	Manuel Becerra	2	40.428745	−3.668519	2	6
	9	2006	Fernández Ladreda	1	40.385159	−3.716601	5	11
	10	2006	Plz. De Castilla	1	40.465717	−3.688875	5	0
	11	2010	Arturo Soria	2	40.439984	−3.639267	5	4
	12	2009	Alto de Extremadura	4	40.407794	−3.741910	4	4
	13	2010	Av. De Moratalaz	4	40.407945	−3.645329	6	7
	14	2006	Isaac Peral	3	40.439421	−3.717853	5	6
	15	2006	Puerta de Toledo	4	40.406411	−3.712897	3	4
	16	2006	Final c/ Alcalá	1	40.448751	−3.609672	4	4
	17	07–08	Santa Eugenia	1	40.379170	−3.602658	6	0
	18	2010	El Pardo	4	40.518130	−3.774716	2	0
	19	2006	Ribera del sena	3	40.460615	−3.616313	4	0
	20	10–11	Castellana	1	40.439825	−3.690213	2	0
	21	2010	Ensanche de Vallecas	5	40.373087	−3.611914	4	0
Malaga 568,305 inhab. 395.13 km^2	22	07–08	Fátima con Martiricos	3	36.726910	−4.427008	5	7
	23	08–09	Agustín Heredia	2	36.714330	−4.423072	4	7
	24	09–10	Alcazabilla	3	36.722520	−4.416997	4	5
	25	08–09	Paseo de los curas	2	36.718450	−4.417339	5	0
	26	07–08	A7	1	36.707006	−4.458520	8	0
	27	07–08	Pintor Sorolla	3	36.723338	−4.394361	7	1

[a] Streets categories go from 1 'Main city roads' to 5 'neighborhood streets'.

Table 2
Amplitudes of the harmonic components. $|\mathcal{F}(SPL^{i,k})|$.

St. (i)	1	2	4	9	10	16	17	20	3	5	7	8	11	6	14	19	12	13	15	18	21
Cat. (k)	1	1	1	1	1	1	1	1	2	2	2	2	2	3	3	3	4	4	4	4	5
A_0	64.5	69.1	67.6	66.8	68.7	62.6	69.5	62.4	63.2	65.9	67.3	62.9	60.1	63.7	64.4	59.1	60.4	61.1	63.4	56.7	59.1
A_1	0.7	0.8	0.8	0.8	0.7	0.5	0.7	1.0	0.9	0.7	1.0	0.6	1.5	1.0	1.1	0.9	0.2	0.9	0.8	0.2	1.1
A_{52}	0.5	0.8	0.6	0.4	0.5	0.5	0.5	0.8	0.9	0.4	0.7	0.5	0.5	0.8	0.8	1.1	0.5	0.5	0.6	0.6	0.6
A_{313}	0.6	0.7	0.8	0.5	0.5	0.5	0.5	0.8	0.8	0.5	0.9	0.6	0.6	0.9	0.8	0.6	0.8	0.7	0.7	0.6	0.7
A_{365}	2.2	2.7	2.5	2.6	2.7	2.4	3.4	2.1	4.1	2.2	4.0	3.5	3.1	3.6	4.1	4.4	3.2	4.5	3.0	4.9	3.7
A_{417}	0.6	0.8	0.8	0.6	0.5	0.6	0.4	0.9	0.9	0.6	0.9	0.6	0.7	0.9	0.8	0.3	0.7	0.7	0.6	0.7	0.5
A_{730}	1.6	1.4	1.5	1.5	1.5	1.7	2.1	1.4	2.2	1.6	2.1	1.9	2.0	1.7	2.1	2.3	1.7	2.6	1.4	2.4	2.2
A_{1095}	0.6	0.4	0.5	0.5	0.7	0.6	0.7	0.5	0.7	0.4	0.7	0.1	0.8	0.5	0.3	0.7	0.4	0.7	0.4	1.2	0.8
A_{1460}	0.6	0.5	0.5	0.4	0.4	0.3	0.5	0.6	0.6	0.4	0.6	0.4	0.6	0.6	0.5	0.8	0.3	0.5	0.8	0.9	0.5

Because x(t) is a function of time and represents a physical signal, the Fourier transform has a standard interpretation as the frequency spectrum of the signal $F(w)$ that is a series of complex numbers, composed by real part $\Re(w)$ or magnitude (amplitude $A_n^{i,k}$) and imaginary part $\Im(w)$ or angle (phase φ_n), i.e.,:

$$\mathcal{F}(x(t)) = F(w) = \Re(w) + j\Im(w) = |\mathcal{F}(w)|e^{j\varphi(w)} \tag{7}$$

Where j represent the imaginary unit.

Taking into account that we have a time series of data instead of a continuous function in time, we apply a discrete Fourier transform. In order to simplify the calculus presented in this paper, we have used the FFT (Cooley and Tukey, 1965).

It is of interest for further analysis to consider that the calculation of the continuous component $A_0^{i,k}$ coincides with linear average of signal and can be ca calculated according to Eq. (8).

$$A_0^{i,k} = \sum_{j=1}^{T} \frac{1}{T} L_{Aeq,1h}^{i,k,j} \tag{8}$$

Where T represents the period of measure ($T = 8760$ h if one complete year is evaluated).

4. Analysis and discussion of the results

Table 2 shows, for each measurement station of Madrid ($i = [1\text{-}21]$), the values of the amplitudes of the fundamental and highest harmonic components for which average values obtained in the set of analyzed stations are greater than 0.5 (where i refers to the station identification number, and k is the category number). In the first row is also displayed the value of the continuous component (Eq. (8)). The continuous component (A_0) should not be compared between measurement points, as a consequence of the absence of standardization to the sound source. It is interesting to observe how the absolute and relative importance of each component in different stations is quite uniform. It can be observed that there are eight components whose values are greater than 0.2 in almost all points. Additionally, the A_{365} component (highest), corresponding to a 24-hour period, is the dominant for all points. Its value never is less than 2.1, often reaching values greater than 4. The second major component is the A_{730}, corresponding to a period of 12 h. Its value is always greater than 1.2, exceeding in many cases the value of 2. Furthermore, it can be seen that 6 components have, in most cases, values greater than 0.5, corresponding to periods of 1 year (A_1), 1 week (A_{52}), 28 h (A_{313}), 21 h (A_{417}), 8 h (A_{1095}) and 6 h (A_{1460}). Fig. 2 shows the FFT analysis and behavior for one measurement station of Madrid.

The predictive capacity that different components have for estimating long-term indicators is analyzed. In Table 3 (rows 1 and 2), the average of the value errors in the estimate of each long-term indicator (e.g., annual SPL) can be observed by using the continuous component, and the first and second highest harmonic component, (according to Eq. (9)) or eight own components for each measurement point for the Fourier series.

$$SPL_{estimated}^{i,k} = \mathcal{F}^{-1}\left\{\mathcal{F}\left(SPL^{i,k}[dB]\right)\right\} \text{ only with } A_0^{i,k}\ A_{365}^{i,k}\ A_{730}^{i,k} \text{ others } A_{1-n}^{i,k} = 0 \tag{9}$$

Where:

$SPL_{estimated}^{i,k}$	is the annual Sound Pressure Level predicted by FFT analysis
$\mathcal{F}^{-1}$	is the inverse Fourier transform
$A_0^{i,k}$	is the continuous component
$A_{365}^{i,k}$	is the highest harmonic component (corresponding to $T = 24$ h)
$A_{730}^{i,k}$	is the second highest harmonic component (corresponding to $T = 12$ h)

It is observed that by using the two most important components, the estimates are fairly close to those obtained by using the eight components. As a consequence of this result and the similarities between the values obtained for these components in different measurement stations located at points with very different urban characteristics, these two components will be used for the development of the predictive model for the present work.

If long-term parameters are estimated by using the averaged components of all the stations of Madrid used in this study, the average results of the errors of the estimates are obtained as presented in Table 3 (row 3). It can be observed that the values obtained are similar to those in rows 1 and 2, and only for a few indicators has a slight increase in the mean and deviations been detected. Observe how, with a single model, the mean errors obtained in the predictions are quite acceptable, finding average values of 1 dB or less in all of the acoustic indicators. Fig. 3 displays the errors of predicted values for all acoustics indicators in the city of Madrid. Therefore, one can speak about the existence of the mean amplitudes of the harmonic components of the Fourier analysis that, regardless of the road type, can be used to estimate long-term parameters. Noteworthy in this estimation are the low number of errors obtained in the acoustics indicators assessing noise annoyance and sleep disturbance (such as L_n, L_{dn} and L_{den}) when the impact of urban noise on the population associated with traffic is measured. The great difficulty of the traditional methods of estimating the night level (L_n) and the importance of this indicator in the measurement of the impact of urban noise on populations should be noted. The effects of urban noise on nocturnal sleep can be the most significant and harmful. If at this point the results are analyzed according to the categorization method (Rey Gozalo et al., 2014) (k index), significant differences can be observed between the two most important components in the values obtained for category 1 ($k = 1$) compared to the other categories 2-5 ($k = [2\text{-}5]$). Therefore, although the categorization method allows finding a significant stratification among the five categories proposed based on the values of sound levels, there does not seem to be this stratification in the five categories in the temporal structure of the series.

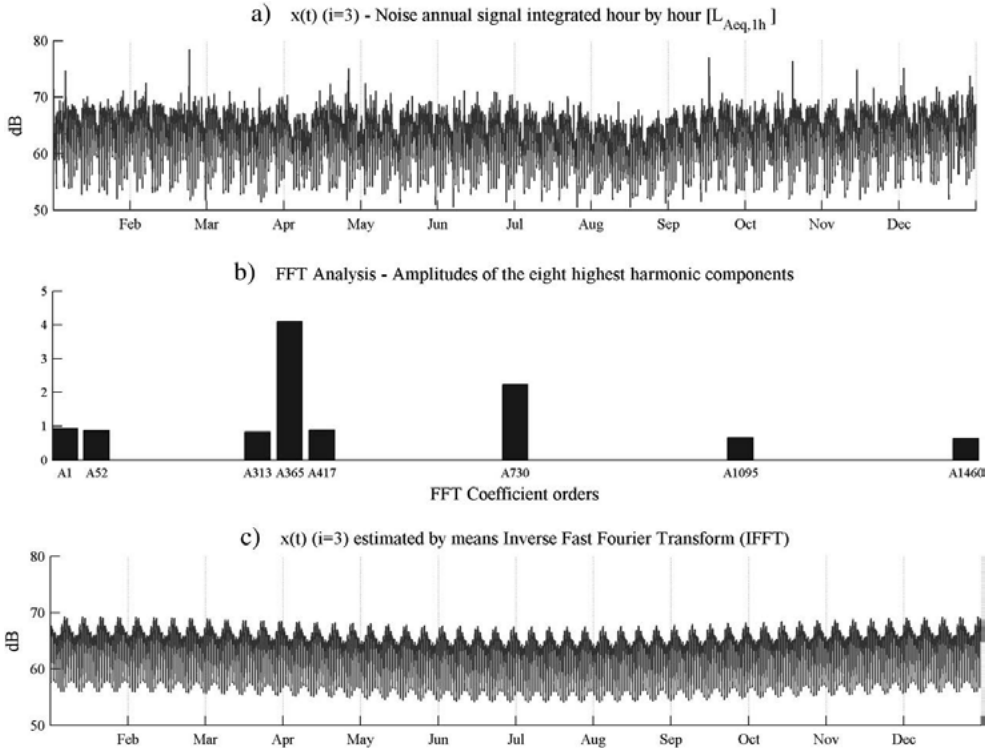

Fig. 2. Example of FFT analysis.

Finally, if in fact the mean amplitudes of the two highest Fourier components found may be considered as generally valid, it is possible to propose the assumption that the Fourier components obtained by using the measurement stations of the city of Madrid can be used as the Fourier components in the city of Malaga ($i = [22\text{-}27]$). This fact implies that the intercity variations on the distribution of the noise have no effects on the indicators. The results are presented in Table 3 (row 4). Note that the unexpected results are quite similar to those obtained in Madrid (row 3). Therefore, it can be said that in the socio-economic area in which this work was carried out, there is a temporal structure of annual variation in the noise levels that in some applications can be parameterized by only two same harmonic components. There is also a set of eight highest harmonic components in most of the measurement stations that have very similar values and equal frequency, confirming the above conclusion.

Will it be possible to obtain the sound levels associated with the traffic noise that exists on the streets of many cities of the sizes studied (500,000-3,000,000 inhabitants) by using the harmonic Fourier components obtained in this work and the A_0 component of each street? If the answer is yes, the progress achieved by the developed model is of primary importance. A nonlinear problem has been transformed into a linear problem because it is only necessary to know the value of A_0 (the A_0 component is the linear average of the annual values) and the harmonic Fourier components already calculated, being possible to estimate the long-term parameters with average errors equal o lower than 1 dB. Moreover, if the categorization method would allow a stratified estimation of the values of A_0, it would be possible to estimate the noise level of a street, without measuring it. Furthermore, if there is a noise level variability in each category that depends on the size of the city (Barrigón Morillas et al., 2010), an estimate could be made in a city directly without having to measure it. Are the acousticians close to the universal harmonic components for the annual urban noise associated with traffic? Perhaps not. It is believed, however, that there are some harmonic components with the potential for great generalization, but the variability must be investigated. Beyond a very detailed analysis of the relationship between these Fourier components and the categorization method, the most important harmonic components that can be found and their relative importance may depend on the different non-acoustic parameters. For example, these components might be influenced by the sociological, climate, and economic aspects… Or, in turn, the presence or absence of one of these components and their relative importance may be a valuable indicator in sociology, economics…

Table 3
Average of the value errors in the estimate. $\Sigma|L_x - L_{x2-8}|/n \pm \sigma$ [dB].

Long-term acoustic indicator	L_d	L_e	L_n	L_{dn}	L_{den}
$\Sigma i\ \forall\ i = [1\text{-}21]$ - 2 own comp.	0.6 ± 0.3	0.2 ± 0.2	0.9 ± 0.5	0.8 ± 0.3	0.6 ± 0.3
$\Sigma i\ \forall\ i = [1\text{-}21]$ - 8 own comp.	0.5 ± 0.3	0.3 ± 0.1	0.7 ± 0.4	0.6 ± 0.3	0.5 ± 0.3
$\Sigma i\ \forall\ i = [1\text{-}21]$ - 2 mean comp.	0.7 ± 0.6	0.4 ± 0.3	1.0 ± 0.7	0.8 ± 0.4	0.7 ± 0.3
$\Sigma i\ \forall\ i = [22\text{-}27]$ - 2 mean comp.	0.6 ± 0.3	0.5 ± 0.4	0.9 ± 0.9	0.8 ± 0.4	0.7 ± 0.3

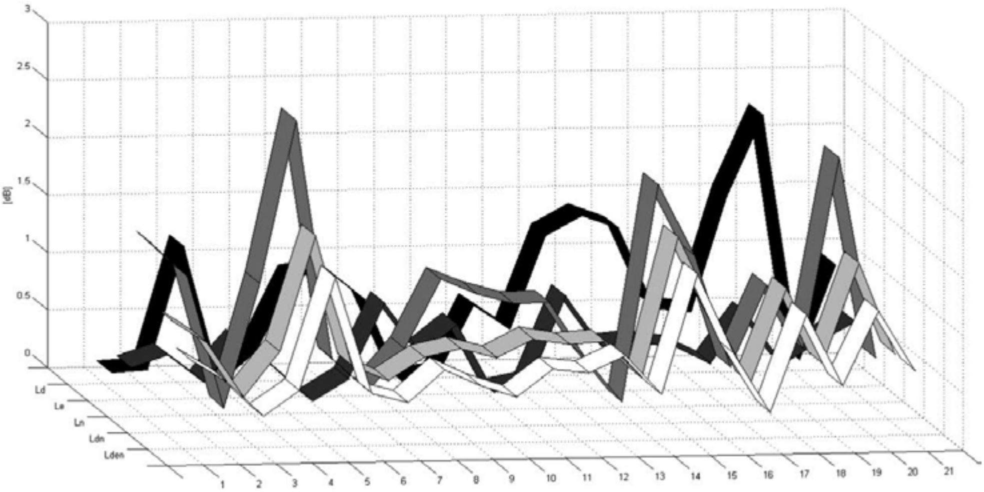

Fig. 3. Absolute error of the annual variables and rating levels when are estimated with 2 mean components.

This is not a closed investigation, but it is possible that this research has opened a new methodology for the study of urban noise, extend to chemical traffic pollution and, perhaps, a field of interaction between the acoustic and other scientific disciplines that should be explored.

5. Conclusions

The annual variability of noise levels associated with traffic has been studied in two Spanish cities with very different geographic, urban planning and size features. By using the measurement stations of Madrid, a model has been proposed for estimating the long-term acoustic indicators from the continuous component (A_0) and mean amplitude values of the first and second highest harmonic component of the Fourier analysis. The errors committed by the application of the model to both cities are, on average, less or equal than 1 dB for all acoustics indicators. Note that the model was not elaborated with the Malaga measurement stations, and note the great difficulty at the moment for estimating the level L_n and the importance of these indicators in measuring the impact of noise on urban populations.

The proposed model allows the transformation of a nonlinear problem (estimating the annual long-term parameters from daily values) into a linear problem (the estimation of the continuous or fixed component (A_0) of the Fourier harmonic series). There are still many unknowns and many avenues of research to develop:

- The studies need to estimate the annual arithmetic mean value of the long-term parameters.
- If models can be developed for other environments with other stable sources of interference, such as for recreational areas, airports and railway zones.
- The evaluation of the importance of different components in the specific values estimated noise levels in other periods of the year (e.g., the seasons).
- If there is any dependence of the values of the different harmonic components and their relative importance on the category, urbanism, sociological aspects, climate, or any other aspect of interest of the country or city studied.
- The possibility of extend this methodology to the study of the chemical pollution associated to traffic.

Acknowledgements

This work was partially supported by the Ministry of Economy and Competitiveness (Project No. TRA2012-37117), the ERDF, the Government of Extremadura (Regional Ministry of Economy, Trade and Innovation, Junta de Extremadura (Project GR10175) and the European Social Fund. This appreciation is extended to the municipality of Madrid and Malaga for selflessly offering us the noise data corresponding to all of their measurement stations. We are pleased to extend greetings to Dr. José Trujillo for contributing at the beginning of this study.

References

Alberola, J., Flindell, I.H., Bullmore, A.J., 2005. Variability in road traffic noise levels. Appl. Acoust. 66, 1180–1195.

ANSI s12.9-1993, 2008. American National Standard Quantities and Procedures for Description and Measurement of Environmental Sound. In: Institute ANS (Ed.), Part 2: Measurements of Long-Term, Wide Area Sound (Acoustical Society of America New York).

Attenborough, K., Clark, S., Utley, W.A., 1976. Background noise levels in the United Kingdom. J. Sound Vib. 48, 359–375.

Ausejo, M., Recuero, M., Asensio, C., Pavón, I., 2011. Reduction in calculated uncertainty of a noise map by improving the traffic model data through two phases. Acta Acust. U. Acust. 97, 761–768.

Banerjee, D., Chakraborty, S.K., Bhattacharyya, S., Gangopadhyay, A., 2009. Appraisal and mapping the spatial-temporal distribution of urban road traffic noise. Int. J. Environ. Sci. Technol. 6, 325–335.

Barrigón Morillas, J.M., Prieto Gajardo, C., 2014. Uncertainty evaluation of continuous noise sampling. Appl. Acoust. 75, 27–36.

Barrigón Morillas, J.M., Gómez Escobar, V., Méndez Sierra, J.A., Vílchez-Gómez, R., Trujillo Carmona, J., 2002. An environmental noise study in the city of Cáceres, Spain. Appl. Acoust. 63, 1061–1070.

Barrigón Morillas, J.M., Gómez Escobar, V., Méndez Sierra, J.A., Vílchez-Gómez, R., Vaquero, J.M., Trujillo Carmona, J., 2005. A categorization method applied to the study of urban road traffic noise. J. Acoust. Soc. Am. 117, 2844–2852.

Barrigón Morillas, J.M., Gómez Escobar, V., Rey Gozalo, G., Vílchez-Gómez, R., 2010. Possible relation of noise levels in streets to the population of the municipalities in which they are located. J. Acoust. Soc. Am. 128, EL86–EL92.

Berglund, B., Lindvall, T., Schwela, D.H., 1999. Guidelines for community noise. World Health Organization, Geneva.

Birk, M., Ivina, O., Von Klot, S., Babisch, W., Heinrich, J., 2011. Road traffic noise: Self-reported noise annoyance versus GIS modelled road traffic noise exposure. J. Environ. Monit. 13, 3237–3245.

Botteldooren, D., De Coensel, B., De Muer, T., 2006. The temporal structure of urban soundscapes. J. Sound Vib. 292, 105–123.

Brown, A.L., Lam, K.C., 1987. Urban noise surveys. Appl. Acoust. 20, 23–29.

Butler, D., 2004. Sound and vision. Nature 427, 480–481.

Can, A., Van Renterghem, T., Rademaker, M., Dauwe, S., Thomas, P., De Baets, B., et al., 2011. Sampling approaches to predict urban street noise levels using fixed and temporary microphones. J. Environ. Monit. 13, 2710–2719.

Chang, T.Y., Liu, C.S., Bao, B.Y., Li, S.F., Chen, T.I., Lin, Y.J., 2011. Characterization of road traffic noise exposure and prevalence of hypertension in central Taiwan. Sci. Total Environ. 409, 1053–1057.
Cooley, J.W., Tukey, J.W., 1965. An Algorithm for the Machine Calculation of Complex Fourier Series. Math. Comput. 19, 297–301.
Doygun, H., Kuşat Gurun, D., 2008. Analysing and mapping spatial and temporal dynamics of urban traffic noise pollution: A case study in Kahramanmaraş, Turkey. Environ. Monit. Assess. 142, 65–72.
European Parliament C, 2002. Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise L 189, pp. 12–25.
Fyhri, A., Aasvang, G.M., 2010. Noise, sleep and poor health: Modeling the relationship between road traffic noise and cardiovascular problems. Sci. Total Environ. 408, 4935–4942.
Gaja, E., Giménez, A., Sancho, S., Reig, A., 2003. Sampling techniques for the estimation of the annual equivalent noise level under urban traffic conditions. Appl. Acoust. 64, 43–53.
Guedes, I.C.M., Bertoli, S.R., Zannin, P.H.T., 2011. Influence of urban shapes on environmental noise: A case study in Aracaju - Brazil. Sci. Total Environ. 412–413, 66–76.
ISO 1996-1, 2003. Acoustics. Description, measurement and assessment of environmental noise. Part 1: Basic quantities and assessment procedures. International Organization for Standardization, Switzerland.
ISO 1996-2, 1987. Acoustics. Description and measurement of environmental noise. Part 2: Acquisition of data pertinent to land use. International Organization for Standardization, Switzerland.
ISO 1996-2, 2007. Acoustics. Description, measurement and assessment of environmental noise. Part 2: Determination of environmental noise levels. International Organization for Standardization, Switzerland.
Kephalopoulos, S., Paviotti, M., Knauss, D., Bérengier, M., 2007. Uncertainties in long-term road noise monitoring including meteorological influences. Noise Control Eng. J. 55, 133–141.
Marquis-Favre, C., Premat, E., Aubrée, D., Vallett, M., 2005. Noise and its effects - A review on qualitative aspects of sound. Part I: Notions and acoustic ratings. Acta Acust. U. Acust. 91, 613–625.
Maruyama, M., Kuno, K., Sone, T., 2013. The minimum measurement time for estimating LAeqT of road traffic noise from the number of vehicle pass-bys. Appl. Acoust. 74, 317–324.
Mehdi, M.R., Kim, M., Seong, J.C., Arsalan, M.H., 2011. Spatio-temporal patterns of road traffic noise pollution in Karachi, Pakistan. Environ. Int. 37, 97–104.
Mohammadi, G., 2009. An investigation of community response to urban traffic noise. Iran. J. Environ. Health Sci. Eng. 6, 137–142.
Öhrström, E., 2004. Longitudinal surveys on effects of changes in road traffic noise - Annoyance, activity disturbances, and psycho-social well-being. J. Acoust. Soc. Am. 115, 719–729.
Omiya, M., Kuno, K., Mishina, Y., Oishi, Y., Hayashi, A., 1997. Comparison of community noise ratings by L50 and LAeq. J. Sound Vib. 205, 545–554.
Oyedepo, O.S., Saadu, A.A., 2010. Evaluation and analysis of noise levels in Ilorin metropolis, Nigeria. Environ. Monit. Assess. 160, 563–577.
Ozer, S., Irmak, M.A., Yilmaz, H., 2008. Determination of roadside noise reduction effectiveness of Pinus sylvestris L. and Populus nigra L. in Erzurum, Turkey. Environ. Monit. Assess. 144, 191–197.
Rey Gozalo, G., Barrigón Morillas, J.M., Gómez Escobar, V., 2013. Urban Streets Functionality As A Tool For Urban Pollution Management. Sci. Total Environ. 461–462, 453–461.
Rey Gozalo, G., Barrigón Morillas, J.M., Gómez Escobar, V., 2014. Analyzing nocturnal noise stratification. Sci. Total Environ. 479–480, 39–47.
Romeu, J., Jiménez, S., Genescà, M., Pàmies, T., Capdevila, R., 2006. Spatial sampling for night levels estimation in urban environments. J. Acoust. Soc. Am. 120, 791–800.
Romeu, J., Genescà, M., Pàmies, T., Jiménez, S., 2011. Street categorization for the estimation of day levels using short-term measurements. Appl. Acoust. 72, 569–577.
Schomer, P.D., DeVor, R.E., 1981. Temporal sampling requirements for estimation of long-term average sound levels in the vicinity of airports. J. Acoust. Soc. Am. 69, 713–719.
Suárez, E., Barros, J.L., 2014. Traffic noise mapping of the city of Santiago de Chile. Sci. Total Environ. 466–467, 539–546.
To, W.M., Ip, R.C.W., Lam, G.C.K., Yau, C.T.H., 2002. A multiple regression model for urban traffic noise in Hong Kong. J. Acoust. Soc. Am. 112, 551–556.
Torija, A.J., Ruiz, D.P., 2012. Using recorded sound spectra profile as input data for real-time short-term urban road-traffic-flow estimation. Sci. Total Environ. 435–436, 270–279.
Torija, A.J., Genaro, N., Ruiz, D.P., Ramos-Ridao, A., Zamorano, M., Requena, I., 2010. Priorization of acoustic variables: Environmental decision support for the physical characterization of urban sound environments. Build. Environ. 45, 1477–1489.
Vlachokostas, C., Achillas, C., Michailidou, A.V., Moussiopoulos, N., 2012. Measuring combined exposure to environmental pressures in urban areas: An air quality and noise pollution assessment approach. Environ. Int. 39, 8–18.
Vlachokostas, C., Banias, G., Athanasiadis, A., Achillas, C., Akylas, V., Moussiopoulos, N., 2014. Cense: A tool to assess combined exposure to environmental health stressors in urban areas. Environ. Int. 63, 1–10.
Walker, J.S., 1996. Fast Fourier Transforms. CRC Press, Boca Raton, Florida.
Zuo, F., Li, Y., Johnson, S., Johnson, J., Varughese, S., Copes, R., et al., 2014. Temporal and spatial variability of traffic-related noise in the City of Toronto, Canada. Sci. Total Environ. 472, 1100–1107.

Objetivo 5: Study of the Categorisation Method Using Long-Term measurements

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Trabajo publicado en

Archive of Acoustics (2013), Vol. 38(3), Págs. 397-405

ARCHIVES OF ACOUSTICS
Vol. **38**, No. 3, pp. 397–405 (2013)

DOI: 10.2478/aoa-2013-0047

Study of the Categorisation Method Using Long-term Measurements

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(*received March 7, 2012; accepted July 15, 2013*)

Previous studies concerning the categorisation method have been based on short daytime measurements. These studies demonstrated urban-noise stratification in the daytime. Nevertheless, legislation and standards refer to noise estimation throughout the day. This paper presents the first attempt to apply the categorisation method to indicators obtained through long-term measurements. The study was conducted in Plasencia, Extremadura (Spain) which has approximately 41,500 inhabitants. First, we conducted a stratification of the roads using the categorisation method. Second, long-term measurements (approximately one week) were conducted at different sampling locations across different categories of streets. The results were analysed by category. Moreover, the profile of the noise-level variation was analysed during the day. The results revealed a stratification of sound levels measured across the different categories. Furthermore, we found health risks due to the noise levels in this town. Short-term measurements were also conducted to complete the categorisation method suitability analysis.

Keywords: noise pollution, sampling methods, street categorisation.

1. Introduction

Noise pollution is an environmental problem present everywhere in developed society. Numerous publications alert us to the dangerous effects of noise (EEA, 2009; WHO, 2011).

Within concern for noise pollution, European legislation demands Member States to elaborate noise maps in population centres with more than 100,000 inhabitants (EU, 2002). Nevertheless, many Europeans live in small towns; thus, they are excluded from these studies. For example, in 2010, 60.2% of the Spanish population lived in towns with less than 100,000 inhabitants (INE, 2010).

The large percentage of people living in small towns makes devoting effort to these places necessary. For the current studies, our research group used a categorisation method to classify streets into different groups based on their use as communication routes. This *in situ* method has shown potential as a simpler and less resource-consuming method than grid-based experimental designs. Furthermore, it has revealed promising results in small (Rey Gozalo *et al.*, 2012) and medium-sized towns (Barrigón Morillas *et al.*, 2002; 2005a; 2005b; Carmona del Río *et al.*, 2011). Recent publications have shown other applications using this methodology (Barrigón Morillas *et al.*, 2010; Rey Gozalo *et al.*, 2013), and it has been compared with other *in situ* methodologies (Barrigón Morillas *et al.*, 2011).

Our previous studies have been based on short-term measurements from which we estimated sound levels during the day (L_{d}). However, the present study analyses, for the first time, the suitability of the categorisation definition by conducting long-term measurements to obtain the L_{d}, L_{e}, L_{n}, and L_{den} indices. Besides, relationships among short-term and long-term results are also analysed.

The main objective of this work was to study the performance of the categorisation method and the behaviour of city sound levels using long-term measurements (for approximately one week).

Besides, as a secondary objective, we analyse the acoustical situation of a small city in relation with international reference values.

2. Methods

2.1. Plasencia

Plasencia has a population of 41,500 inhabitants and is located in the north of the Extremadura region in south-western Spain. Despite its number of inhabitants, Plasencia is the second most populated town in the province and the fourth most populous in the region. The city's economy is based primarily on the trade and services sector which represents 68.3% of the employed population. It also contributes to the construction and industry sectors (19.3% and 8.7% of the employed population, respectively). The industry sector specialises in agricultural products. For over eight centuries, this village remained locked in a walled area and contact with the outside was conducted through doors and wall shutters. During the nineteenth century, the city grew outside the wall, primarily beside the Jerte River. As a consequence of this history (i.e. excessively narrow and elongated streets), there are problems with modern urban mobility.

2.2. Categorisation method

The categorisation method is based on the widely accepted assumption that road traffic is the primary source of noise in most streets. The category definitions used in the present study are the same as in a previous work (Barrigón Morillas *et al.*, 2005a). A summary of the steps needed to apply this method can also be found in this publication.

2.3. Street categorisation

The town categorisation consisted in classifying each street into one of six categories. This step required approximately one week: one to two days of study using a map and the assistance of one of the town's residents, and four to five days of *in situ* study.

The final categorisation of Plasencia is shown in Fig. 1. Only streets with housing were considered. All streets other than pedestrian, restricted-access, and so on not included in Categories 1 to 4 were included in Category 5.

2.4. Sampling point selection

Two types of measurements were conducted for the present study: short-term measurements and long-term measurements.

For the short-term measurements, once every street of the city had been assigned to one of five categories, ten sampling points were randomly selected in each category. Two methods were used: one for Categories 1 to 4 streets and the other for Category 5 streets. In the

Fig. 1. Map of Plasencia including the different categories and sampling points with both short- and long-term measurements.

former method, the total length of streets that belonged to each category was calculated and denoted by L_i, the length of category i ($i = 1, ..., 4$). Ten sampling points were located randomly between 0 and L_i. The only restriction was that equivalent points (i.e., those located on the same street section with no intersection between them) were avoided; thus, only 9 sampling points for Categories 1 and 2 were chosen because it was impossible to select more non-equivalent points. Another random strategy was used in the latter method due to the large number of streets involved in Category 5 (n_5). Each street was taken as a single potential sampling point (p_i, $i = 1, ..., n_5$) and ten sampling point selected randomly between 1 and n_5 and located in the middle of the segment that corresponded to the entire street. Locations of the 48 short-term measurement points are shown in Fig. 1 and are superimposed on the street categorisation.

For the long-term measurements, several non-equivalent points were selected for each of the categories to locate the maximum number of sampling points. Special care was taken when selecting these points to assure the security of the monitoring equipment with respect to adverse weather conditions and vandalism. The locations of the 18 long-term measurement locations are presented in Fig. 1.

Importantly, the categories do not have a standard size. Thus, to obtain average values for the entire city, each category was weighted by length. Table 1 shows the number of points measured in each category as well as the length percentage and the proportion of the population that lives in each category.

Table 1. The number of sampling points measured for each category. The percentage of each category's street length is determined with respect to the total street length of Plasencia and in proportion to the population that lives in each category.

Category	1	2	3	4	5
Number of long-term measurements	4	4	4	3	3
Number of short-term measurements	9	9	10	10	10
% Length	5.2	8.0	5.9	10.6	70.3
% Population	2.1	3.5	4.9	8.7	80.8

2.5. Measurement equipment and procedure

In-situ noise short-term measurements were made from Monday to Friday in the daytime. Daytime was defined by the European Directive 20002/49/EC (COM, 2002) as from 7:00 a.m. to 7:00 p.m. This period was divided into four 3-hour periods and one noise measurement of 15 minutes of duration was carried out in each period to obtain a set of four independent measurements for each sampling point. Using this method, only one measurement was performed at each location per day and never during the same time interval.

All measurements were conducted following the ISO 1996-2 guidelines (ISO 1996-2, 2007) using 2260 and 2238 Brüel & Kjær Type-1 sound level meters equipped with a tripod and a windshield. For the long-term measurements, a 2-metre extension pole separated the microphone from the building facade. For the short-term measurements, the sound level meter was located at a height of 1.5 metres and one metre from the curb. Calibration was performed using a 4231 Brüel & Kjær calibrator twice a day. The measurement lasted for approximately a week for the long-term measurements.

3. Results and discussion

3.1. Preliminary analysis of long-term measurements

In the first step, long-term measurements values were normalised to the reference height of 4 metres (EU, 2002). For these calculations, the normalisation effects of geometric divergence for open profile streets (considering streets as a source of line noise) were considered, whereas the French Standard *Guide du Bruit* corrected the data from streets with a U-shape (CETUR, 1980). Variation of long-term measurements values during a week are shown in Fig. 2 for four sampling points.

In the second step, due to the significant differences between the sound levels of the different categories found in previous studies for short-term measurements (Barrigón Morillas *et al.*, 2005a), we decided to use the long-term measurements to analyse the sound level during a full week to search for similarities, tendencies, differences among categories, and so on. For instance, we analysed the difference between the temporal structure of noise levels in each category in order to check if this structure was similar in all the categories or if, as it happens with noise values, there were differences between categories. For this purpose, we used continuous partial trend models (Tomé, Miranda, 2005a; 2005b). This technique allows for a multiple linear fit by fitting least-squares continuous line segments to a continuous series with a minimum mean square error. After observing the sound-pressure profile of the long-term measurements (Fig. 2) and adjusting calculations with regard to 3, 4, and 5 breakpoints, we decided to analyse each day independently using 3 breakpoints. Table 2 presents the average values of the different breakpoints and the slopes of the lines that join these points for each category.

Considering the time at which a breakpoint first occurs, we are able to observe similar behaviours for the different categories:

- Workdays: The first breakpoint occurs from 4:00–5:00 a.m., which coincides with the start of city

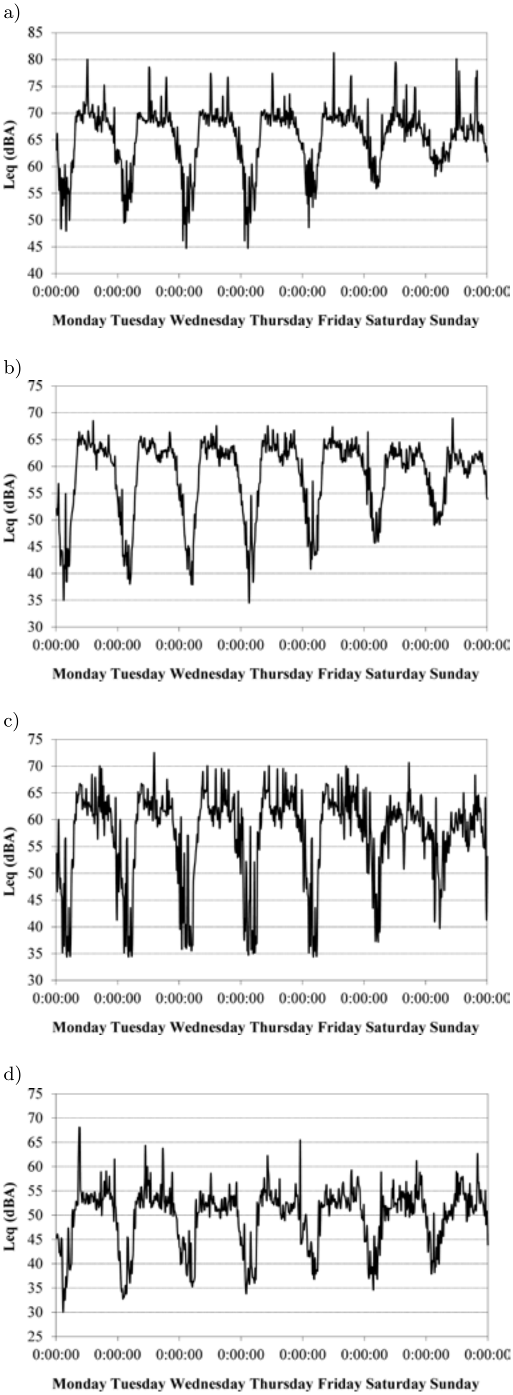

Fig. 2. The weeklong variation of L_{eq}, 15 min for some long-term sampling points: a) Point 1.01; b) Point 2.01; c) Point 4.01; and d) Point 5.01.

Table 2. Average breakpoints and slopes calculated from continuous partial trend models.

Category	Day	Breakpoint		Slope	
		Code	Finish hour	Code	Value
1	Workdays	1	4	1	−2.48
		2	9	2	4.06
		3	22	3	−0.07
	Weekend	1	6	1	−1.84
		2	11	2	1.92
		3	23	3	−0.12
2	Workdays	1	5	1	−2.86
		2	9	2	4.71
		3	22	3	−0.16
	Weekend	1	6	1	−2.83
		2	10	2	2.63
		3	23	3	0.11
3	Workdays	1	5	1	−2.76
		2	9	2	4.95
		3	22	3	0.01
	Weekend	1	5	1	−2.36
		2	11	2	1.68
		3	23	3	0.05
4	Workdays	1	5	1	−2.51
		2	9	2	5.52
		3	22	3	−0.06
	Weekend	1	6	1	−2.83
		2	10	2	2.61
		3	22	3	0.07
5	Workdays	1	5	1	−2.47
		2	8	2	6.25
		3	22	3	−0.14
	Weekend	1	5	1	−2.26
		2	9	2	3.68
		3	23	3	0.05

traffic (i.e. garbage trucks, the first human movements, and so on). The second breakpoint occurs from 8:00–9:00 a.m. when noise levels begin to rise. The third breakpoint occurs at 10:00 p.m. when sound levels stabilise and begin to decrease.

- Weekend: Human activity began later; thus, the first breakpoint is approximately at 5:00–6:00 a.m. Noise levels begin to rise at 10:00–11:00 a.m. (except in Category 5 in which noise rises at 9:00 a.m.). Finally, sound levels stabilise and start to decrease at 10:00–11:00 p.m.

Therefore, there were no important differences between the studied categories; however, we observed differences between workdays and weekend with respect to the breakpoints. Specifically, the first breakpoint occurs one to two hours later than in working days than weekends.

Then, considering the slope of the lines that join the breakpoints:

- Without considering the category, the slopes of Lines 1 (a reduction in noise levels from 10:00–11:00 p.m. to 4:00–6:00 a.m.) and 2 (an increase in noise levels from 4:00–6:00 a.m. to 8:00–11:00 a.m.) are more pronounced in workdays than weekends, whereas there was no difference with regard to the slope of Line 3. Line 3 has a slope value close to zero because the sound levels are approximately stable between 9:00 a.m. and 10:00 p.m.
- Comparing the slope means of the lines representing different categories, the slopes of Lines 1 and 3 do not differ across the different categories. Nevertheless, the slope of Line 2 increases when the category increases, especially on workdays.

Thus, the sound level variation profiles of the different categories have many similarities to each other during the day. In any case, according to our long-term measurements, the slope that corresponds to the increase of sound levels from the morning (between 4:00 and 6:00 a.m.) to the evening (between 8:00 and 10:00 p.m.) increases with the street category. This finding might indicate other differences between the categories that should be investigated in the future.

Finally, the L_{d}, L_{e}, L_{n}, and L_{den} long-term measurement indices were calculated for each category (Table 3 presents these values). Two indices were calculated for L_{d}: L_{d12} was calculated from 7:00 a.m. to 7:00 p.m., and L_{d16} was calculated from 7:00 a.m. to 11:00 p.m. Thus, considering the international reference values (e.g. 65 dBA, 55 dBA, or 45 dBA) and the average sonorous values for each category (Table 3), only the Category 5 L_{d16} was under 55 dBA, a level that the WHO considers as a serious annoyance (WHO, 1999). This represents the 19% of the population living in this town (see Table 1). L_{d16} levels above 65 dBA (the value that the OECD suggests as the daytime exposure limit; OECD, 1986) were exceeded by Category 1 and Category 2. At night, the L_{n} index was under 45 dBA (a value considered by the WHO as a reference value for sleep disturbance; WHO, 1999) at only in workdays in Category 5. Finally, 11% of the population live in “black acoustic zones” ($L_{\mathrm{den}} > 65$ dBA), 89% in “grey acoustic zones” (65 dBA $> L_{\mathrm{den}} > 55$ dBA) and 0% in “white acoustic zones” ($L_{\mathrm{den}} < 55$ dBA), using the OECD criteria terminology (OECD, 1991).

Therefore, we conclude from the long-term measurement results that Plasencia, despite being a small city, has noise levels that might seriously affect the health and quality of life of a significant percentage of its population, especially at night.

Table 3. Average values of L_{d12}, L_{e}, L_{d16}, L_{n}, and L_{den} indices (in dBA) for each category.

Category	Sound Index	Average value (workdays) [dBA]	Average value (weekend) [dBA]	Average value (weekly) [dBA]
1	L_{d12}	67.7±2.8	66.0±3.0	67.3±2.8
	L_{e}	66.4±2.1	66.4±3.1	66.4±2.3
	L_{d16}	67.4±2.6	66.1±3.1	67.1±2.7
	L_{n}	58.1±3.2	61.2±2.6	59.3±2.8
	L_{den}	69.4±2.5	70.2±2.8	69.7±2.6
2	L_{d12}	66.1±0.8	63.2±0.9	65.4±0.8
	L_{e}	64.8±1.4	64.7±1.7	64.8±1.5
	L_{d16}	65.8±0.9	63.6±1.1	65.3±0.9
	L_{n}	55.3±1.5	59.2±1.0	56.8±1.3
	L_{den}	67.6±1.1	68.2±1.2	67.8±1.1
3	L_{d12}	63.2±2.6	60.5±1.5	62.6±2.3
	L_{e}	63.4±2.0	61.7±1.8	63.0±1.8
	L_{d16}	63.2±2.4	60.9±1.5	62.7±2.2
	L_{n}	54.1±1.8	57.1±1.3	55.2±1.5
	L_{den}	65.9±2.0	65.7±1.3	65.8±1.7
4	L_{d12}	60.5±2.4	57.9±1.5	59.9±2.3
	L_{e}	60.4±1.4	59.0±1.6	60.0±1.5
	L_{d16}	60.5±2.1	58.2±1.5	60.0±1.9
	L_{n}	50.8±1.5	53.0±3.1	51.6±2.1
	L_{den}	62.9±1.5	62.3±2.1	62.7±1.7
5	L_{d12}	53.6±0.5	50.8±1.1	53.0±0.4
	L_{e}	52.8±0.8	52.5±1.7	52.7±1.0
	L_{d16}	53.4±0.3	51.3±1.3	52.9±0.4
	L_{n}	44.5±3.0	46.2±0.3	45.2±2.0
	L_{den}	55.9±0.6	55.7±0.9	55.8±0.5

3.2. Analysis of categorisation method

As shown in Table 3, the long-term measurement average values of all the analysed indices decrease when the number of the category increases. These results seem to indicate the existence of noise-level stratification in the city. Nevertheless, sampling point locations are not similar and obtained values must to be normalised.

Thus, long-term measurements were used to obtain the sound power level per length of traffic source (assuming it is linear). This calculation was necessary to compare the long-term results with the short-term results because different distances to the source must be considered with the reflection effects (ISO 9613-2, 1996). The average power level was evaluated in each category after accounting for these divergence and reflection effects. One order of reflection was considered; reflections on vertical obstacles were treated with the help of image-sources, as used in several national calculation methods (EC, 2003). As shown in Table 4,

Table 4. Sound power levels (L_w, in dBA) of the linear traffic source for each category.

Category	L_{d16w} [dBA]			L_{nw} [dBA]			L_{d24w} [dBA]		
	Average value (workdays)	Average value (weekend)	Average value (weekly)	Average value (workdays)	Average value (weekend)	Average value (weekly)	Average value (workdays)	Average value (weekens)	Average value (weekly)
1	81.9±0.6	80.6±1.2	81.6±0.7	72.6±1.2	75.7±0.7	73.8±0.8	80.4±0.6	79.5±1.1	80.2±0.6
2	80.1±0.4	77.9±0.7	79.6±0.5	69.6±1.3	73.5±0.9	71.1±1.1	78.6±0.4	76.8±0.6	78.1±0.4
3	76.5±1.5	74.2±1.5	76.0±1.4	67.4±0.4	70.4±0.6	68.5±0.3	75.1±1.4	73.2±1.3	74.6±1.3
4	73.0±0.5	70.6±1.1	72.5±0.6	63.2±1.3	65.4±1.7	64.0±1.2	71.5±0.5	69.5±1.0	71.0±0.6
5	66.2±0.4	64.1±1.5	65.7±0.6	57.3±3.0	59.0±0.2	58.0±2.0	64.7±0.5	62.9±1.3	64.3±0.6

Category	L_{d12w} [dBA]			L_{ew} [dBA]		
	Average value (workdays)	Average value (Weekends)	Average value (weekly)	Average value (workdays)	Average value (Weekends)	Average value (weekly)
1	82.2±0.7	80.5±1.2	81.8±0.8	80.8±0.4	80.9±1.3	80.9±0.4
2	80.4±0.4	77.4±0.6	79.7±0.3	79.1±1.0	79.0±1.3	79.1±1.0
3	76.5±1.7	73.8±1.3	75.9±1.6	76.6±1.0	75.0±2.2	76.3±1.0
4	73.0±0.2	70.3±1.0	72.4±0.2	72.9±1.8	71.5±1.3	72.5±1.7
5	66.3±0.6	63.6±1.3	65.7±0.6	65.5±0.9	65.2±1.9	65.5±1.2

the sound power levels decrease when the category number increases, and there is practically no overlap. Table 4 clearly shows the existence of noise stratification in all of the time periods considered across the city. In addition, these results indicate that the categorisation method suitably characterises the noise stratification in the city. Nevertheless, the long-term measurements cannot statistically demonstrate that the categorisation method suitably discriminates this stratification due to the small number of sampling points (a maximum of four points per category). Thus, the existence of the mentioned stratification will be analysed using the results of the short-term measurements and checking the coherence among short-term and long-term results.

Short-term measurements allowed us to obtain a dataset large enough to statistically examine the possible differences between the measured sound levels. In previous studies, approximately 10 sampling points per category were sufficient to analyse the differences between five categories (Barrigón Morillas *et al.*, 2002; 2005a; 2011). Thus, as previously mentioned, 9–10 points were selected in Plasencia per category (see Table 1) to characterise the noise of the city that was not examined with the long-term measurements.

Table 5 shows the average L_{eq} values obtained for each category for short-term measurements and average sound power levels calculated both from short-term and long-term measurements (the latter being previously shown in Table 4). L_{eq} values were obtained as the arithmetic mean of the sound level values of the points of each category. Sound power per unit length values for short-term measurements were obtained as the arithmetic mean of the power values of the different points which were obtained from the measured sound pressure levels with the same calculation procedure used for long-term measurements.

Table 5. L_{d12h} and sound power levels obtained for short-term measurements. The L_{d12w} obtained for workdays is also shown.

Category	L_{d12} [dBA] Workdays Short-term measurements	L_{d12w} [dBA] Workdays Short-term measurements	L_{d12w} [dBA] Workdays Long-term measurements
1	71.5±0.8	81.6±0.8	82.2±0.7
2	69.5±0.8	79.9±0.7	80.4±0.4
3	67.1±1.5	77.0±1.2	76.5±1.7
4	64.7±1.3	73.3±2.5	73.0±0.2
5	59.7±3.2	68.1±3.3	66.3±0.6

As can be seen in Table 5, sound power values are similar between short-term measurements and long-term measurements. These results indicate that, when averaging by category, short-term sound levels provide a sufficient approximation of the weekly sound levels in daytime period.

We performed a statistical analysis of the sound power values obtained from the street to examine the differences in sound power levels among the five categories. We sought to determine whether these differences were significant at a 95% confidence interval.

We proposed the following hypotheses for the analysis below:

- H_0 = There were no significant differences among the sound power level means of the different categories.

- H_1 = There were significant differences among the sound power level means of the different categories.

Before conducting the appropriate statistical test to address the hypotheses, we analysed the normality of the data using the Shapiro-Wilk test (Shapiro, 1965). We obtained a p-value of 0.0072, indicating that these data significantly differed from a normal distribution. This lack of normality, together with the small number of data in each category, suggests the use of nonparametric tests because the results are less disputable.

Thus, we first analysed the different categories using the Kruskal-Wallis test (Kruskal, Wallis, 1952). We obtained a p-value of $1.037 \cdot 10^{-8}$ which indicates a significant difference among the categories. Then, we used the Mann-Whitney U test with a Bonferroni correction to perform multiple comparisons between different category pairs (Mann, Whitney, 1947; Martin, Altman, 1995). The results of this test are shown in Table 6.

As shown in Table 6, there were differences between all category pairs at a significance level less than or equal to 0.05. Thus, the categorisation method is a suitable method of studying the noise stratification in small cities.

As a second proof of this suitability, we used the ROC analysis (Hand, Till, 2001; Fawcett, 2006) to demonstrate the predictive capacity of this method. ROC has been previously and successfully used to support similar aims (Carmona del Río *et al.*, 2011). Table 7 shows the results of this analysis. As can be seen, the marks of the strata were close to the means of all categories. This proximity is indicative of the internal coherence of the category method.

ROC analysis sensitivity is a measure of the capacity to include the previously assigned streets in the stratum. The results presented in Table 7 are encouraging: the sensitivity was 100% in Stratum 1, and 70% or greater in the other strata. Consequently, the overall sensitivity of the method was over 85%: of a group of five streets, four presented sound values that corresponded to the stratum to which they were assigned in the initial categorisation (prior to measurement).

The nonspecificity measures the proportion of streets that were not initially assigned to a certain stratum but for which the ROC analysis indicates that they belong to that stratum. As shown in Table 7, only Strata 4 and 5 revealed a nonspecificity greater than 5%. These values were less than 3% for the rest of the strata. The overall nonspecificity was 14.6% which is consistent with the overall sensitivity. This result means that, on average, the ROC analysis assigned less than one of the five streets to a stratum that was different from the one to which the categorisation method had assigned it.

Finally, the predictive values of the different strata represent the proportion of the streets that the ROC analysis assigned to the stratum that matched the categories to which they were initially assigned, relative

Table 6. Mann-Whitney U test results with a Bonferroni correction: (***) $p < 0.001$, (**) $p < 0.01$, and (*) $p < 0.05$.

		Category			
		1	2	3	4
Category	2	0.00288(**)	–	–	–
	3	0.00022(***)	0.00152(**)	–	–
	4	0.00022(***)	0.00022(***)	0.00325(**)	–
	5	0.00022(***)	0.00022(***)	0.00011(***)	0.01505(*)

Table 7. ROC analysis results.

Stratum	1		2		3		4		5	all
Mark	81.5		79.4		77.1		73.9		66.9	
Upper limit	82.5		80.4		78.3		75.8		72.0	
Lower limit	80.4		78.3		75.8		72.0		61.8	
Amplitude	2.1		2.1		2.6		3.8		10.2	
AUC		0.96		0.96		0.94		0.90		
Sensitivity (nº)	9		8		8		7		9	41
Sensitivity (%)	100		88.9		80.0		70.0		90.0	85.4
Nonspecificity (nº)	1		1		1		2		2	7
Nonspecificity (%)	2.6		2.6		2.6		5.3		5.3	14.6
Predictive value (%)	90.0		88.9		88.9		77.8		81.8	85.4

to the total number of streets that the ROC analysis determined for the stratum. Table 7 shows that, except for Stratum 4, the predictive values were greater than 80%. The overall predictive value was 85%.

4. Conclusions

The primary conclusions of the present study are as follows:

- Considering that linear noise sources are similar for short and long-term measurements, the sound power levels in the daytime indicate that short-term measurements are sufficient when an adequate number of long-term measurements cannot be conducted.
- Significant short-term measurement differences were found among the different categories with regard to sound levels in the streets. This finding demonstrates the effectiveness of the categorisation method.
- We found a clear differentiation among the different categories with regard to the indices calculated from the long-term measurements.

From these conclusions, we surmise that the categorisation method can be expected to sufficiently estimate the long-term indicators recommended in the European Directive. Nevertheless, more studies are necessary to confirm this conclusion.

- We found that sound level variation behaves similarly throughout the day across the different categories. This finding implies that the city's sound is homogeneous across locations.
- The ROC analysis that examined the predictive capacity of the categorisation method in Plasencia found overall sensitivities and predictive values higher than 85% with regard to the categorisation method.

Acknowledgments

The University of Extremadura (Acción III. Plan Iniciación a la Investigación, Desarrollo Tecnológico e Innovación 2011), the European Social Fund, the European Regional Development Fund (ERDF), and Junta de Extremadura (Projects PRI06A271, PD10166, and GR10175), Consejería de Economía, Comercio e Innovación supported this work.

References

1. Barrigón Morillas J.M., Gómez Escobar V., Méndez Sierra J.A., Vílchez-Gómez R., Trujillo Carmona J. (2002), *An environmental noise study in the city of Cáceres, Spain*, Appl. Acoust., **63**, 1061–1070.
2. Barrigón Morillas J.M., Gómez Escobar V., Méndez Sierra J.A., Vílchez-Gómez R., Vaquero J.M., Trujillo Carmona J. (2005a), *A categorization method applied to the study of urban road traffic noise*, J. Acoust. Soc. Am., **117**, 2844–2852.
3. Barrigón Morillas J.M., Gómez Escobar V., Vaquero J.M, Méndez Sierra J.A., Vílchez-Gómez R. (2005b), *Measurements of noise pollution in Badajoz City, Spain*, Acta Acustica united with Acustica, **91**, 797–801.
4. Barrigón J.M., Gómez Escobar V., Rey Gozalo G., Vílchez-Gómez R. (2010), *Possible relation of noise levels in streets to the population of the municipalities in which they are located*, J. Acoust. Soc. Am., **128**, EL86–EL92.
5. Barrigón Morillas J.M., Gómez Escobar V., Méndez Sierra J.A., Vílchez-Gómez R., Carmona del Río J., Trujillo Carmona J. (2011), *Comparison of two procedures for the evaluation of urban noise*, Appl. Acoust., **71**, 760–771.
6. Carmona del Río F.J., Gómez Escobar V., Trujillo Carmona J., Vílchez-Gómez R., Méndez Sierra J.A., Rey Gozalo G., Barrigón Morillas J.M. (2011), *Application of a street categorization method to the study of urban noise: the Valladolid (Spain) study*, Environmental Engineering Science, **28**, 811–817.
7. CETUR, Centre d'Etudes des Transports Urbains (1980), *Guide du Bruit des Transports Terrestres. Prévision des niveaux sonores*, CETUR, France.
8. EC (European Commision) (2003), *Adaptation and revision of the interim noise computation methods for the purpose of strategic noise mapping*, European Commision DG Environment, reference: B4-3040/2001/329750/MAR/C1.
9. EU (European Union) (2002), *Directive 2002/49/EC relating to the Assessment and Management of Environmental Noise*, Official Journal of the European Communities, No. L 189.
10. Fawcett T. (2006), *An introduction to ROC analysis*, Pattern Recognition Letters, **27**, 861–874.
11. Hand D.J., Till R.J. (2001), *A simple generalisation of the area under the ROC curve for multiple class classification problems*, Machine Learning, **45**, 171–186.
12. INE, Instituto Nacional de Estadística (2010), *Padrón municipal: cifras oficiales de población*, INE, Madrid.
13. ISO 1996-2: 2007 (2007), *Description, measurement and assessment of environmental noise. Part 2: Determination of environmental noise levels*, International Organization for Standardization, Switzerland.
14. ISO 9613-2: 1996 (1996), *Acoustic-attenuation of sound during propagation outdoors. Part 2: General method of calculation*, International Organization for Standardization, Switzerland.

15. Kruskal W.H., Wallis W.A. (1952), *Use of ranks in one-criterion variance analysis*, Journal of American Statistical Association, **47**, 583–621.

16. Mann H.B., Whitney D.R. (1947), *On a test of whether one of two random variables is stochastically larger than the other*, Annals of Mathematical Statistics, **18**, 50–60.

17. Martin J., Altman D.G. (1995), *Statistic notes: Multiple significance test: the Bonferroni method*, British Medical Journal, **310**, 170.

18. OECD, Organization for Economic Cooperation and Development (1986), *Fighting Noise: Strengthening Noise Abatement Policies*, OECD Publications, Paris.

19. OECD, Organization for Economic Cooperation and Development (1991), *Fighting noise in 1990s*, OECD Publications, Paris.

20. Rey Gozalo G., Barrigón Morillas J.M., Gómez Escobar V. (2013), *Urban streets functionality as a tool for urban pollution management*, Science of the Total Environment, 461–462, 453-–461.

21. Rey Gozalo G., Barrigón Morillas J.M., Gómez Escobar V. (2012), *Analysis of noise exposure in two small towns*, Acta Acustica united with Acustica, **98**, 884–893.

22. Shapiro S.S. (1965), *An analysis of variance test for normality (complete samples)*, Biometrika, **52** (3–4), 591–611.

23. Tomé A.R., Miranda P.M.A. (2005a), *Continuous partial trends and low-frequency oscillations of time series*, Nonlinear Processes in Geophysics, **12**, 451–460.

24. Tomé A.R., Miranda P.M.A. (2005b), *Large scale spatial structure of observed temperature trends*, Proceeding 16th Conference on Climate Variability and Change, American Meteorological Society.

25. WHO, World Health Organization (1999), *Guidelines for Community Noise*, WHO, Geneva.

26. WHO, World Health Organization (2011), *Burden of disease from environmental noise. Quantification of healthy life years lost in Europe*, WHO, Geneva.

Objetivo 6: Urban Noise Functional Stratification for Estimating Average Annual Sound Level

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Trabajo publicado en

Journal of the Acoustical Society of America (2015), Vol. 137(6), Págs. 3198-32085

Urban noise functional stratification for estimating average annual sound level

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(Received 3 October 2014; revised 19 April 2015; accepted 2 May 2015)

Road traffic noise causes many health problems and the deterioration of the quality of urban life; thus, adequate spatial noise and temporal assessment methods are required. Different methods have been proposed for the spatial evaluation of noise in cities, including the categorization method. Until now, this method has only been applied for the study of spatial variability with measurements taken over a week. In this work, continuous measurements of 1 year carried out in 21 different locations in Madrid (Spain), which has more than three million inhabitants, were analyzed. The annual average sound levels and the temporal variability were studied in the proposed categories. The results show that the three proposed categories highlight the spatial noise stratification of the studied city in each period of the day (day, evening, and night) and in the overall indicators (L_{Adn}, L_{Aden}, and L_{A24}). Also, significant differences between the diurnal and nocturnal sound levels show functional stratification in these categories. Therefore, this functional stratification offers advantages from both spatial and temporal perspectives by reducing the sampling points and the measurement time. © *2015 Acoustical Society of America*. [http://dx.doi.org/10.1121/1.4921283]

[GB] Pages: 3198–3208

I. INTRODUCTION

Noise pollution is a major environmental problem which can affect cities of any population size[1,2] and represents a risk to people's health and quality of life.[3] Recent publications relate road traffic noise to health problems that affect a large part of the world's population. The latter are a clear priority in the action plans of healthcare systems: cardiovascular diseases,[4] diabetes,[5] etc. Such health problems and the quality of life as a measure of mental and physical health are associated with noise exposure or noise annoyance, and express degrees of dissatisfaction and disturbance with regard to noise exposure.[6] Therefore, as a first step, precise determination of noise exposure is required.

Most countries today conduct demographic censuses which allow us to estimate with sufficient precision the population residing in the different buildings of a city. The Spanish Statistical Office, UK National Statistics, etc., are the responsible bodies. Nevertheless, these censuses do not facilitate determination of spatial and temporal variability in sound levels, so computational methods are usually recommended by different standards and legislations.[7,8] These methods need a comprehensive spatial and temporal registry of the vehicular traffic flow of a city for adequate characterization of the sound source. However, most cities do not possess vehicle traffic counters or such counters are generally available for main roads only.[9] Therefore, the recommended computation methods for road traffic noise need different kinds of *in situ* measurements. Noise measurements to calibrate the model and to check the precision of the estimated noise values are also necessary.[10]

In this context, our research group has been working for some years on the development of a low-cost sampling method for *in situ* noise measurements. We term this method: categorization method. On the basis of the concept of street functionality, each stratum defined by the categorization method presents a sound level variability lower than the total sound spatial variability in a city. This has shown significant improvements in the reduction of sample points and in the estimation of noise levels in unsampled streets.[1,11] Recently, its applicability has been studied for urban centers whose populations range from 2000 inhabitants to 700 000.[2] It is a firm candidate to substitute the grid method, spatial sampling strategy collected by ISO 1996-2 standard in both the old[12] and the revised.[8] Recent studies show the advantages of the categorization method compared with the grid method.[1,11] Moreover, the definition of categories allows for a simple update when there are changes in the organization of road traffic. Consequently, this method could be applied to urban planning. These methodological innovations have not gone unnoticed in the scientific community, and several authors have adopted them with some variations.[13–16]

The second variable of importance in the sampling strategy is temporal variability. Noise indicators must be determined over the period of a year according to the European Directive[7] and some international standards.[8] This assessment can easily be performed with modern acoustical instrumentation, but noise-monitoring stations are quite expensive and installation (administrative permissions) and measurements can be time-consuming. For this reason, noise-monitoring stations can only be used at very specific locations. Thus, as an alternative, the

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 0001-4966/2015/137(6)/3198/11/$30.00

best temporal strategy is to register measurements for less than a year and extrapolate from them to obtain data for a year. The duration of most of these measurements is from minutes to hours.[13,15,17,18] Unfortunately, methods for assessing the L_{Aden} (day-evening-night sound level) from short-term measurements can produce significant inaccuracies if the measurement period is not representative of the period of a year, as in the case of singular noise events.[19] This error in short-term measurement has a strong relation with sound level variability.[20,21] It is evident that the lower the variability, the less error estimation will occur, and thus, a lower duration and a lower measurement number will be necessary to estimate the sound period evaluated.

The scientific literature describes statistical models used to evaluate the evolution of noise levels, as well as an attempt to predict the levels that would be achieved with a given probability.[22,23] However, many of these studies are restricted to a particular station,[24] and the resultant mathematical models are not applicable to other temporal series.

One important step similar to the functional stratification of spatial sound variability is the functional stratification of temporal sound variability. Thus, the precision of measurements should increase and categories requiring less measurements or a minor duration of short-term measurements should be identified.

In view of the above, the main hypothesis of this study is as follows: the variability of sound levels is related to the functionality of urban streets and this variability presents a statistically significant stratification. This hypothesis considers two perspectives: the spatial one and the temporal one. From the spatial perspective, recent research[25] has demonstrated the existence of significant functional stratification in average sound values of the different time periods (L_{Ad}, L_{Ae}, L_{An}, and L_{Aden}) measured over a week in the town of Cáceres (Spain). In the present study, the functional stratification of the average values of indicators L_{Ad}, L_{Ae}, L_{An}, L_{Adn}, L_{Aden}, and L_{A24}, in measurements over a year in Madrid, which has more than three million inhabitants, was analyzed. Besides, the hypothesis was resolved from a temporal perspective which had not been studied previously. To that end, the distributions of sound levels which were registered over a year in 21 measurement stations located on different kinds of urban roads were analyzed. Last, the relation between temporal variability of sound levels and the success probability in average annual levels was studied.

Section II describes the method and the city where the measurements were carried out. Section III presents and discusses the results. Finally, Sec. IV presents the most relevant conclusions.

II. METHODS

A. Characterization and location of measurement stations

In this study, sonorous values registered over a year in 21 measurement stations in Madrid were analyzed. The measurement stations were those in which road traffic was the main noise source. Madrid is the capital of Spain, and it is strategically located in the geographic center of the Iberian Peninsula. Its population is approximately 3 255 944 inhabitants and its urban area is 605.8 km^2.[26] Madrid is the major business center of Spain and the tertiary sector, the service sector, is the main economic sector. The principal Madrid highways have a radial shape (A1, A2, A3, A4, A5, and A6), and there are also ring roads (M30, M40, M45, and M50). Madrid is 655 m above sea level, because it is on a plateau, and the surrounding mountains account for the weather, which is characterized by hot summers and relatively cold winters. The mean annual temperature and rainfall are 15.0 °C and 400 mm, respectively.[27]

The measurement stations were equipped with the 4435 Brüel & Kjær (Nærum, Denmark) analyzers and the 4184 Brüel & Kjær microphones (compliant with both IEC 61672-1[41] type 1 and ANSI S1.4[42] type 1). The microphones were used with a windscreen and windscreen holder (to protect them from adverse weather conditions) and installed on a mast 4.0 m above ground level. The parameter registered by analyzers was the continuous equivalent A-weighted level integrated every hour ($L_{Aeq,1h}$) over the years from 2006 to 2011.

The measurement stations were located on different kinds of urban roads and were classified in reference to their functionality according to the proposed definitions of the categorization method:[28]

(1) Category 1 includes those preferred streets whose function is to form connections with other Spanish towns and to interconnect those streets. In general, these streets are indicated by a system of road signs.
(2) Category 2 includes those streets that provide access to the major distribution nodes of the town. For the purpose of this study, a distribution node is considered to exist when at least four major streets meet. This definition does not include any possible nodes of preferred streets as defined in category 1, above. This category also includes streets normally used as alternatives to category 1 streets in the case of traffic saturation.
(3) Category 3 includes streets that lead to regional roads, streets that provide access from streets of category 1 and 2 to centers of interest in the town (hospitals, shopping malls, etc.), and streets that clearly allow communication between streets of category 1 and 2.
(4) Category 4 includes all other streets that clearly allow communication between the three previously defined categories of street, as well as the principal streets of the different districts of the town that were not included in the previously defined categories.
(5) Category 5 comprises the rest of the streets of the town except pedestrian-only streets.
(6) Category 6 comprises all the pedestrian-only streets.

Figure 1 shows the category in which the measurement stations are located: nine in category 1 (sampling points 1 to 9), four in category 2 (sampling points 10 to 13), four in category 3 (sampling points 14 to 17), two in category 4 (sampling points 18 and 19), and two in category 5 (sampling points 20 and 21).

B. Statistical analysis

The continuous equivalent sound level integrated every hour ($L_{Aeq,1h}$) was chosen for the different statistical tests used to analyze the results and evaluate the quality of the category classification.

First, the spatial variability of average sound levels (L_{Ad}, L_{Ae}, L_{An}, L_{Adn}, L_{Aden}, and L_{A24}) which were registered in the different measurement stations was analyzed. In this analysis of average values, the sound levels from the measurement stations which were 6.0 m further from the curb (where most of the measurement stations were located) were normalized. For corrections, the methods described in some ISO standards were considered.[8,29] Next, it was studied if sound average levels had a significant stratification according to the category where measurement stations were located. This hypothesis was resolved with the nonparametric Kruskal-Wallis and Mann-Whitney U tests.[30,31] These nonparametric tests were used because of the small number of samples, which made a normal distribution unlikely. Although the number of stations is high for these types of continuous measurements, in some categories only a few stations were available for inferential analysis. This is why, from the perspective of the categorization method basis, adjacent categories with a smaller number of measurements were grouped in a new category for the different inferential analyses. These new categories were as follows: category A comprised the measurement stations located in category 1 (nine measurement stations); category B comprised the measurement stations located in category 2 (four measurement stations) and category 3 (four measurement stations); and category C comprised the measurement stations located in category 4 (two measurement stations) and category 5 (two measurement stations).

The Kruskal-Wallis test was used to compare all the categories to identify any significant differences. When such differences were found, Mann-Whitney U tests were used to compare pairs of categories. The Mann-Whitney U test is a nonparametric test for assessing whether two independent samples or observations come from the same distribution. This test was used to compare pairs of separate categories within the same population.

In contrast to previous statistical tests, the receiver operating characteristics analysis (ROC)[32,33] was used to evaluate the discriminative capacity of the categorization method, in other words, its ability to differentiate the sound values of the sampling points between pairs of categories (category *i* versus category *j*).

Originally the categorization method, without knowing the sound values at different sampling points, classified them in different categories. After, once sound levels are recorded and from these, the ROC analysis generates a predictive ROC classification in which sound levels have statistically significant differences. Through the comparison of categories established by both methods, the categorization method's ability to discriminate sonorous values was evaluated. For this, the functional stratification carried out by the categorization method was taken as reference and in the strata proposed by ROC classification the sensitivity (capacity to include previously

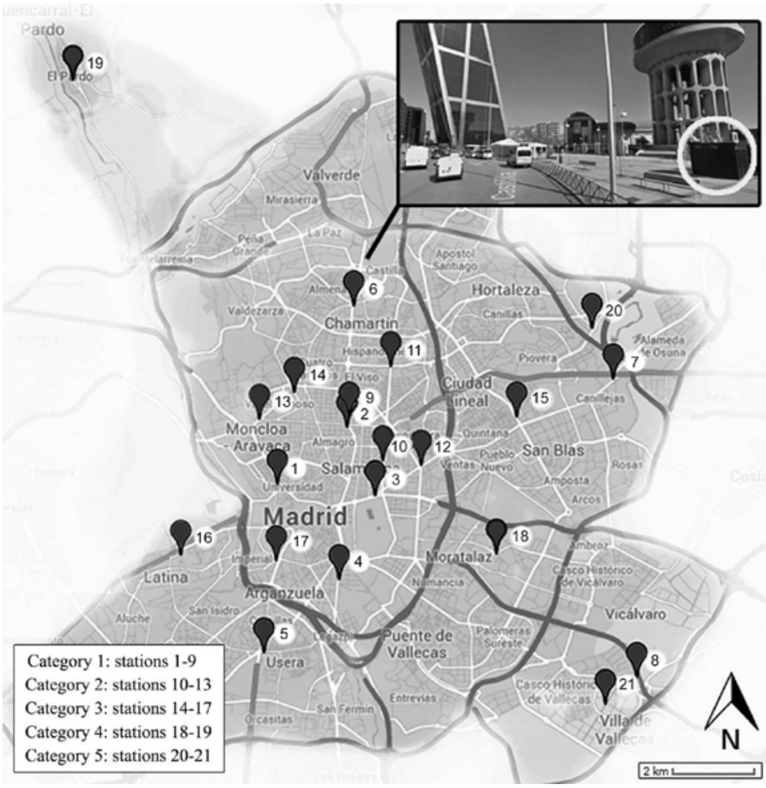

FIG. 1. Location of stations in Madrid city. Category 1: measurement points 1–9; category 2: measurement points 10–13; category 3: measurement points 14–17; category 4: measurement points 18–19; and category 5: measurement points 20–21.

assigned sampling points in the category), non-specificity (proportion of sampling points that were not initially assigned to a certain category but that the ROC classification indicated belonged to that category), and predictive values (proportion of the sampling points that the ROC classification assigned to a category that matched the categories to which they were initially assigned, relative to the total number of sampling points that the ROC classification determined for the category) were calculated with the following equations:

$$\text{sensitivity} = \frac{\text{True } i}{\text{True } i + \text{False } j}, \quad (1)$$

$$\text{non-specificity} = \frac{\text{False } i}{\text{True } j + \text{False } i}, \quad (2)$$

$$\text{predictive value} = \frac{\text{True } i}{\text{True } i + \text{False } i}, \quad (3)$$

where [see Fig. 2(a)]

(1) True *i*: number of sampling points assigned correctly to category *i* by ROC classification.
(2) False *i*: number of sampling points assigned incorrectly to category *i* by ROC classification.
(3) True *j*: number of sampling points assigned correctly to category *j* by ROC classification.
(4) False *j*: number of sampling points assigned incorrectly to category *j* by ROC classification.

From the depiction of sensitivity and non-specificity of each of the sampling point is obtained a ROC curve [see Fig. 2(b)]. The optimal cut-off point is the last sampling point belonging to category *i* (ROC classification) and it has the highest sensitivity and specificity (1 – non-specificity) jointly in the ROC curve. This point is obtained when the distance from the point (0,1) is the lowest. This distance was calculated with the following equation:

$$\text{distance} = \sqrt{(\text{non-specificity})^2 + (1 - \text{sensitivity})^2}. \quad (4)$$

Therefore, the optimal cut-off value is the average of sound values registered in the optimal cut-off point and in the previous sampling point with a lower value.

A ROC curve is a two-dimensional depiction of classifier performance, but a common method to reduce ROC performance to a single scalar value representing expected performance is to calculate the area under the ROC curve (AUC).[34,35] The formal definition is

$$\text{AUC} = \int_0^1 \text{ROC}(v)dv, \quad (5)$$

where v is the value of sensitivity-non-specificity sampling points.

AUC value will always be between 0 and 1.0. Therefore, values closer to 1.0 have better discriminatory power. However, because random guessing produces the diagonal line between (0,0) and (1,1), which has an area of 0.5. Values between 0.5 and 0.7 indicate low precision, values between 0.7 and 0.9 are considered useful and values greater than 0.9 indicate high precision.[36] The AUC has an important

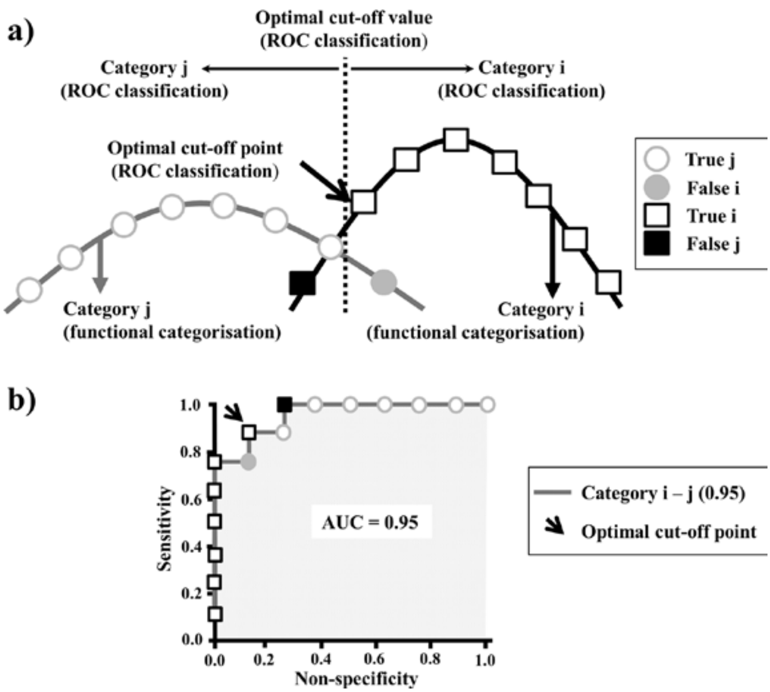

FIG. 2. ROC classification examples: the evaluation of (a) the discrimination ability in the categorization method and (b) the representation of a ROC curve.

statistical property: the AUC of a classifier is equivalent to the probability that the classifier will rank a randomly chosen category *i* higher than a randomly chosen category *j*.[33]

Regarding the predictive value [Eq. (3)], known by Fawcett[33] as precision, is a ratio that indicates the relation between the functional stratification and the ROC classification of sound levels. The closer to 100%, the better the prediction of the classification of sound levels by functional categorization.

After studying the spatial variability of average sound levels, our aim was to analyze if there was a spatial stratification of temporal variability of $L_{Aeq,1h}$ levels registered in the different measurement stations. To do this, the distribution of sound levels registered over the year was analyzed. The first hypothesis concerned whether the distributions presented significant differences from normal distribution (p-value ≤ 0.001). This hypothesis was resolved by the Kolmogorov test and all sound distributions had significant differences in respect of normal distribution (p-value ≤ 0.001), similar to information found in road traffic sound level distribution studies.[37] Therefore, in this study parameters such as mean, standard deviation, variance, skewness, kurtosis, etc., were not used. The parameters of median, percentile, and different types of range were analyzed: R_{50} range or interquartile range (percentile P_{75} − percentile P_{25}), R_{80} range ($P_{90} - P_{10}$), R_{90} range ($P_{95} - P_{5}$), R_{95} range ($P_{97.5} - P_{2.5}$), and R_{99} ($P_{99.5} - P_{0.5}$). The types of range and the differences between median and percentiles gave information about the form of distribution and thus about the variability of sound levels. Moreover, recent studies show the importance of analyzing the percentiles because of their relation with the soundscape perception.[38,39] Average values of these parameters were compared among different categories to look for significant stratification. For this reason, the Kruskal-Wallis test and Mann-Whitney U test were used.

Finally, it was analyzed if the temporal variability registered in the different measurement stations had a significant relation with the success probability of the annual average sound level. The success probability was obtained by the percentage of values $L_{Aeq,1h}$ which were included in the interval $L_{A24} \pm \varepsilon$ ($\varepsilon = 0.5$, 1, 2, and 3 dB). The hypothesis was resolved by Spearman's rho.

III. RESULTS AND DISCUSSION

A. Analysis of average sound level variability

Table I shows the mean values of the different sonorous indicators: L_{Ad}, L_{Ae}, L_{An}, L_{Adn}, L_{Aden}, and L_{A24}. In all the sub-day periods studied [day (from 7.0 a.m to 7.0 p.m.) (L_{Ad}), evening (from 7.0 p.m. to 11.0 p.m.) (L_{Ae}), night (from 11.0 p.m. to 7.0 a.m.) (L_{An}), and over the whole day (L_{Adn}, L_{Aden}, and L_{A24})], there is a clear tendency of noise levels to decrease as the category number increases.

TABLE I. Average values and standard deviation of L_{Ax} values of the sonorous indicators. The results are shown separately for each category.

	$\overline{L_{Ax}} \pm \sigma$ (dB)				
Indicator	Category 1	Category 2	Category 3	Category 4	Category 5
L_{Ad}	70.5 ± 1.3	68.5 ± 1.2	65.1 ± 1.9	63.6 ± 0.8	62.5 ± 0.9
L_{Ae}	70.1 ± 1.0	67.8 ± 1.1	64.4 ± 1.6	63.1 ± 1.1	61.4 ± 0.3
L_{An}	66.8 ± 0.9	62.5 ± 1.3	60.4 ± 1.7	58.0 ± 0.6	55.8 ± 0.7
L_{Adn}	73.8 ± 1.6	69.6 ± 1.2	67.6 ± 1.2	65.8 ± 0.2	63.4 ± 1.1
L_{Aden}	74.6 ± 0.9	71.4 ± 1.3	68.5 ± 2.0	66.7 ± 1.2	65.2 ± 0.2
L_{A24}	68.6 ± 1.0	65.6 ± 1.3	62.4 ± 1.5	60.4 ± 1.0	59.1 ± 0.0

Then, it was analyzed if the differences in average values of sonorous indicators among different categories were statistically significant. Before resolving this hypothesis, as mentioned previously, because of the number of data by categories, the categories were grouped into three new categories: category A (category 1), category B (categories 2 and 3), category C (categories 4 and 5). Throughout this study and in the posterior analysis, only these three categories were used.

The hypothesis was resolved first by the Kruskal-Wallis test. This test indicated significant differences (p-value ≤ 0.001) for all the sonorous indicators studied. Thus, the Mann-Whitney U test was then applied to analyze the differences among category pairs (Table II). As shown in Table II, the Mann-Whitney U test found significant differences (p-value ≤ 0.05) among all pairs of categories studied for all sound indicators analyzed. This finding indicates that the functional stratification of noise levels observed in previous weekly measurement studies is also found for annual measurements and is equally present in all the studied temporal periods. Thus, the categorization method is a very powerful method of spatial noise assessment, allowing the noise values of cities to be characterized by using a reduced number of sampling points.

Finally, to corroborate the quality of the previous results and to obtain more information about the categorization method, the classification capacity of this method was studied via ROC analysis. The results of this analysis are shown in Fig. 3. From the results shown in these graphs, the following can be noted:

(1) Regarding the ROC curve (sensitivity and non-specificity), the AUC indicator (capacity of the method to discriminate correctly the sound levels for two different categories) present values better than 0.94 for all pairs of categories of all sound indicators [see Figs. 3(a)–3(f)]. Thus, the values indicate high precision. These high

TABLE II. Results of the Mann-Whitney U test applied to pairs of categories.

	Category	A	B
L_{Ad}	B	9.9×10^{-4} [a]	—
	C	2.8×10^{-3} [b]	2.8×10^{-2} [c]
L_{Ae}	B	3.3×10^{-4} [a]	—
	C	2.8×10^{-3} [b]	8.1×10^{-3} [b]
L_{An}	B	8.2×10^{-5} [a]	—
	C	2.8×10^{-3} [b]	8.1×10^{-3} [b]
L_{Adn}	B	3.3×10^{-4} [a]	—
	C	2.8×10^{-3} [b]	1.1×10^{-2} [c]
L_{Aden}	B	8.2×10^{-5} [a]	—
	C	2.8×10^{-3} [b]	8.1×10^{-3} [b]
L_{A24}	B	8.2×10^{-5} [a]	—
	C	2.8×10^{-3} [b]	8.1×10^{-3} [b]

[a]Significant at $p \leq 0.001$.
[b]Significant at $p \leq 0.01$.
[c]Significant at $p \leq 0.05$.

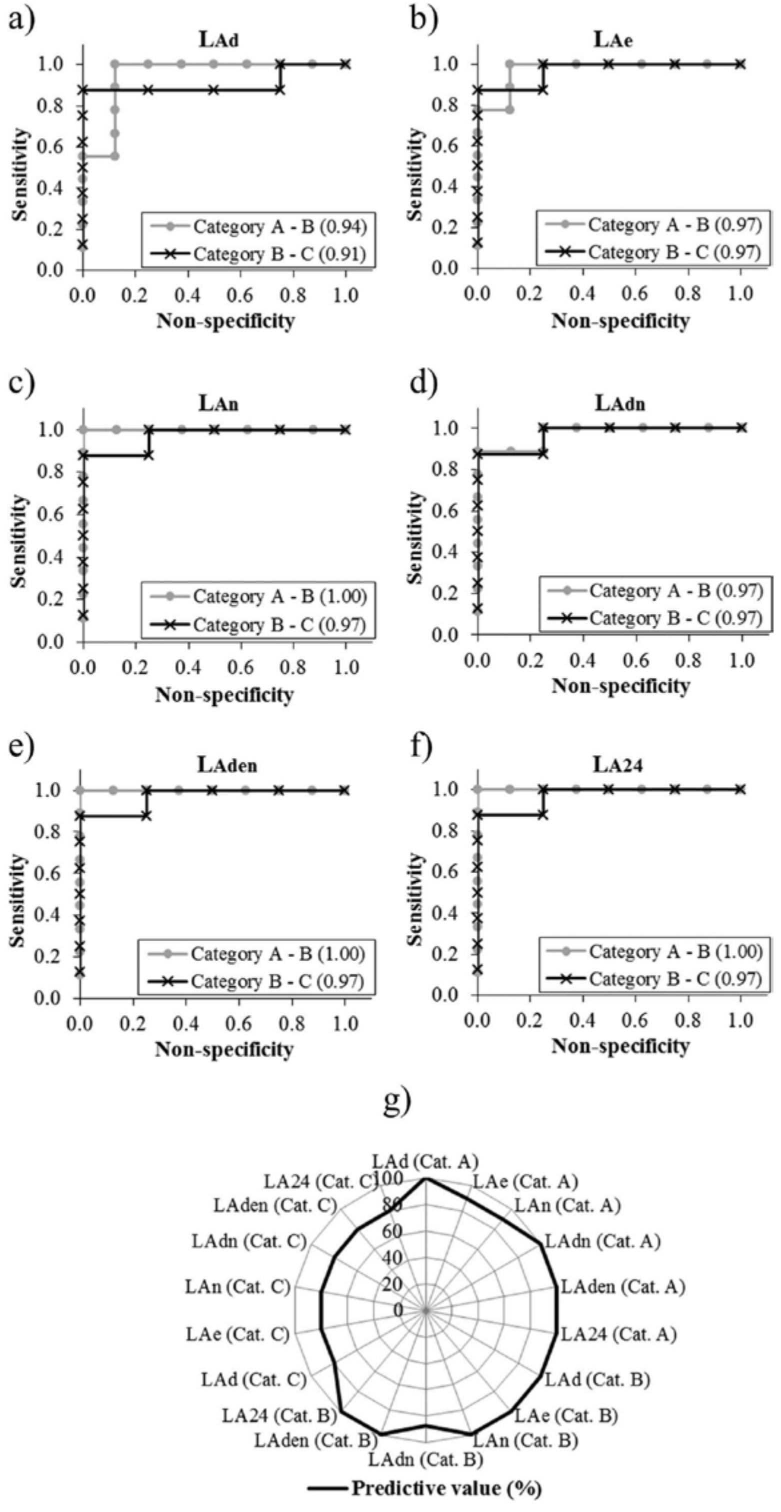

FIG. 3. Results of ROC analysis of sound indicators: (a) L_{Ad}, (b) L_{Ae}, (c) L_{An}, (d) L_{Adn}, (e) L_{Aden}, (f) L_{A24}, and (g) predictive value.

TABLE III. Upper and lower limit obtained from ROC classification for the L_{Ax} (dB) values in the category A, B, and C.

Indicator (dB)	Limit	Category A	Category B	Category C
L_{Ad}	Upper	72.9	68.9	64.4
	Lower	68.9	64.4	61.8
L_{Ae}	Upper	72.0	68.3	64.0
	Lower	68.3	64.0	61.2
L_{An}	Upper	68.7	65.0	59.2
	Lower	65.0	59.2	55.3
L_{Adn}	Upper	76.3	71.9	66.8
	Lower	71.9	66.8	62.6
L_{Aden}	Upper	76.3	73.3	67.7
	Lower	73.3	67.7	65.1
L_{A24}	Upper	70.5	67.4	61.6
	Lower	67.4	61.6	59.1

AUC values [Eq. (4)] indicate, in turn, higher values of sensitivity [Eq. (1)], close to 100%, and very low values of non-specificity [Eq. (2)], close to 0%. The optimal cut-off values of categories A, B, and C are determined from ROC curves, and the results are showed in Table III. These values show the upper and lower limit of sound values registered in different categories according to ROC classification.

(2) Finally, the predictive values of the different strata [Eq. (3)] are very good [see Fig. 3(g)]: categories A and B present values of 100% [except L_{Ae} (category A), L_{An} (category A), and L_{Adn} (category B) which present values of 90%] and category C presents values of 80% for the different sonorous index.

Therefore, for each of the three periods analyzed and for the overall indicators (L_{Adn}, L_{Aden}, and L_{A24}), the results showed the method had high discrimination and predictive capacity. These results suggest a great advance in the validity of the categorization method because of its application to an agglomeration with more than three million inhabitants and sound measurements taken over a year.

Thus, because of its high discrimination and prediction capacity, this procedure seems to be very suitable for further applications such as noise prediction and the design of environmental policy.

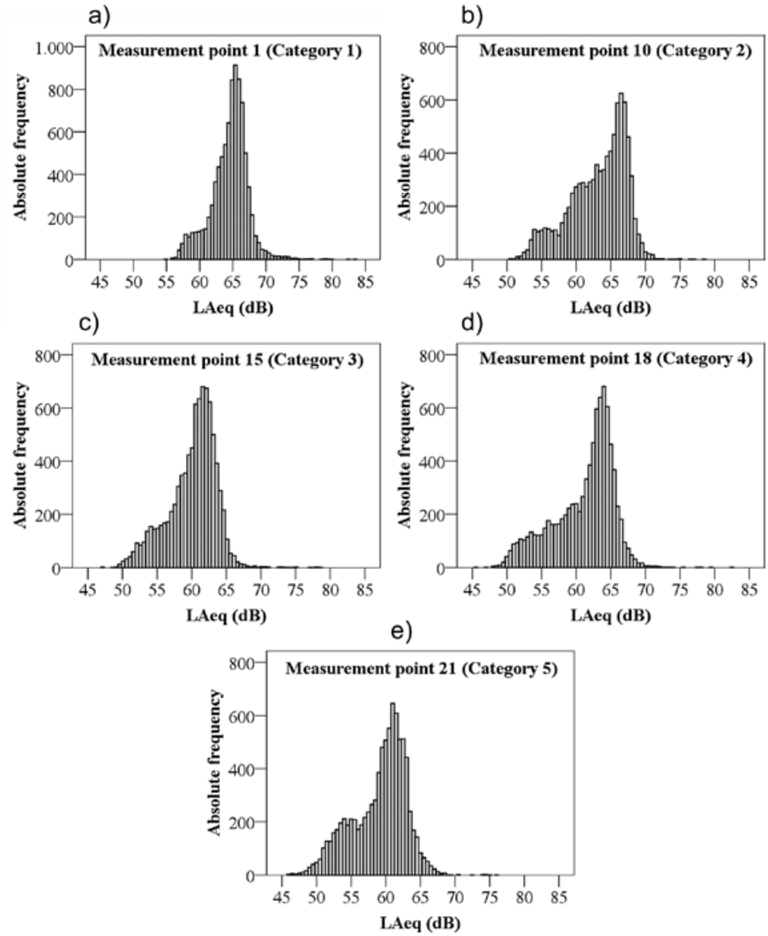

FIG. 4. Histogram of $L_{Aeq,1h}$ in (a) category 1, (b) category 2, (c) category 3, (d) category 4, and (e) category 5.

TABLE IV. Average values and standard deviation of the different ranges (R_{50}, R_{80}, R_{90}, R_{95}, and R_{99}) of $L_{Aeq,1h}$ values registered in the measurement stations. The results are shown separately for each category. Range R_{50} describes the difference between percentiles P_{75} and P_{25} (also named interquartile range), R_{80} range is the difference between P_{90} and P_{10}, R_{90} range is the difference between P_{95} and P_5, R_{95} range is the difference between $P_{97.5}$ and $P_{2.5}$ and R_{99} range is the difference between $P_{99.5}$ and $P_{0.5}$.

	Range (dB)				
Category	R_{50}	R_{80}	R_{90}	R_{95}	R_{99}
A	3.5 ± 0.5	7.2 ± 0.6	9.5 ± 0.6	11.2 ± 0.5	14.8 ± 1.6
B	4.9 ± 0.7	9.5 ± 1.0	12.1 ± 1.1	14.2 ± 1.0	17.9 ± 1.0
C	5.6 ± 0.7	11.2 ± 0.9	14.0 ± 1.2	16.2 ± 1.6	21.0 ± 2.7

B. Analysis of temporal sound variability

First, before descriptive and inferential analysis of the different statistic parameters related to the variability of sound levels, the distribution of values $L_{Aeq,1h}$ was analyzed over the year. Figure 4 shows different histogram models obtained for measurement stations located in different categories. *A priori*, it can be observed that the distributions differ among categories and are also different from normal distribution. Figure 4(a) (category 1) has an approximately symmetrical distribution, albeit leptokurtic (slender). The remaining histograms have a noticeably negative skew (left-skewed) which increases when the number of category increases as well. In contrast to categories 2 and 3 [Figs. 4(b) and 4(c)], categories 4 and 5 [Figs. 4(d) and 4(e)] do not show a progressive decrease of sound levels from average values to low values.

Second, all hypotheses were resolved with the aid of statistic inference. The Kolmogorov test verified that all distributions had significant differences from normal distribution (p-value ≤ 0.001). Thus, different types of range were taken as a measure of the sound variability: range R_{50} derives from the difference of percentiles P_{75} and P_{25} (also named interquartile range); R_{80} range is the difference between P_{90} and P_{10}; R_{90} range is the difference between P_{95} and P_5; R_{95} range is the difference between $P_{97.5}$ and $P_{2.5}$; and R_{99} range is the difference between $P_{99.5}$ and $P_{0.5}$. These types of range give the information about distribution and therefore about the sound variability regarding distance from the median. Table IV shows the average values and the standard deviation of ranges in different categories. A decreasing tendency is observed from category A to category C.

These differences in range were analyzed with Kruskal-Wallis and Mann-Whitney U tests. The Kruskal-Wallis test showed significant differences (p-value ≤ 0.001) for all the ranges studied. Thus, the Mann-Whitney U test was then applied to analyze the differences among category pairs (Table V). As shown in Table V, the Mann-Whitney U test found significant differences (p-value ≤ 0.05) among all pairs of categories for all ranges analyzed. Consequently, the functionality of roads allows significant stratification of the variability of sound levels registered over the year. This is very important from the perspective of temporal strategy as it allows estimation of the annual average sound level because it permits reduction in the number or the time of measurements.

TABLE V. Results of the Mann-Whitney U test applied to pairs of categories.

	Category	A	B
R_{50}	B	1.8×10^{-3} [a]	—
	C	2.8×10^{-3} [a]	4.9×10^{-2} [b]
R_{80}	B	1.3×10^{-3} [a]	—
	C	6.9×10^{-3} [a]	2.8×10^{-2} [b]
R_{90}	B	1.6×10^{-4} [c]	—
	C	2.8×10^{-3} [a]	2.8×10^{-2} [b]
R_{95}	B	8.2×10^{-5} [c]	—
	C	2.8×10^{-3} [a]	2.8×10^{-2} [b]
R_{99}	B	2.5×10^{-3} [a]	—
	C	2.8×10^{-3} [a]	2.8×10^{-2} [b]

[a]Significant at $p \leq 0.01$.
[b]Significant at $p \leq 0.05$.
[c]Significant at $p \leq 0.001$.

The following objective was to look for the differences among the sound levels which meant that the types of range were significantly different among the three analyzed categories. To do this, the distances on both sides of the median, whose sum is the range: percentile P_x − median (M_e) and median (M_e) − percentile P_x were analyzed. Thus, significant stratification caused by differences between average and low sound values (typical difference between diurnal and nocturnal sound values) or between average and high sound values (typical difference between diurnal values) could be detected. The averages of these differences between percentiles and medians are shown in Table VI. It can be seen first that the $P_x - M_e$ value is quite superior to the $M_e - P_x$ value in the different types of range. This difference was foreseeable because the different distributions have a noticeable negative skew (Fig. 4). Second, there is a higher decrease in the $P_x - M_e$ value from category A to category C than in the $M_e - P_x$ value. These differences were analyzed through the Mann-Whitney U test and the results are shown in Table VII. The results show that differences between

TABLE VI. Average values of differences among percentiles (P_x) and median (M_e) and vice versa for different types of range (R_{50}, R_{80}, R_{90}, R_{95}, and R_{99}). The results are shown separately for each category.

	R_{50} (dB)		R_{80} (dB)		R_{90} (dB)		R_{95} (dB)		R_{99} (dB)	
Category	$P_{75} - M_e$	$M_e - P_{25}$	$P_{90} - M_e$	$M_e - P_{10}$	$P_{95} - M_e$	$M_e - P_5$	$P_{97.5} - M_e$	$M_e - P_{2.5}$	$P_{99.5} - M_e$	$M_e - P_{0.5}$
A	2.1	1.4	4.8	2.4	6.3	3.1	7.2	4.0	8.4	6.4
B	3.0	2.0	6.2	3.3	7.9	4.2	8.9	5.2	10.4	7.5
C	3.6	2.0	7.9	3.4	9.6	4.3	10.9	5.4	13.0	8.0

TABLE VII. Results of the Mann-Whitney U test applied to pairs of categories.

	Category	A	B
$P_{75} - M_e$	B	5.2×10^{-3} [a]	—
	C	1.1×10^{-2} [b]	4.9×10^{-2} [b]
$P_{90} - M_e$	B	3.3×10^{-3} [a]	—
	C	6.9×10^{-3} [a]	1.6×10^{-2} [b]
$P_{95} - M_e$	B	2.4×10^{-3} [a]	—
	C	6.9×10^{-3} [a]	4.9×10^{-2} [b]
$P_{97.5} - M_e$	B	1.2×10^{-3} [a]	—
	C	6.9×10^{-3} [a]	6.1×10^{-2} [c]
$P_{99.5} - M_e$	B	3.3×10^{-3} [a]	—
	C	6.9×10^{-3} [a]	2.7×10^{-2} [b]
M_e -P_{25}	B	5.9×10^{-3} [a]	—
	C	1.6×10^{-3} [a]	7.3×10^{-1} [c]
$M_e - P_{10}$	B	2.8×10^{-3} [a]	—
	C	6.8×10^{-3} [a]	9.3×10^{-1} [c]
$M_e - P_5$	B	3.4×10^{-3} [a]	—
	C	6.9×10^{-3} [a]	1.0 [c]
$M_e - P_{2.5}$	B	6.1×10^{-3} [a]	—
	C	1.1×10^{-2} [b]	6.1×10^{-1} [c]
$M_e - P_{0.5}$	B	1.0×10^{-1} [c]	—
	C	7.6×10^{-2} [c]	5.7×10^{-1} [c]

[a]Significant at $p \leq 0.01$.
[b]Significant at $p \leq 0.05$.
[c]Non-significant difference ($p > 0.05$).

$P_x - M_e$ values, as occurs in the different types of range, have significant differences (p-value ≤ 0.05). However, the differences between $M_e - P_x$ values between categories B and C in all cases have a p-value > 0.05 (not significant). Therefore, this result corroborates the hypothesis that the stratification of variability among the three analyzed categories is largely the result of the difference between average sound values and low sound values.

Finally, the differences between sound values registered in the diurnal period (L_{Ad}) and nocturnal period (L_{An}) and between the diurnal period (L_{Ad}) and evening period (L_{Ae}) in the different categories were analyzed. The average values of these differences are shown in Table VIII. The results show that differences are more noticeable between different categories in $L_{Ad} - L_{An}$. Then, the averages of these differences were analyzed through the Mann-Whitney U test and the results are shown in Table IX. The results show that differences between nocturnal and diurnal levels are significant among the three categories analyzed. This result differs from results published in previous works, where their categories were reduced to two significantly distinguishable categories.[40] As regards differences between the diurnal and evening level, as was expected from descriptive analyses there were no significant differences (p-value > 0.05).

TABLE VIII. Average values of differences among sound indicators L_{Ad}, L_{An}, and L_{Ae} for each category.

Category	$L_{Ad} - L_{An}$ (dB)	$L_{Ad} - L_{Ae}$ (dB)
A	4.1	0.3
B	5.7	0.3
C	7.2	0.5

TABLE IX. Results of the Mann-Whitney U test applied to pairs of categories.

	Category	A	B
$L_{Ad} - L_{An}$	B	2.5×10^{-3} [a]	—
	C	2.8×10^{-3} [a]	2.8×10^{-2} [b]
$L_{Ad} - L_{Ae}$	B	5.4×10^{-1} [c]	—
	C	7.1×10^{-1} [c]	9.3×10^{-1} [c]

[a]Significant at $p \leq 0.01$.
[b]Significant at $p \leq 0.05$.
[c]Non-significant difference ($p > 0.05$).

The two last analyses resolved the hypothesis that the significant stratification of temporal sound variability among different categories was mainly owed to differences between diurnal and nocturnal sound values.

C. Relation between temporal sound variability and probability of success

In Sec. III B, it was demonstrated that average temporal sound variability through the ranges R_{80}, R_{90}, R_{95}, and R_{99} had a significant functional stratification in the studied categories. This is important from the perspective of estimating the average annual sound value because it could determine those roads which need less time or fewer measurements.

This hypothesis of a relation between the different types of range and the probability of success was analyzed through Spearman's rho. The success probability was obtained from the percentage of values $L_{Aeq,1h}$ which were included in the interval $L_{A24} \pm \varepsilon$ ($\varepsilon = 0.5$, 1, 2, and 3 dB). The Spearman's rho results are shown in Table X. The correlation coefficients are very near to unity and with a p-value ≤ 0.01 indicate a highly significant relation between range and the probability of success.

In short, the categorization method not only allows significant functional stratification of average annual sound values to be carried out but also functional stratification of temporal sound variability. This could allow important savings in terms of the number and the time of measurements from spatial and temporal perspectives.

IV. CONCLUSIONS

The present study which was carried out in an agglomeration with more than three million inhabitants (Madrid) shows that the categorization method is an adequate tool for assessment of temporal and spatial noise, thus enabling the functional stratification of noise in cities to be identified. Therefore, this method has advantages in terms of the reduction of sampling points and measurement time.

The analysis of sound levels registered over a year in the 21 measurement stations located on roads with different functionality implies the following additional conclusions:

(1) The mean values of the analyzed sound indicators (L_{Ad}, L_{Ae}, L_{An}, L_{Adn}, L_{Aden}, and L_{A24}) decrease as the number of the category increases. A comparison of sound levels with the Kruskal-Wallis and Mann-Whitney U tests shows that the differences among values of functional

TABLE X. Results for Spearman's rho between types of range (R_{50}, R_{80}, R_{90}, R_{95}, and R_{99}) and probability of success (% $L_{Aeq,1h}$ values in the interval $L_{A24} \pm \varepsilon$ for $\varepsilon = 0.5$, 1, 2, and 3 dB).

	% $L_{Aeq,1h}$ values in the interval $L_{A24} \pm \varepsilon$			
Range	$\varepsilon = 0.5$	$\varepsilon = 1.0$	$\varepsilon = 2.0$	$\varepsilon = 3.0$
R_{50}	−0.94[a]	−0.95[a]	−0.98[a]	−0.98[a]
R_{80}	−0.92[a]	−0.95[a]	−0.95[a]	−0.96[a]
R_{90}	−0.89[a]	−0.92[a]	−0.93[a]	−0.95[a]
R_{95}	−0.87[a]	−0.89[a]	−0.91[a]	−0.92[a]
R_{99}	−0.58[b]	−0.64[b]	−0.70[a]	−0.77[a]

[a]Significant at $p \leq 0.001$.
[b]Significant at $p \leq 0.01$.

categories are statistically significant for a confidence interval of 95%. This finding demonstrates the applicability of the categorization method to spatial assessment, as it can be applied to all periods of the day.

(2) When analyzing the discrimination capacity of the categorization method using predictive ROC classification, we found that all the pairs of categories presented AUC values above 0.94, indicating the high precision of the method. These values are the result of sensitivity and non-specificity close to 100% and 0%, respectively. Also, ROC classification has a good predictive capacity for non-measured values. A 100% predictive capacity was found in categories A and B [except L_{Ae} (category A), L_{An} (category A), and L_{Adn} (category B) which have values of 90%] and 80% predictive capacity in category C for all sonorous indicators.

(3) The mean values of the analyzed range types (R_{50}, R_{80}, R_{90}, R_{95}, and R_{99}) decrease from category A to category C. A comparison of mean values with the Kruskal-Wallis and Mann-Whitney U tests showed that the differences among values of functional categories are statistically significant for a confidence interval of 95%. This finding demonstrates the applicability of the categorization method to temporal assessment. This significant functional stratification of temporal variability was mainly owed to the significant differences between average and low sound values (percentile P_x − median M_e). Also, the difference between diurnal and nocturnal sound levels ($L_{Ad} - L_{An}$) presented functional stratification in the three analyzed categories. This has never been achieved in previous studies.

(4) The highly significant relation among types of range as a measurement of temporal variability and the success probability of average annual sound value corroborate the advantages from temporal perspective of the traffic roads stratification according to their functionality.

ACKNOWLEDGMENTS

The authors wish to thank the Government of Extremadura, the Regional Ministry of Economy, Trade and Innovation and the European Social Fund for funding the project. This work was also partially supported by the Spanish Ministerio de Economía y Competitividad (Project TRA2012-37117) and the European Regional Development Fund (ERDF).

[1]G. Rey Gozalo, J. M. Barrigón Morillas, and V. Gómez Escobar, "Analysis of noise exposure in two small towns," Acta Acust. Acust. **98**, 884–893 (2012).

[2]G. Rey Gozalo, J. M. Barrigón Morillas, and V. Gómez Escobar, "Urban streets functionality as a tool for urban pollution management," Sci. Total Environ. **461–462**, 453–461 (2013).

[3]World Health Organization, "Burden of disease from environmental noise. Quantification of healthy life years lost in Europe" (World Health Organization, Geneva, 2011).

[4]W. Babisch, "Updated exposure-response relationship between road traffic noise and coronary heart diseases: A meta-analysis," Noise Health **16**, 1–9 (2014).

[5]M. Sørensen, Z. J. Andersen, R. B. Nordsborg, T. Becker, A. Tjønneland, K. Overvad, and O. Raaschou-Nielsen, "Long-term exposure to road traffic noise and incident diabetes: A cohort study," Environ. Health Persp. **121**, 217–222 (2013).

[6]J. Dratva, E. Zemp, D. F. Dietrich, P-O. Bridevaux, T. Rochat, C. Schindler, and M. W. Gerbase, "Impact of road traffic noise annoyance on health-related quality of life: Results from a population-based study," Qual. Life Res. **19**, 37–46 (2010).

[7]European Commission, "Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise (END)" (Official Journal L 189 12-26, European Parliament and the Council of the European Union, Brussels, Belgium, 2002).

[8]ISO 1996-2, *Description, Measurement and Assessment of Environmental Noise. Part 2: Determination of Environmental Noise Levels* (International Organization for Standardization, Geneva, Switzerland, 2007).

[9]M. Ausejo, M. Recuero, C. Asensio, I. Pavón, and J. M. López, "Study of precision, deviations and uncertainty in the design of the strategic noise map of the macrocenter of the city of Buenos Aires, Argentina," Environ. Model. Assess. **15**, 125–135 (2009).

[10]European Commission Working Group–Assessment of Exposure to Noise, "Good practice guide for strategic noise mapping and the production associated data on noise exposure, Version 2," European Commission, Brussels, Belgium, 2007.

[11]J. M. Barrigón Morillas, V. Gómez Escobar, J. Trujillo Carmona, J. A. Méndez Sierra, R. Vílchez-Gómez, and F. J. Carmona del Río, "Analysis of the prediction capacity of a categorization method for urban noise assessment," Appl. Acoust. **72**, 760–771 (2011).

[12]ISO 1996-2, *Description and Measurement of Environmental Noise. Part 2: Acquisition of Data Pertinent to Land Use* (International Organization for Standardization, Geneva, Switzerland, 1987).

[13]H. Doygun and D. K. Gurun, "Analyzing and mapping spatial and temporal dynamics of urban traffic noise pollution: A case study in Kahramanmaras, Turkey," Environ. Monit. Assess. **142**, 65–72 (2008).

[14]J. H. Ko, S. I. Chang, and B. C. Lee, "Noise impact assessment by utilizing noise map and GIS: A case study in the city of Chungju, Republic of Korea," Appl. Acoust. **72**, 544–550 (2011).

[15]J. Romeu, T. Genescà, T. Pàmies, and S. Jiménez, "Street categorization for the estimation of day levels using short-term measurements," Appl. Acoust. **72**, 569–577 (2011).

[16]E. Suárez and J. L. Barros, "Traffic noise mapping of the city of Santiago de Chile," Sci. Total Environ. **466–467**, 539–546 (2014).

[17]P. H. Zannin and D. Queiroz de Sant'Ana, "Noise mapping at different stages of a freeway redevelopment project—A case study in Brazil," Appl. Acoust. **72**, 479–486 (2011).

[18]C. Prieto Gajardo and J. M. Barrigón Morillas, "Stabilisation patterns of hourly urban sound levels," Environ. Monit. Assess. **187**, 1–16 (2014).

[19]C. Prieto Gajardo, J. M. Barrigón Morillas, V. Gómez Escobar, R. Vílchez-Gómez, and G. Rey Gozalo, "Effects of singular noisy events on long-term environmental noise measurements," Pol. J. Environ. Stud. **23**, 2007–2017 (2014). Available at http://www.pjoes.com/pdf/23.6/Pol.J.Environ.Stud.Vol.23.No.6.2007-2017.pdf.

[20]R. Makarewicz and M. Gałuszka, "Empirical revision of noise mapping," Appl. Acoust. **72**, 578–581 (2011).

[21]J. M. Barrigón Morillas and C. Prieto Gajardo, "Uncertainty evaluation of continuous noise sampling," Appl. Acoust. **75**, 27–36 (2014).

[22]R. E. De Vor, P. D. Shomer, W. A. Kline, and R. D. Neathamer, "Development of temporal sampling strategies for monitoring noise," J. Acoust. Soc. Am. **66**, 763–771 (1979).
[23]P. D. Schomer and R. E. De Vor, "Temporal sampling requirement for estimations of long-term average sound levels in the vicinity of airports," J. Acoust. Soc. Am. **69**, 713–719 (1981).
[24]E. Gaja, A. Gimenez, S. Sancho, and A. Reig, "Sampling techniques for the estimation of the annual equivalent noise level under urban traffic conditions," Appl. Acoust. **64**, 43–53 (2003).
[25]G. Rey Gozalo, J. M. Barrigón Morillas, and V. Gómez Escobar, "Analyzing nocturnal noise stratification," Sci. Total Environ. **479–480**, 39–47 (2014).
[26]INE, "Population, area and density by municipality," National Statistics Institute, Madrid, Spain, 2012.
[27]AEMET, "Summary guide of Spanish climate (1981–2010)," State Meteorological Agency, Madrid, Spain, 2012.
[28]J. M. Barrigón Morillas, V. Gómez Escobar, J. A. Méndez Sierra, R. Vílchez-Gómez, J. M. Vaquero, and J. Trujillo Carmona, "A categorization method applied to the study of urban road traffic noise," J. Acoust. Soc. Am. **117**, 2844–2852 (2005).
[29]ISO 9613-2, *Attenuation of Sound During Propagation Outdoors. Part 2: General Method of Calculation* (International Organization for Standardization, Geneva, Switzerland, 1996).
[30]H. B. Mann and D. R. Whitney, "On a test of whether one of two random variables is stochastically larger than the other," Ann. Math. Stat. **18**, 50–60 (1947).
[31]W. H. Kruskal and W. A. Wallis, "Use of ranks in one-criterion variance analysis," J. Am. Stat. Assoc. **47**, 583–621 (1952).
[32]D. J. Hand and R. J. Till, "A simple generalisation of the area under the ROC curve for multiple class classification problems," Mach. Learn. **45**, 171–186 (2001).
[33]T. Fawcett, "An introduction to ROC analysis," Pattern Recogn. Lett. **27**, 861–874 (2006).
[34]J. A. Hanley and B. J. McNeil, "The meaning and use of the area under a receiver operating characteristic (ROC) curve," Radiology **143**, 29–36 (1982).
[35]A. P. Bradley, "The use of the area under the ROC curve in the evaluation of machine learning algorithms," Pattern Recogn. **30**, 1145–1159 (1997).
[36]J. A. Swets, "Measuring the accuracy of diagnostic systems," Science **240**, 1285–1293 (1988).
[37]C. G. Don and I. G. Rees, "Road traffic sound level distributions," J. Sound Vib. **100**, 41–53 (1985).
[38]G. Brambilla, L. Maffei, M. Di Gabriele, and V. Gallo, "The perceived quality of soundscape in three urban parks in Rome," J. Acoust. Soc. Am. **134**, 782–790 (2013).
[39]G. Brambilla, V. Gallo, F. Asdrubali, and F. D'Alessandro, "The perceived quality of soundscape in three urban parks in Rome," J. Acoust. Soc. Am. **134**, 832–839 (2013).
[40]S. Jiménez, M. Genescà, J. Romeu, and A. Sanchez, "Estimation of night traffic noise levels," Acta Acust. Acust. **94**, 563–567 (2008).
[41]IEC 61672-1, Electroacoustics – Sound level meters – Part 1: Specifications (International Electrotechnical Commission, Geneva, Switzerland, 2002).
[42]ANSI S1.4 (R2006), Specification for sound level meters (American National Standards Institute, New York, 1983).

Objetivo 7: Numerical Analisis of Acoustic Barriers with a Diffusive Surface Using a 2.5D Boundary Element Model

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Trabajo publicado en

Journal of Computational Acoustics (2015), Vol. 23(3)

Journal of Computational Acoustics, Vol. 23 (2015) 1550009 (29 pages)

DOI: 10.1142/S0218396X15500095

INTERNATIONAL ASSOCIATION
FOR MATHEMATICS AND
COMPUTERS IN SIMULATION

Numerical Analysis of Acoustic Barriers with a Diffusive Surface Using a 2.5D Boundary Element Model

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Received 18 September 2014
Accepted 2 February 2015
Published 17 April 2015

Acoustic barriers are a well-known environmental noise mitigation solution, which is widely used nowadays. In this work, it is expected to contribute to the body of knowledge regarding the physical and technical behavior of those barriers by developing and implementing a set of models that allow an accurate analysis of noise barriers with new configuration types. A 2.5D boundary-only numerical model is developed and implemented, and computational analyses are performed in order to compare different surface profiles of the acoustic barriers. The particular case in which two acoustic barriers are used, one at each side of the road, is addressed.

Keywords: Environmental noise; road traffic; acoustic barriers; BEM method; QRD diffusers; 2.5D solution.

1. Introduction

The economic growth and social evolution in developed cities have contributed, during the last decades, to an excess of environmental noise pollution resulting mainly from means of transport (air, rail and road).[1] As a consequence of this problem, the World Health Organization (WHO) provides a series of recommendations[2] to avoid and overcome the negative effects that noise has on the health of individuals.[3–6]

A popularly widespread and effective solution in fighting noise from road and rail traffic is the use of noise barriers located between the emitting source and sensible receivers. Under normal conditions, the insertion loss associated with these barriers can reach between 5 and 10 dB for usual dimensions of those devices, depending on their geometry and their diffusion and absorption characteristics,[7–9] and higher attenuations are possible using taller barriers.

In order to study the behavior of noise barriers, several authors have developed analytical models to calculate the barriers' insertion loss,[10–12] taking into account, among other factors, methods based on the diffraction produced by the barrier in the presence of other obstacles[13] and modeling of two and three-dimensional (2D and 3D) geometries.[14]

In the mid of the last century, techniques based on the theory of boundary elements were developed, making the study of the scattering of sound waves in barriers possible.[15,16] Later, these methods were improved to analyze the behavior of flat barriers and fully reflective surfaces.[17]

The boundary element method (known as BEM) is, according to several authors, one of the most effective ways to analyze the behavior and propagation of pressure waves in unbounded media.[18,19] The main feature that has popularized this method, making it more effective than other analysis tools for infinite or semi-infinite spaces, is that it is only necessary to discretize the interface boundaries instead of the domain itself, allowing for a very compact description of the problem. Consequently, the size of the system matrix decreases[20,21] and so does the required computational time when compared to other domain discretization techniques. Additionally, since the Green's functions used automatically satisfy the far-field radiation conditions, the BEM does not require any special treatment to account for infinite domains. Incorporating symmetry conditions, such as those generated by a rigid horizontal ground floor, is also straightforward making use of Green's functions derived with the image-source methodology.[21]

In several works by Monazzam and Lam,[22,23] Morgan *et al.*[24] and Baulac *et al.*,[25,26] the boundary element method (2D BEM) is used to analyze the insertion loss provided by the barrier, evaluating the influence of its shape and the absorptive characteristics of the surface on the wave propagation behavior over the medium.

On the other hand, Duhamel[27] developed a numerical method (also based on the BEM) for calculating the 3D sound pressure around the sound barrier from 2D solutions. Thereafter, the method was further developed to take into account any absorption on the boundaries.[28] The fluid medium is excited by a point pressure source and in order to evaluate the wave propagation's 3D behavior, without discretizing the entire domain, a spatial Fourier transform along the direction in which the (arbitrary shaped) geometry does not change was used,[27,29,30] defining the so-called 2.5D formulation. In fact, the 3D solution may be expressed as an integration of 2D problems, each one solved for a specific wavenumber, dependent on the axial wavenumber along the z axis (along which the problem geometry remains constant). This integration becomes discrete if a set of virtual sources is equally spaced along the z direction, requiring the spacing to be large enough in order to avoid spatial contamination of the response.[31] The problem is formulated in the frequency domain and complex frequencies[32] can be used in order to minimize the influence of the neighboring fictitious sources and avoid the aliasing phenomena. After computing the integrated results for a set frequencies, an inverse fast Fourier transformation is applied in order to obtain responses in the time domain. One common pulse type used in this process is the Ricker pulse, as can be found for example in Ref. 27.

Numerical simulations of different acoustic barriers' configurations were performed by Monazzam and co-workers and have demonstrated that the use of T and Y type barriers, with their tops designed using QRD type diffusers ("Quadratic-Residue Diffusers", the most common Schroeder diffusers), can be very efficient and that the insertion loss can be increased (around 1 dB for the QRD design frequency of 400 Hz) when compared to those produced by the typical T type barriers using absorbent material.[22,25,33] Alternatively, several authors have shown that the most efficient design is the flat vertical T type barrier with a soft top, i.e. incorporating diffusion and absorption elements.[22,34,35]

Another important feature of barriers based on QRD type diffusers is that their working frequency can be changed by shifting the design frequency of the QRD diffuser. On the other hand, they can also be easily constructed, resistant, economical and durable. Monazzam and Lam showed that by reducing the QRD design frequency the performance of the barrier is moved to a lower frequency range. Therefore, according to the authors, the design frequency that best fits the frequency spectrum of traffic noise (main noise source in the city) is 400 Hz (compared with 500 Hz and 1000 Hz).[22]

In order to evaluate the possible estimation error produced in the results obtained using 2D BEM simulations, authors such as Monazzam and Lam[23] or Cianfrini *et al.*[36] made experimental measurements in scale models of acoustic barriers (at 1:4 and 1:10 scales, respectively) and concluded that numerical prediction methods are highly accurate.

Technically, although the most common option consists of barriers with absorbing surfaces, in order to attenuate the reflections that return to the road side of those barriers, rigid materials such as regular concrete can hardly be used in an isolated manner for that purpose. The alternative of adopting a diffusive surface for the barrier, which helps spreading the incident energy, can help avoiding specular reflections and thus produce a beneficial effect.

Having this idea in mind, and following the research works identified before and their results and conclusions, the present work is based on a 2.5D BEM formulation, implemented to analyze the 3D sound pressure field generated by a point source located between two parallel vertical noise barriers, which can be flat or present an irregular profile. In this work, the surface irregularities are implemented with a simplified QRD design, here designated as sQRD. As will be seen later in this work, the sQRD design allows a much easier and less expensive production of large monolithic panels using rigid materials such as concrete. Additionally, in order to better understand the behavior and the effect of such irregularities, the more demanding case in which two parallel barriers exist is here addressed.

It is important to note that the main contributions of the present work are focused in two distinct aspects:

(1) To the authors knowledge, no previously published works adopted a 2.5D formulation to the analysis of sound diffusers. However, in some cases, the sound energy is generated comparatively close to the diffuser panel's surface, and thus the incident pulses impinge the diffusive panel surfaces with different inclinations, depending on the distance to the

source. The scattered field under such conditions is no longer well described/quantified in 2D and can only be studied using 3D models (or 2.5D models if the geometry remains constant in one direction, while the point pressure source keeps the 3D behavior);

(2) Adopting a geometrically simple diffusive surface profile for acoustic barriers can be quite easy from a technical point of view if, for example, concrete is used for their construction; by contrast, and, as mentioned before, it can be complex to give absorbing properties to a concrete surface without additional materials. Additionally, placing two parallel barriers, one at each side of the road, is known to generate a tunnel effect (if the barriers are tall enough). A diffusive surface may help compensating the lack of absorption that occurs, and the present paper aims at studying this effect.

The remaining part of the paper is organized as follows: first, a definition of the 2.5D problem formulation is presented; then, a Dual-BEM model is formulated in the frequency domain, assuming the presence of a harmonic (steady state) line load whose amplitude varies sinusoidally in the third (longitudinal) dimension. The pressure field generated by the wave propagation and scattering at both protective devices is calculated using a dual boundary element formulation, since thin bodies can be present in the problem geometry. It should be noted that adopting a Dual-BEM model allows adequately modeling thinner barriers or barrier parts. The main part of the article is devoted to analyzing the acoustical behavior of the noise barriers with sQRD diffuser on the surface in 2D and 2.5D, and simulating the propagation of sound generated by a point pressure source in the vicinity of two parallel barriers over a rigid ground, calculated using the Dual-BEM model.

2. Mathematical Formulation

2.1. 2.5*D problem formulation*

Acoustic scattering in the frequency domain is usually assumed to be governed by the well-known Helmholtz equation, which takes the form

$$\nabla^2 p(x,\omega) + \left(\frac{\omega}{c}\right)^2 p(x,\omega) = 0, \tag{1}$$

where c is the pressure wave velocity of the medium, $p(x,\omega)$ is the acoustic pressure at point x for an excitation frequency ω and $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$ for 3D problems, and $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$ for 2D problems.

When the medium is excited by an harmonic monopole load, and considering an implicit time dependence of $e^{i\omega t}$, the generated pressure field in free field can be described by

$$p_{\text{inc}}(x', x'_s, \omega) = A\frac{e^{-i\frac{\omega}{c}r'}}{r'}, \tag{2}$$

which fulfills Eq. (1) in an unbounded domain, and the far-field radiation conditions for acoustic problems, and in which x'_s represents the position of the load and x' is the receiver's position in the 3D space, the subscript inc denotes the incident field, A is the wave amplitude, $i = \sqrt{-1}$ and $r' = \|x' - x'_s\|$.

Fourier-transforming Eq. (2) in the z longitudinal direction, and using the effective wavenumbers, $k_\alpha = \sqrt{\frac{\omega^2}{c^2} - k_z^2}$ with $\mathrm{Im}\, k_\alpha < 0$, where k_z is the axial wavenumber, we obtain

$$\hat{p}_{\mathrm{inc}}(x, x_s, \omega, k_z) = \frac{-iA}{2} H_0^{(2)}(k_\alpha r), \tag{3}$$

in which the $H_n^{(2)}(\cdots)$ are second Hankel functions of order n, x_s and x correspond to the coordinates of the source and receiver in the 2D plane xy, respectively; and $r = \|x - x_s\|$.

If one assumes the existence of an infinite set of evenly-spaced sources along the z direction, the former incident field may be written as

$$p_{\mathrm{inc}}(x', x_s', \omega) = \frac{2\pi}{L} \sum_{m=-\infty}^{\infty} \hat{p}_{\mathrm{inc}}(x, x_s, \omega, k_z) e^{-ik_z z}, \tag{4}$$

where L is the spatial source interval, and $k_z = \frac{2\pi}{L} m$. Thus, the 3D pressure field may be obtained as the pressure irradiated by a sum of harmonic (steady-state) line loads whose amplitude varies sinusoidally in the third dimension. This sum converges and can be approximated by a finite number of terms. When time responses are to be calculated within a time window T, the spatial separation, L, must be large enough to guarantee that the response of the fictitious sources occurs at times later than T, thereby avoiding contamination of the response. The analysis also benefits from the use of complex frequencies defined as $\omega_c = \omega - i\zeta$, with $\zeta = 0.7\Delta\omega$, which can further reduce the influence of the neighboring fictitious sources and avoid the aliasing phenomena.

The problem to be solved concerns a spatially uniform acoustic medium either unbounded or bounded by one horizontal flat surface, simulating a rigid ground. One or two rigid obstacles are placed inside the propagation medium. The pressure field defined by Eq. (4) needs to be reformulated to satisfy the boundary conditions: null normal velocities at the horizontal flat surface. When an unbounded medium is considered, the standard Green's function for frequency-domain acoustic problems can be used, incorporating the axial wavenumber directly within the parameter k_α. Under these conditions, the Green's function can be written as

$$G(x, x_s, \omega, k_z) = \frac{-i}{4} H_0^{(2)}(k_\alpha r). \tag{5}$$

The effect of the horizontal rigid ground can be introduced by means of the image-source technique, using an additional (virtual) source in a symmetrical position with respect to the horizontal plane. In such case, the Green's function becomes

$$G_{\mathrm{half}}(x, x_s, \omega, k_z) = \frac{-i}{4} H_0^{(2)}(k_\alpha r) + \frac{-i}{4} H_0^{(2)}(k_\alpha r_0), \tag{6}$$

in which $r_0 = \sqrt{(x - x_s)^2 + (y + y_s)^2}$ and (x_s, y_s) being the coordinates of the real source. It should be noted that the combination of these two symmetrically positioned sources exactly fulfills the null normal velocity conditions of the rigid ground.

2.2. *Boundary integral formulation*

This section describes the Dual-BEM formulation used to obtain the scattered acoustic pressure wave field, i.e. the pressure in the host medium generated by the incident 3D pressure waves illuminating the heterogeneity(ies). Following the procedure previously described, the scattered field caused by a 3D point pressure load in the presence of the 2D geometry can be computed by means of a discrete summation of 2D harmonic line loads, with different values of the axial wavenumber k_z.

The classical boundary integral equation can be derived from the Helmholtz equation in the frequency domain by applying the reciprocity theorem, leading to:

$$\begin{aligned} Cp(x_0, k_z, \omega) = & \int_\Gamma q(x, k_z, \omega, \mathbf{n}) G(x, x_0, \omega, k_z) d\Gamma \\ & - \int_\Gamma H(x, x_0, \omega, k_z, \mathbf{n}) p(x, \omega, k_z) d\Gamma + p_{\text{inc}}(x_0, x_s, \omega, k_z), \end{aligned} \tag{7}$$

where G represents the Green's function for the pressure defined before, and H is its first derivative with respect to the normal direction to the boundary Γ; similarly, p and q are the pressure and its first derivative in the normal direction to the boundary ($\mathbf{n}$), at point x. The factor C equals 1/2 if Γ is regular, and 1 for points not in the boundary but within the domain ($x \in \Omega$).

It is well-known that the direct BEM formulation, described above, poses difficulties whenever thin bodies need to be modeled, since it degenerates and originates an unstable equation system. A good approach to tackle this problem is to jointly use the direct BEM and the so-called Traction-BEM (TBEM), which allows efficiently overcoming this issue.[37,38] In principle, whenever a thin body needs to be modeled, the BEM and TBEM equations are established, one at each side of the thin body, and thus two different equations are generated. The traction boundary integral equation can be derived by applying the gradient operator to the boundary integral Eq. (7), and thus the required additional integral equation can be expressed as:

$$\begin{aligned} & Ap(x_0, k_z, \omega) + Cq(x_0, k_z, \omega, \mathbf{n}) \\ & \quad = \int_\Gamma q(x, k_z, \omega, \mathbf{n}) G'(x, x_0, \omega, k_z, \mathbf{n}_2) d\Gamma - \int_\Gamma H'(x, x_0, \omega, k_z, \mathbf{n}, \mathbf{n}_2) p(x, \omega, k_z) d\Gamma \\ & \quad + p'_{\text{inc}}(x_0, x_s, \omega, k_z, \mathbf{n}_2). \end{aligned} \tag{8}$$

The Green's functions G' and H' are defined by applying the traction operator to G and H, and thus can be seen as the derivatives of these former Green's functions with respect to the normal to the boundary at the loaded point, $\mathbf{n}_2$. In this equation, the factor A equals zero for piecewise straight boundary elements.[39]

In the case of Eq. (8), the relevant Green's function for an unbounded space can be defined as:

$$G'(x, x_i, \omega, k_z, \mathbf{n}_2) = \frac{i}{4} k_\alpha H_1^{(2)}(k_\alpha r) \frac{\partial r}{\partial \mathbf{n}_2}, \tag{9}$$

while the incident field can be written as

$$p'_{\text{inc}}(x_0, x_s, \omega, k_z, \mathbf{n}_2) = \frac{i}{2} k_\alpha H_1^{(2)}(k_\alpha r) \frac{\partial r}{\partial \mathbf{n}_2}. \tag{10}$$

Green's functions which include an additional image source to simulate the rigid ground can be defined in a similar manner, just including an additional contribution from the virtual source.

For a generic problem, in which the boundary is discretized into N straight boundary segments (elements), each of the previous equations can be defined at each nodal point i, and the relevant integrals can be transformed in discrete summations as

$$\begin{aligned} Cp(x_i, k_z, \omega) = {} & \sum_{m=1}^{N} \left[q(x_m, k_z, \omega, \mathbf{n}_m) \int_{\Gamma_m} G(x, x_i, \omega, k_z) d\Gamma_m \right] \\ & - \sum_{m=1}^{N} \left[p(x_m, \omega, k_z) \int_{\Gamma_m} H(x, x_i, \omega, k_z, \mathbf{n}_m) d\Gamma_m \right] \\ & + p_{\text{inc}}(x_i, x_s, \omega, k_z) \end{aligned} \tag{11}$$

$$\begin{aligned} Ap(x_i, k_z, \omega) + Cq(x_i, k_z, \omega, \mathbf{n}_i) = {} & \sum_{m=1}^{N} \left[q(x_m, k_z, \omega, \mathbf{n}_m) \int_{\Gamma_m} G'(x, x_i, \omega, k_z, \mathbf{n}_i) d\Gamma_m \right] \\ & - \sum_{m=1}^{N} \left[p(x_m, \omega, k_z) \int_{\Gamma} H'(x, x_i, \omega, k_z, \mathbf{n}_m, \mathbf{n}_i) d\Gamma_m \right] \\ & + p'_{\text{inc}}(x_i, x_s, \omega, k_z, \mathbf{n}_i) \end{aligned} \tag{12}$$

where $\mathbf{n}_k$ represents the outwards pointing normal to the element k.

In the specific case of the configurations studied in this paper, Eqs. (11) and (12) can be further simplified, since only heterogeneities with rigid surfaces will be considered. Thus, the normal derivative of the pressure field, q, along the boundary remains always null, and the following equations can therefore be written as

$$Cp(x_i, k_z, \omega) + \sum_{m=1}^{N} \left[p(x_m, \omega, k_z) \int_{\Gamma_m} H(x, x_i, \omega, k_z, \mathbf{n}_m) d\Gamma_m \right] = p_{\text{inc}}(x_i, x_s, \omega, k_z) \tag{13}$$

$$Ap(x_i, k_z, \omega) + \sum_{m=1}^{N} \left[p(x_m, \omega, k_z) \int_{\Gamma} H'(x, x_i, \omega, k_z, \mathbf{n}_m, \mathbf{n}_i) d\Gamma_m \right] = p'_{\text{inc}}(x_i, x_s, \omega, k_z, \mathbf{n}_i). \tag{14}$$

Writing one of these two equations for each node, an equation system can be constructed, in which the unknowns are the nodal pressure values $p(x_i, \omega, k_z)$, for $i = 1 \cdots N$. It should be noted that the integrals in Eqs. (13) and (14) can, in general, be evaluated using standard techniques such as Gauss–Legendre quadrature. However, in Eq. (14), when the integrated element contains the loaded point, a singularity arises, and alternative strategies must be employed. Further details on this integration and on the formulation of the TBEM can be found in the works by Tadeu *et al.*[40]

After solving the boundary integral equations identified above, the response at any given domain point (x) for a given value of k_z can be computed by Eq. (7). Once the pressure is obtained for the full set of values of k_z, the corresponding full 3D response can be computed as

$$p_{3D}(x', \omega) = \frac{2\pi}{L} \sum_{m=-\infty}^{\infty} p(x, \omega, k_z) e^{-ik_z z}, \tag{15}$$

3. Model Verification

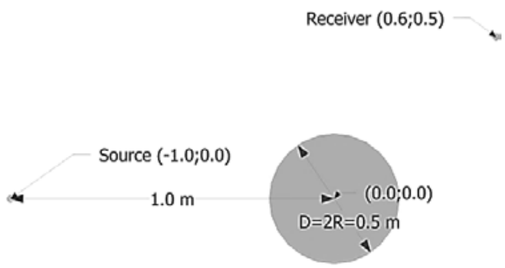
In order to verify the proposed Dual-BEM model formulation, consider a rigid circular cylindrical inclusion with radius of 0.25 m, centered at (0.0 m; 0.0 m), illuminated by a harmonic line load positioned at (−1.0 m; 0.0 m). This load oscillates with a frequency $\omega = 2\pi f$, and is harmonic along the z axis, with a wavenumber k_z. For this case, the analytical solutions defined in the paper by Tadeu *et al.*[41] can be used as reference solutions, and are very useful in the verification of the proposed scheme. The geometry of this first verification problem is shown in Fig. 1(a).

To perform this verification, frequencies between 5 Hz and 1000 Hz are considered, together with two different values of the axial wavenumber, given by $k_z = 0.0$ rad/m and $k_z = 4.0$ rad/m. Half the inclusion is modeled using the direct BEM, while the remaining part is modeled using the Traction-BEM, thus forming a Dual-BEM discretization approach. The properties of the host fluid are assumed to be those of air, with a density $\rho = 1.22\,\mathrm{kg/m^3}$ and allowing sound waves to travel with a velocity $c = 343$ m/s. The number of elements has been defined imposing that ten elements are used per wavelength, with a minimum of 12 (in order to correctly define the geometry with sufficient detail). Figures 1(b1) and 1(b2) illustrate the analytical versus the Dual-BEM responses, computed at a receiver placed at (0.6 m; 0.5 m), revealing a very good agreement between both models. Clearly, the 2.5D Dual-BEM model presents good numerical behavior for both values of k_2, and can be used for this kind of computational analysis.

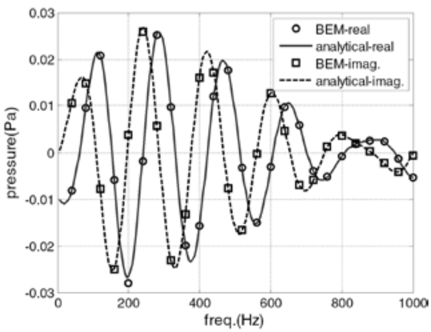
To better illustrate the numerical behavior of the method in terms of convergence, Fig. 2 presents the relative error for two different excitation frequencies, and for $k_z = 4.0$ rad/m, calculated as $|p_{\text{analytic}} - p_{\text{BEM}}|/|p_{\text{analytic}}|$. The calculation was performed using a progressively increasing number of boundary elements. The results plotted in that figure reveal an evidently convergent behavior, for both analyzed frequencies, with the relative error decreasing as larger numbers of elements are considered.

4. Definition and Study of a Simplified QRD (sQRD) Diffuser

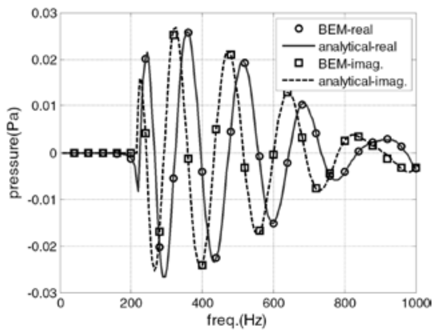
The use of diffusers in indoor environments has been quite explored, and is nowadays a widely used technical solution. The origin of most of the modern diffuser solutions is usually credited to the works of M. Schroeder, who developed a new way to design diffusing surfaces



(a)



(b1)



(b2)

Fig. 1. (a) Schematic representation of the verification problem; (b1) Verification results for $k_z = 0.0\,\text{rad/m}$ and (b2) $k_z = 4.0\,\text{rad/m}$.

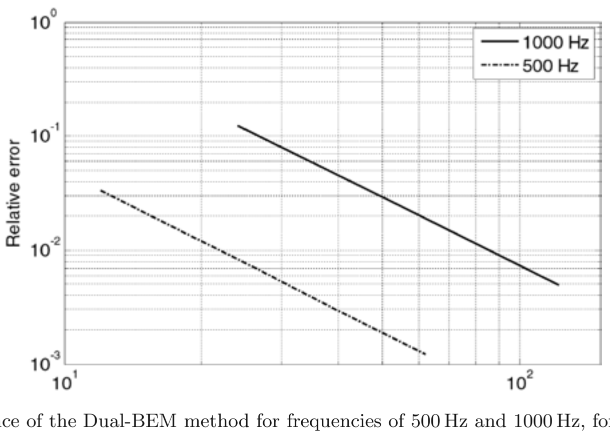


Fig. 2. Convergence of the Dual-BEM method for frequencies of 500 Hz and 1000 Hz, for $k_z = 4.0\,\text{rad/m}$.

and proposed structures that improve the reflected sound pressure over larger bandwidths, which were called QRD ("Quadratic-Residue Diffuser").[42] Some of the most important parameters when characterizing a diffuser of this type are:

— the order N or number of wells per module;
— the design frequency of the QRD;
— the absorption coefficient of the surface of the QRD (not treated in this study).

A QRD diffuser is composed by a number of wells (which depends on the order N) with different depths (see Fig. 3). It will cause phase shifts in the incident sound and, therefore, a uniform dispersion of the energy (homogenizing) in the 3D space, achieving a better balance of the reflected sound pressure. In this work, QRD diffusers' behavior was simulated and assessed in order to verify their applicability to traffic noise barriers.

The expression used to determine the depth factor (D_f) of the wells in a QRD diffuser was described by M. Schroeder, and is represented as follows:

$$D_f = (\text{well position})^2 \quad \text{mod } N, \tag{16}$$

where N (the QRD order) is a prime number that represents the number of wells per module. Moreover, the well width and the deepest well determine the upper frequency limit of diffusion and the diffuser's lower limit, respectively. As the order N increases, more even and smooth diffusion will occur throughout the frequency spectrum.

Thereby, a number of configurations and designs has been selected and analyzed by means of numerical computation, all of them considering perfectly reflective surfaces. With the goal of studying mostly high order diffusers, although still feasible from a practical construction point of view, orders N and design frequencies of the QRD diffusers evaluated in this study were $N = 11$ and 17 and $F_{\text{d}} = 400$ Hz, 500 Hz and 1000 Hz, respectively. In Fig. 3, the cross-section of a QRD module with design frequency of 1000 Hz and orders of $N = 11$ and $N = 17$ is depicted.

As can be seen, the width of the diffuser is proportional to the order N. In contrast, when the QRD design frequency increases, the height decreases. Size characteristics are presented in Table 1 for the different QRD diffusers type configurations evaluated in this work.

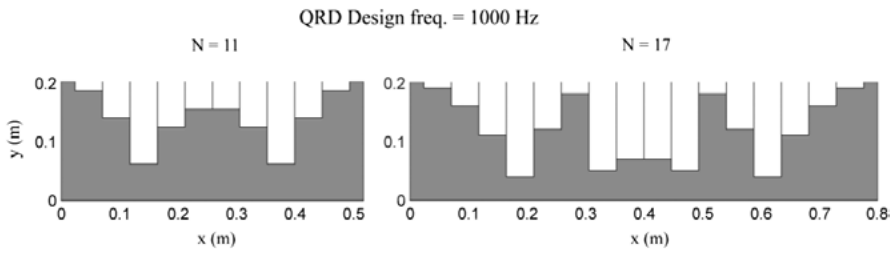


Fig. 3. QRD module ($N = 11$ & $N = 17$) cross-section. Design frequency of 1000 Hz.

Table 1. Size characteristics for QRD configurations when the order is $N = 11$ and $N = 17$.

		Width [m]	
Design Freq. [Hz]	Height [m]	$N = 11$	$N = 17$
400	0.5	1.3	2.0
500	0.4	1.0	1.6
1000	0.2	0.5	0.8

From a practical point of view, the presence of the lateral walls that separate neighboring wells adds a significant complexity to the construction of these diffusers. Although when dealing with wood diffusers these walls can be implemented with more simplicity, for the case of a concrete diffuser it requires adding individual elements made from a different material. Thus, a simplified configuration of QRD diffusers, here designated as sQRD, is proposed by simply removing these walls. This simplified sQRD configuration can lead to additional benefits when applied to noise barriers (as is intended in the present paper), allowing the definition of solutions with high stability, mechanical strength and resistance to impact, while ensuring ease of maintenance and durability. In Fig. 4, the cross section of a QRD and sQRD module with order $N = 11$ is shown.

4.1. 2*D analysis*

In order to analyze and evaluate the behavior of the reflected acoustic wave from the diffusers, different configurations of QRD and sQRD panels were studied in this research. Initially, a study of the diffusion coefficient was done in 2D, when the order N, the design frequency and the incident frequency were modified, comparing the two diffuser types. In Fig. 5, the resulting polar plots for both designs are depicted, computed using the Dual-BEM model and considering the acoustic source to be positioned 10 m away from the panel, and a semi-circle of receivers located 5 m away from the center of the diffuser. It should be noted that the Dual-BEM model described in Sec. 2 is essential to allow the analysis of the classic QRD configurations due to the very thin walls that separate the different wells.

From the presented plots, it is interesting to note that the absence of the lateral walls induces a marked change in the polar response of the diffuser, with the simplified sQRD diffuser no longer evidencing a peak performance at the design frequency. Analyzing, for

Fig. 4. QRD and simplified QRD (sQRD) 2D design when order $N = 11$.

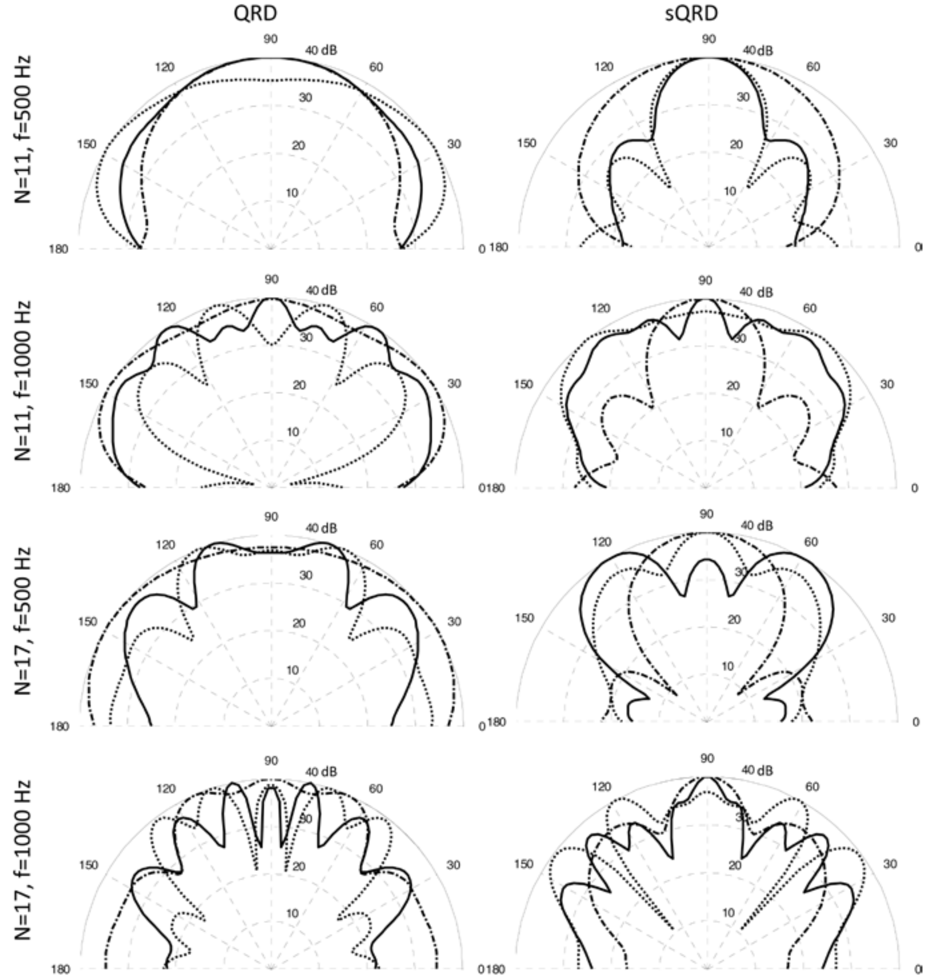


Fig. 5. Polar diagrams of spatial response ($N = [11, 17]$; Inc. Freq. = [500, 1000] Hz; QRD & sQRD diffuser configurations), for design frequencies of 400 Hz (−), 500 Hz (··) and 1000 Hz (−·).

example, the third line of Fig. 5, it can be seen that for a design frequency of 500 Hz, and for an incident wave with the same frequency, the sQRD even shows a quite specular pattern, while the conventional QRD design is much more effective in spreading the energy under these conditions (first line of Fig. 5). However, when the incident wave has a frequency of 1000 Hz, the sQRD with so-called design frequencies of 400 Hz and 500 Hz reveals an effective dispersion effect (although theoretically not designed for that frequency), clearly

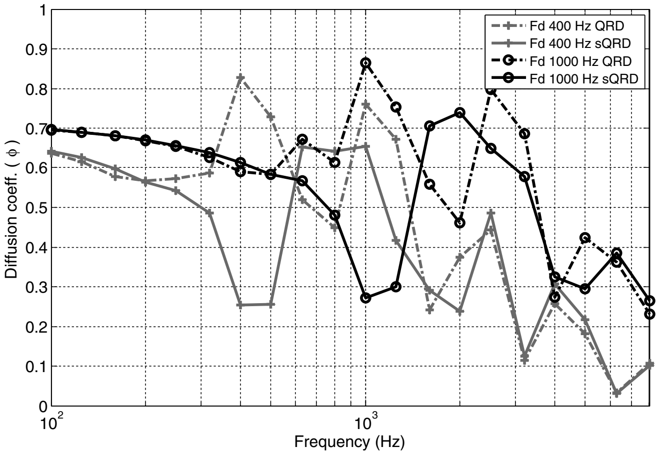


Fig. 6. Diffusion coefficient (bandwidth = [100–8000] Hz; $N = 11$).

surpassing the classic version. It thus seems that the absence of the well walls induces a shift of the peak performance to higher frequencies.

To confirm these findings, let us now analyze the behavior of the QRD and sQRD panels for a complete frequency range, between 100 Hz and 8000 Hz. In this analysis, the diffusion coefficient is calculated according to Cox and D'António,[40] and the corresponding results are plotted in Fig. 6.

As expected, for the classic QRD diffuser, the maximum peak occurs around the design frequency of the diffuser, and can be seen clearly both for design frequencies of 400 Hz and of 1000 Hz. This maximum completely disappears when the sQRD is analyzed, revealing the importance of the vertical walls in creating individual waveguides with different depths that help in controlling the scattering effects. However, a maximum peak is now registered at a higher frequency, which is around 800 Hz when $F_d = 400$ Hz, and around 2000 Hz when $F_d = 1000$ Hz, at which very significant dispersion of the energy occurs. This result is consistent with the observations described for Fig. 5, and indicates that the sQRD diffuser still exhibits good scattering properties, although at different frequencies (approximately twice the design frequency).

From a practical standpoint, this behavior can be quite interesting, since it allows designing panels with larger wells that can be efficient at higher frequencies, and this can be advantageous when dealing with larger scale structures such as acoustic barriers.

4.2. 2.5*D behavior of sQRD diffusers*

One of the concerns of the present study is the analysis of the behavior of diffuser panels when subject to a point load, corresponding to a 3D problem. In that case, considering that the cross-section of the diffuser remains constant along one direction, the formulation defined in Sec. 2 of the present paper may be used to determine the response of the proposed sQRD profiles. The main interest of such analysis is to understand the variation of the sound scattering characteristics in different planes perpendicular to the diffuser. In all presented results, the cross-section of the diffuser is assumed to remain constant along the z direction, and the diffusion pattern is analyzed in three planes, corresponding to $z = 0\,\text{m}$, $z = 10\,\text{m}$ and $z = 20\,\text{m}$. One should keep in mind that the aim of the present paper is to analyze the effect of acoustic barriers with diffusive cross-section profiles, for which case, and assuming that the barrier may be several dozens of meters long, it is relevant to understand what happens not only in the plane containing the source, but also in planes placed further away from it.

Figure 7 illustrates the behavior of two sQRD diffusers of orders $N = 11$ and $N = 17$, with a cross-section designed for a frequency of 400 Hz, and for incident sound frequencies of 500 Hz and 1000 Hz; in addition, a reference result considering a flat panel is also presented for comparison purposes. The presented polar plots exhibit varying scattering patterns,

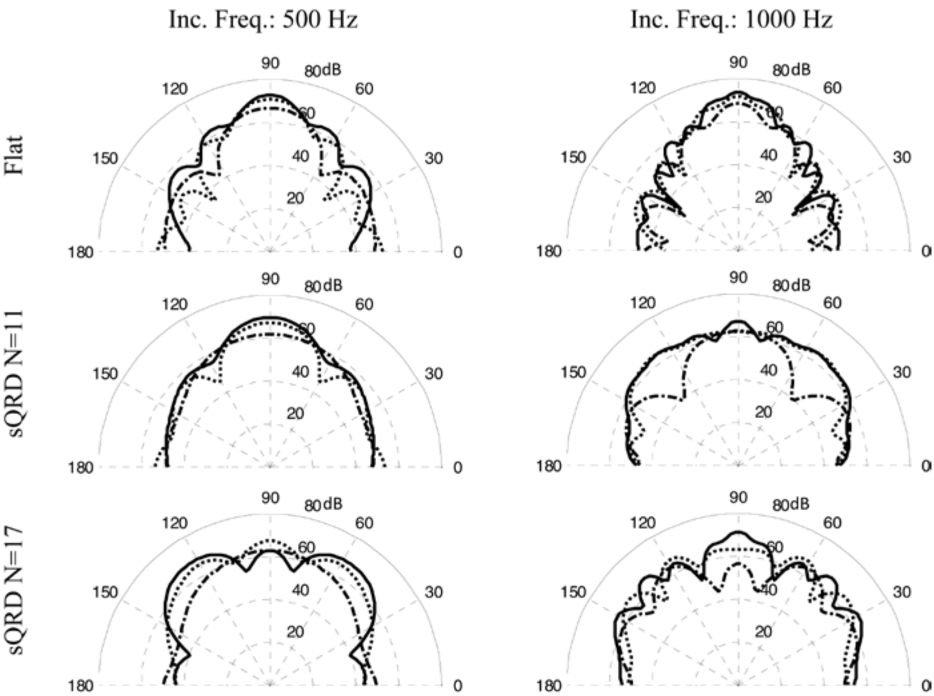


Fig. 7. 2.5D polar diagrams when $z = 0\,\text{m}$ (−), 10 m (··) and 20 m (−·), for a flat surface and for sQRDs with design frequency of 400 Hz, when $N = 11$ and $N = 17$.

with differentiated behaviors depending on both the incident wave frequency, on the order N and on the selected vertical plane of analysis. A first and immediate conclusion is that the diffusion pattern at receivers positioned at $z = 0\,\text{m}$ is quite similar to the one computed for the 2D case, and illustrated in Fig. 5, with only slight and expected changes due to the 3D nature of the problem. As planes further away in z are analyzed, this situation changes visibly, with patterns at $z = 20\,\text{m}$ tending to reveal a less dispersive effect from the panel. The observed behavior was possibly expectable, since the incident wave is now arriving at the panel with a steeper inclination (contrasting with the normal incidence in 2D), and with a longer projected wavelength. A good example of this occurs when the panel with $N = 11$ is analyzed for an incident wave with a frequency of 1000 Hz, for which case the formation of a pattern with one very significant central lobe is clearly visible at $z = 20\,\text{m}$. Therefore, comparing the results computed with the sQRD configurations with those computed for the flat panel, it seems that the proposed configurations (both in the $N = 11$ and $N = 17$ versions) exhibit improved diffusive characteristics, allowing the incident energy to be spread laterally in a more efficient way. Indeed, when a flat panel is modeled, a stronger response is visible for angles around 90°, indicating the important specular reflection effect, and then decaying for angles below 60° and higher than 120°, particularly for an incident frequency of 1000 Hz. This effect is greatly attenuated when diffusive sQRD surfaces are adopted.

The results presented in this sub-section reveal that it can be quite important to correctly address the 3D effects when the diffuser panels are long, since the sound scattering effect generated at the panel's surface can exhibit significant changes when planes placed away from the source are analyzed. In addition, comparison with results computed for the case of a flat surface indicates that the proposed sQRD configuration can lead to a visible improvement in the dispersion of incident sound waves. The tested configurations seem to lead to very adequate dispersion effects when the incident frequency is of 1000 Hz; notice that this frequency matches the well-known peak frequency occurring in the traffic noise spectrum, and thus the proposed configuration may be of use in dispersion of this kind of noise.

5. Application of sQRD to Traffic Noise Attenuation Devices

In the present section, in order to better understand the behavior of sQRD diffuser panels, a more demanding application case is now addressed, in which two rigid parallel barriers exist along a road traffic way and a point pressure source is excited. Therefore, the proposed 2.5D numerical approach is used to study the effect of adopting parallel diffusive acoustics sQRD barriers and its effect is compared with the equivalent use of flat barriers when sound propagation is simulated over a rigid ground.

Two acoustic barriers are considered, 10 m spaced apart at each side of a road traffic way. The cross sectional geometry of the system remains constant along a longitudinal direction that corresponds to the road alignment. Two different diffuser panels are modeled, corresponding to previously described sQRD geometries with order numbers of $N = 11$ and $N = 17$, and a design frequency of $F_\text{d} = 400\,\text{Hz}$. Additionally, a flat barrier with the same

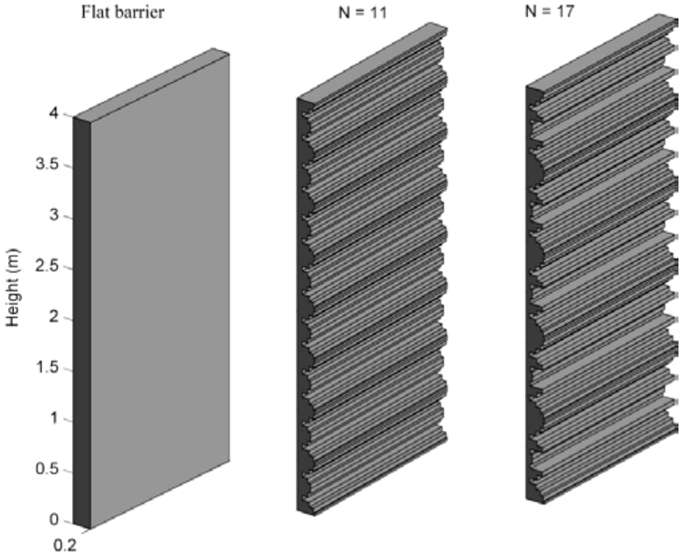


Fig. 8. Flat barrier and sQRD ($N = 11$ & $N = 17$) 3D barrier configurations.

height is adopted for comparative purposes. The height of the barrier is considered to be 4 m and a schematic 3D representation of a barrier segment is illustrated in Fig. 8.

A point pressure load is illuminating the physical system, located 0.6 m above the rigid ground, at the vertical plane $z = 0$ m. Two different positions are considered, one at mid distance from the parallel barriers, i.e. at a point with coordinates (5 m, 0.6 m, 0 m), and the other in a noncentered position at (3 m, 0.6 m, 0 m).

The responses are evaluated at separate grids of 81×41 receivers over the propagation domain, corresponding to vertical planes, perpendicular to the barriers, with different z longitudinal coordinates, namely at $z = 0$ m and $z = 10$ m. Receivers are regularly spaced at intervals of 0.2 m along x and y directions, ranging from $x = -3$ m to $x = 13$ m and from $y = 0$ m to $y = 8$ m. The rigid ground corresponds to a horizontal plane with $y = 0$ m.

Next, the acoustic behavior of these systems is analyzed. In a first sub-section, using the same barriers' configurations described above, the propagation of the acoustic wavefield is first illustrated along the grids of receivers, at different time instants; results in terms of frequency band responses are also presented and discussed. A second sub-section is dedicated to a more in-depth analysis of the acoustic performance of the proposed barriers.

5.1. *Time signals and 1/3 octave band frequency results*

The effect of the sQRD acoustic barriers on the 3D propagation of a spherical pulse and its scattered wavefield was first analyzed by observing the corresponding time domain responses. In order to achieve this analysis, a set of 128 frequencies was computed, in the range of 10 Hz to 1280 Hz. A frequency step of 10 Hz was adopted, making it possible to define a maximum time window of 0.100 s. An inverse Fast Fourier transformation is applied to the results in the frequency domain to get time domain responses on numerical receivers. The time evolution of the emitting pulse corresponds to a Ricker pulse, with a central frequency of 500 Hz. The computed results correspond to the total pressure wavefield, resulting from the incident field from the source added to the scattered field from the rigid boundaries and obstacles of the physical system, and they are illustrated by a set of snapshots, at two time instants, for the same barrier configurations described above.

In the first column of Fig. 9, the acoustic wavefield is illustrated at time instant $t = 17.7$ ms, along two grids of receivers at vertical planes $z = 0$ m and $z = 10$ m, for the case in which the emitting source is located at $x = 5$ m. In the case of two flat parallel barriers, a total reflection is initially observed on the rigid ground and, at later time instants, on the flat surface of the barriers. Since the source is placed at mid distance from the parallel barriers, the reflected pulses are symmetric and propagate towards the domain between the barriers. The diffracted wave pulses at the upper tips of the barriers are visible at their initial stages. At this time instant, the wave pulses have not yet reached the vertical plane $z = 10$ m. When the barriers correspond to sQRD panels, the reflected pulses are significantly modified, resulting from multiple interactions with the irregular geometry of the barrier surface. The scattered pressure field is thus much more complex and exhibits a clear diffusive character (with these characteristics being slightly strengthened for the higher order of the sQRD).

At time instant 34.3 ms, snapshots on the second column of Fig. 10 illustrate the pressure field along the same vertical planes. When the flat barriers are used, complete reflections continue to propagate between these parallel reflective surfaces, and a similar wave pattern is observed farther away from the source plane, although with decreasing wave amplitude. At the same time instant, when sQRD profiles are adopted, the pressure fields are indeed more complex, resulting from the reflections and diffusive effects on the barriers surface irregularities. One can observe that some constructive pulse interferences seem to be attenuated by incorporating the diffuser profiles on the barriers' surface.

In Fig. 10, the propagation phenomena is illustrated for the case in which the source is located at $x = 3$ m. For this case, only results computed for the sQRD barriers and when $N = 17$ are displayed. Observing the plot representing the pressure distribution for the initial time instant, it is possible to observe that no energy has yet reached the grid placed further away along the z axis, but that the incident waves have already impinged on one of the barriers. The pattern of energy spreading near this barrier can be immediately perceived, with a multitude of pulses being visible in the plot as a result of the irregular surface of the barrier. At this time, the wavefront has not yet reached the second barrier. In the right plot, corresponding to a later time instant, the observed patterns at $z = 0$ m reveal an intricate combination of the different pulses generated at the barrier's surface due to the presence of the sQRD configuration. For the second plane of receivers ($z = 10$ m), the propagating waves are now visible, and the reflection pattern from the barrier is also

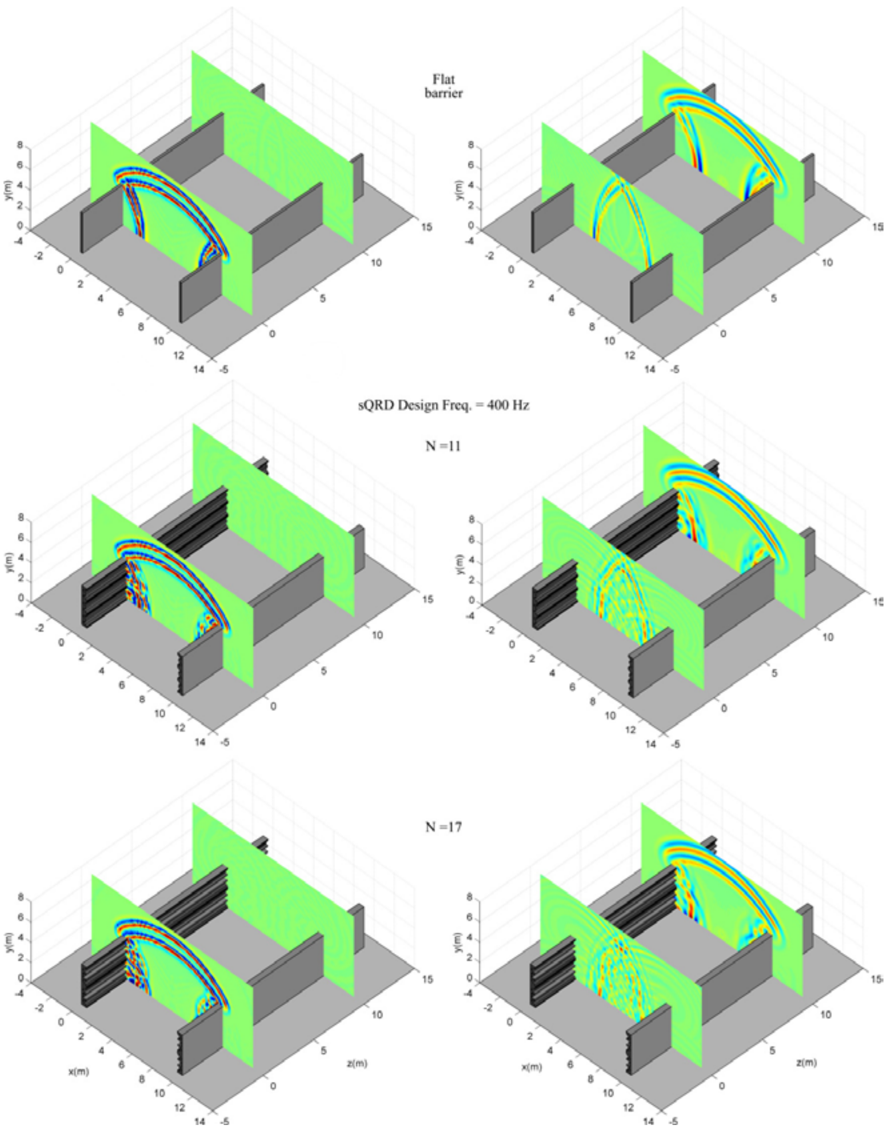


Fig. 9. 3D time response for an incident pulse, generated by a source at $x = 5\,\mathrm{m}$ with a characteristic frequency of 500 Hz, considering Flat and sQRD parallel barriers, with sound pressure field being represented at vertical grids of receivers for $z = [0, 10]\,\mathrm{m}$. The left column corresponds to $t = 17.7\,\mathrm{ms}$, while the right column refers to $t = 34.3\,\mathrm{ms}$.

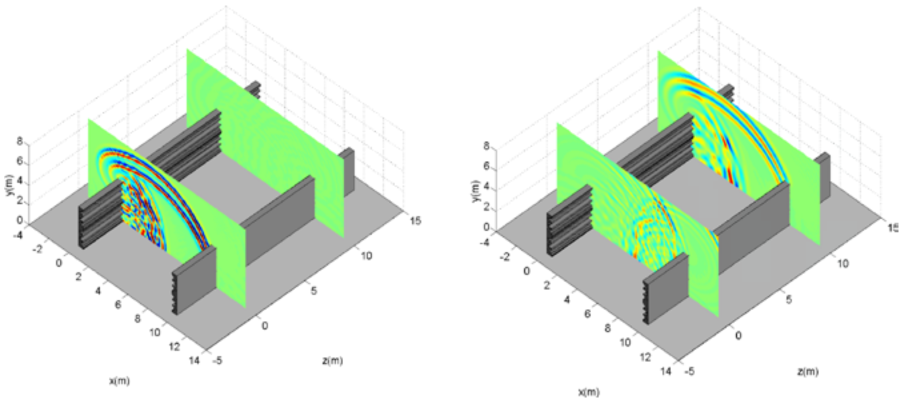


Fig. 10. 3D time response for an incident pulse, generated by a source at $x = 3\,\text{m}$ with a characteristic frequency of 500 Hz, considering sQRD parallel barriers with $N = 17$, with sound pressure field being represented at vertical grids of receivers for $z = [0, 10]\,\text{m}$. The left column corresponds to $t = 17.7\,\text{ms}$, while the right column refers to $t = 34.3\,\text{ms}$.

visible in this plane. Clearly, for this second source position, the main features of the sound propagation are very similar to the ones described for a source centered between the two barriers.

To better understand the behavior of the proposed systems, the computed responses were also analyzed for two $1/3^{\text{rd}}$ octave frequency bands, 500 Hz and 1000 Hz, by applying a band-pass filter to the response and then integrated the sound energy at each receiver. The same two grids of numerical receivers (at $z = 0\,\text{m}$ and $z = 10\,\text{m}$) are used, for which the scattered sound pressure level (neglecting the incident field and the first reflection from the ground) is evaluated by the expression $SPL_{\text{scat}} = 20\log(|p_{\text{scat}}|/2 \times 10^{-5})\,[\text{dB}]$. Figure 11 illustrates the corresponding results computed in the presence of the selected flat and sQRD profiles of the parallel barriers.

In the first column, the scattered SPL pattern is illustrated for the lower frequency band of 500 Hz, for which some noticeable differences are observed between the three geometric configurations, both at the vertical plane containing the source, and at the second plane, located at $z = 10\,\text{m}$. When the diffuser profiles are used, and since the well depth varies along the barrier surface, the scattered waves propagate in multiple directions, producing a more diffuse wavefiled than that observed with the flat barriers. When the receivers are placed farther from the source (at $z = 10\,\text{m}$), the differences in the scattered SPL are subtler between geometrical configurations, but yet reveal the 3D character of the acoustic system. It is, however, possible to observe that the SPL registered at receivers located closer to the ground tends to become less pronounced, indicating that the sound energy is more efficiently dispersed to the upper region.

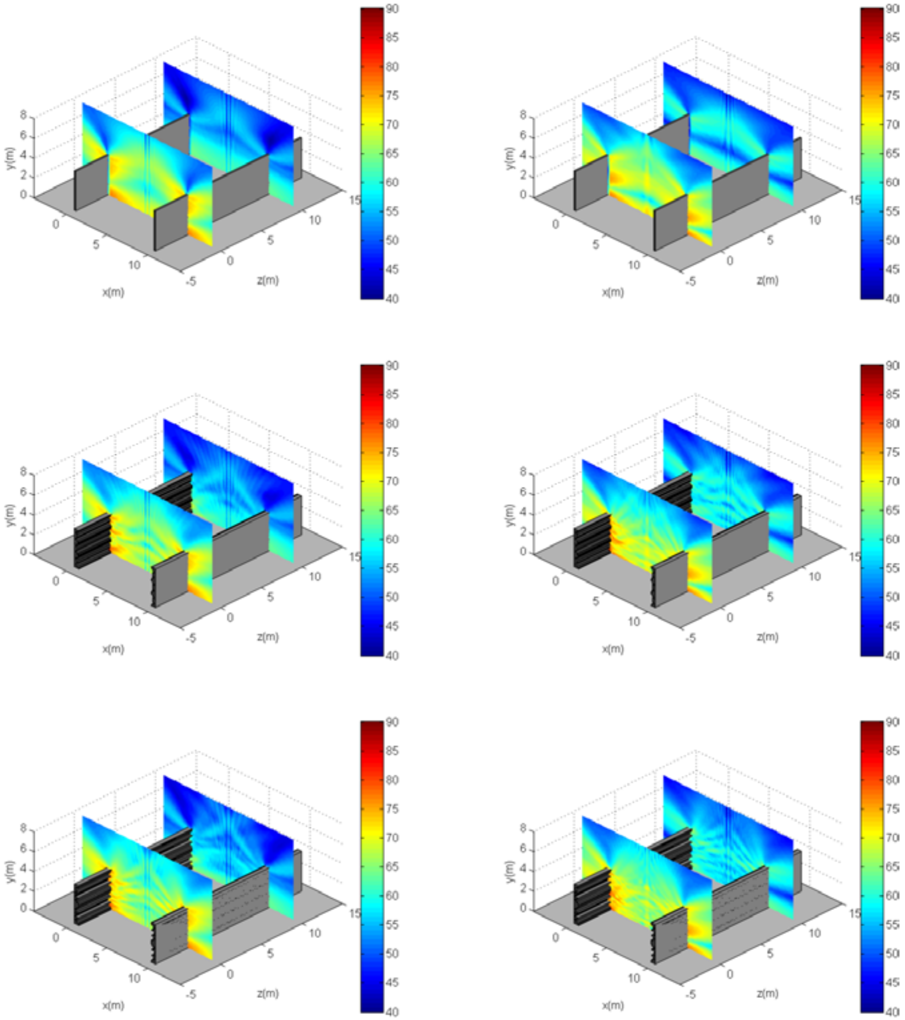


Fig. 11. 3D frequency behavior of Flat and sQRD barriers, in terms of scattered sound pressure levels represented at vertical grids of receivers for $z = [0, 10]$ m, for $1/3^{\text{rd}}$ octave bands of 500 Hz (left) and 1000 Hz (right).

At the higher frequency band of 1000 Hz, the diffusive effect of the presence of the sQRD profiles becomes much more evident. It is now clear that the effect of the multiple pulse interactions is quite pronounced, in particular along the vertical plane $z = 0$ m, originating complex patterns. It must also be noted that a stronger concentration of energy occurs in

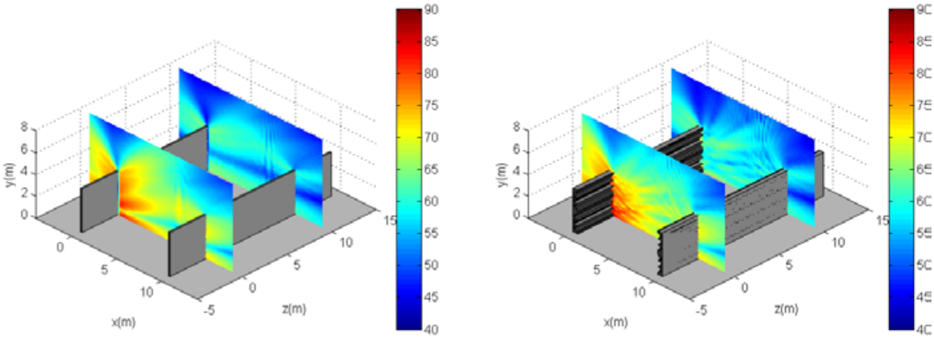


Fig. 12. 3D frequency behavior of Flat (left) and sQRD barriers with $N = 17$ (right), in terms of scattered sound pressure levels at vertical grids of receivers for $z = [0, 10]$ m, when the source is located at $x = 3$ m, considering the $1/3^{\rm rd}$ octave band 1000 Hz.

the closest vicinity of the barriers' surfaces, and the SPLs near the center become lower in the presence of the sQRD. One may also note that the scattering patterns still show some dependency of the order N of the sQRD design, although both designs exhibit quite similar performances. The same findings can also be observed when the source is moved away from the center, as illustrated in Fig. 12. For the two frequency bands analyzed here, it becomes clear the changes introduced in the sound field between the two barriers. That is, indeed, the main focus of the present study.

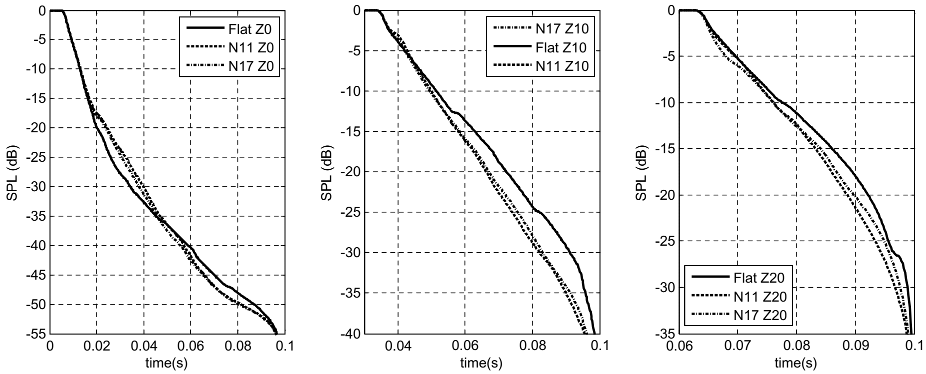
5.2. *Acoustic performance of the solutions*

Since the purpose of the proposed barriers is mostly to allow an additional control over the sound field produced between the two acoustic barriers, it is important to analyze the specific behavior of those solutions in what concerns the noise generated within the region between barriers, where vehicles circulate.

With this purpose, and to have a better insight of the time evolution of the acoustic energy trapped between the two structures, energy decay curves were computed for the three cases illustrated above. In those calculations, a complete set of receivers placed between the two barriers, between $y = 0.8$ m and $y = 2.0$ m, was analyzed, and the average decay curve was evaluated as:

$$E(t) = \int_0^T \sum_{i=1}^{nrec} p_i(t)^2 \, \mathrm{d}t - \int_0^t \sum_{i=1}^{nrec} p_i(t)^2 \, \mathrm{d}t. \tag{17}$$

In this process, and in order to analyze the specific effect of the barrier's surface in the frequency band of 1000 Hz (as already said, usually considered to be a dominant frequency band in traffic noise), a band-pass filter was first applied to the signal, with cutoff frequencies of 890 Hz and 1120 Hz. The resulting decay curves computed at different vertical planes are



(a) (b) (c)

Fig. 13. Sound pressure level decay curves computed for flat and sQRD barriers, at different vertical planes: (a) $z = 0\,\text{m}$; (b) $z = 10\,\text{m}$ and (c) $z = 20\,\text{m}$.

presented in Fig. 13, for the sQRD barriers with $N = 11$ and $N = 17$, and for the reference flat barrier.

The presented curves reveal a progressive energy decay, starting after the first pulse arrivals. In those plots, a more stable and linear decay can be observed for the sQRD barriers, while the flat surface leads to decays with more variable slopes throughout the analysis time. This smoother behavior of the sQRD barriers can be justified by their more effective diffusion capacity, which avoids the specular reflection effects at the different surfaces. Indeed, this phenomenon can also be observed in Figs. 9 and 10, in which it is clear that upon reflection at the rigid surface of a sQRD barrier, the pulses are dispersed originating multiple smaller wavefronts.

Observing the results obtained at $z = 0\,\text{m}$, the initial decay is very similar in all three configurations, up to an SPL decay of approximately 15 dB; the decay between this level and 35 dB seems to occur faster for the flat barrier. After this point, the decay rate of the flat barrier becomes smaller, and the two sQRD configurations lead to higher decreases in the SPL. However, for this plane, there is little relevance in the observed differences, since the initial decay is very similar in all three cases. This situation changes markedly when planes placed farther in z are considered. Indeed, for those cases, both the sQRD barriers with $N = 11$ and $N = 17$ exhibit decay curves that are consistently below that provided by the flat barrier, with a faster decay of the sound pressure levels in those cases. In those plots, differences up to 4 dB can be observed between the flat barrier and the sQRD solutions. Comparing the $N = 11$ and $N = 17$ solutions, it can be concluded that they present quite similar behaviors, although with some advantage for the solution with $N = 11$.

Overall, it can be said that the computed time responses and decay curves indicate that there is a sensible performance gain when sQRD profiles are used, mostly in what concerns the dispersion of the energy reflected by the two parallel barriers.

A relevant point that is worth investigating within the scope of the present application corresponds to the amplitude of the sound field reflected by the two parallel barriers, and that affects the acoustic comfort within the transportation means that travel in the road or railway. For this purpose, the previously presented time responses need to be conveniently treated by first removing the incident pulses (and their first reflection on the rigid ground, which are both independent from the type of barrier used), and then by computing the integral of the sound energy that passes at each of the receivers. In this process, a bandpass filter is applied to allow computing SPLs for some specific 1/3$^{\text{rd}}$ octave bands. The SPL maps depicted in Figs. 14 and 15, for planes at $z = 0\,\text{m}$ and $z = 10\,\text{m}$ and for sources located at $x = 5\,\text{m}$ and $x = 3\,\text{m}$, are thus produced.

When $z = 0\,\text{m}$, and for both frequency bands analyzed, the results in Fig. 14 make it possible to clearly observe that the interference between the many reflected pulses originates a very noticeable change in the SPL patterns throughout the grid of receivers. For the lower frequency band, it can be immediately seen that the diffusive sQRD surfaces lead to a decrease of the SPLs in the lower part of the plot, helping to spread the reflected energy to the upper region. The same phenomenon is seen for the 1000 Hz frequency band, with the sQRD surfaces clearly destroying the structured character of the sound pressure level distribution seen in Fig. 14(a2). Indeed, in that plot, the flat barrier originates two important

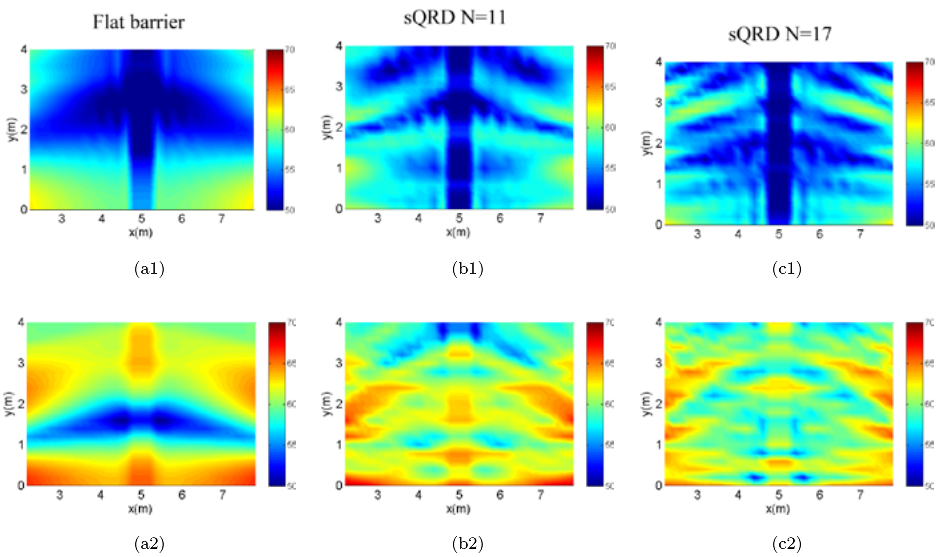


Fig. 14. SPL of the reflected field at $z = 0\,\text{m}$: (a) flat barrier (b) $N = 11$; (c) $N = 17$. First line ((a1), (b1) and (c1)) obtained applying a bandpass filter for the frequency band of 500 Hz, and second line ((a2), (b2) and (c2)) for the frequency band of 1000 Hz.

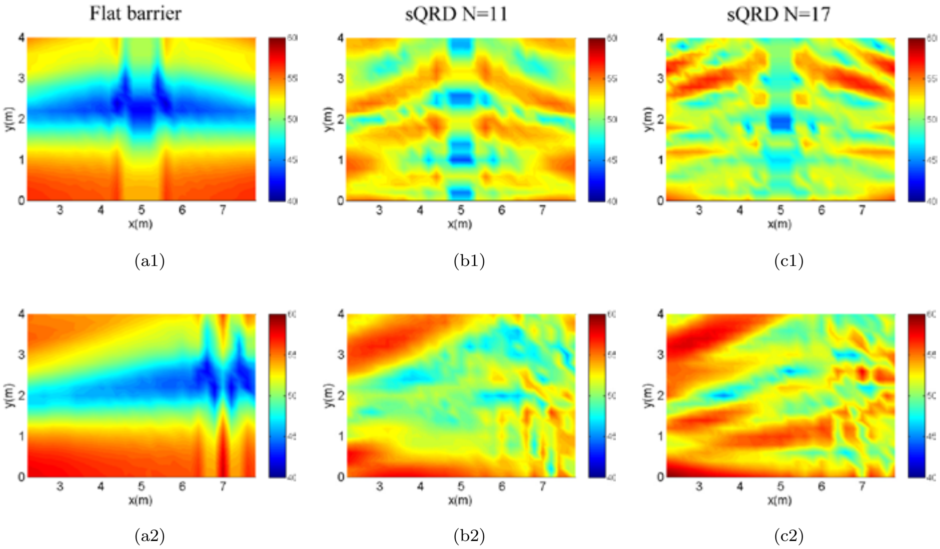
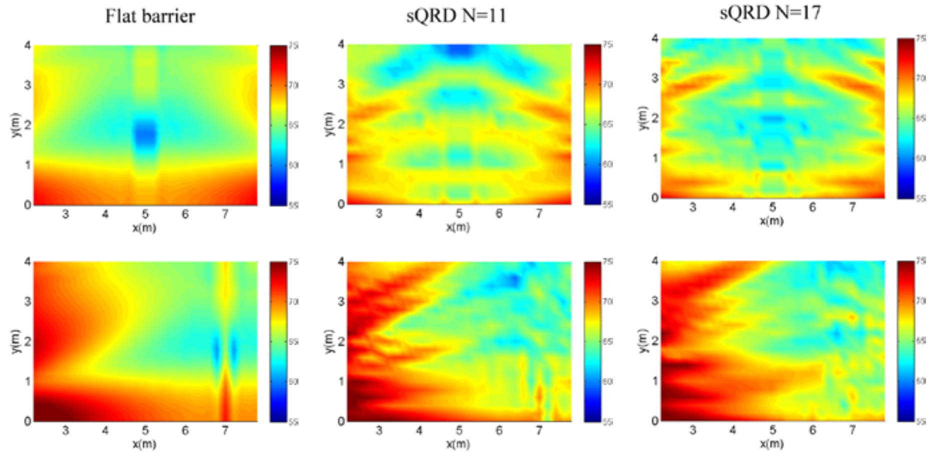


Fig. 15. SPL of the reflected field at $z = 10\,\text{m}$ and for the $1/3^{\text{rd}}$ octave band of 1000 Hz: (a) flat barrier (b) $N = 11$; (c) $N = 17$. First line ((a1), (b1) and (c1)) obtained for a source at $x = 5\,\text{m}$, and second line ((a2), (b2) and (c2)) for a source at $x = 3\,\text{m}$.

regions with increased SPL, one of them bellow 1.0 m, and the other above 2.0 m. These two regions are greatly attenuated with the sQRD structures, with the $N = 17$ configuration revealing a more diffuse sound field.

To complement this analysis, Fig. 15 presents the results calculated using the same methodology for $z = 10\,\text{m}$, and using the 1000 Hz band-pass filter, and considering sources at $x = 5\,\text{m}$, $x = 3\,\text{m}$. These results further corroborate the findings from Fig. 14, evidencing the importance of the diffusive surfaces in destroying the structured sound field produced when the reflecting surface is flat. As in the previous case, although both sQRD solutions exhibit similar behaviors, the effect of the sQRD with $N = 17$ seems to be somewhat stronger in dispersing the acoustic energy.

To have a more consistent view of the effect of sQRD barriers in the sound field, the results were further post-processed in order to allow including the effect of a source weighted by the traffic noise spectrum given in ISO 717-1; given the calculated frequency range (between 10 Hz and 1280 Hz), only the $1/3^{\text{rd}}$ octave bands between 100 Hz and 1000 Hz were included in this analysis. As an example, the corresponding SPL plots at $z = 0\,\text{m}$ are shown in Fig. 16 for a centered source ($x = 5\,\text{m}$) and for a noncentered source ($x = 3\,\text{m}$), at $z = 0\,\text{m}$. The destruction of the structured character of the response seen for the flat barrier is clear



(a) (b) (c)

Fig. 16. SPL of the reflected field weighted using the traffic noise spectrum of ISO 717-1 at $z = 0\,\mathrm{m}$: (a) flat barrier, (b) $N = 11$; (c) $N = 17$.

for the remaining two solutions; lower magnitudes of the sound field can also be observed at the lower placed receivers when sQRD solutions are simulated. When a noncentered source is considered, it is possible to observe that significant energy concentration occurs at receivers closer to the barrier's surface, for all three cases. For the sQRD barriers, a sensible decrease of the SPL occurs, however, at receivers placed on the lower right quadrant in the plotted figures.

For both sources, the global SPL considering all receivers located below $y = 2\,\mathrm{m}$ (the region of interest where circulation occurs, and which is indeed the target zone where energy concentration must be avoided) was computed for the three barrier types, and for the two source positions. Figure 17 illustrates the corresponding results at $z = 0\,\mathrm{m}$ and at $z = 10\,\mathrm{m}$. Observing the bar plots depicted in that figure, it can be seen that there is a global tendency for the sound pressure level to decrease at all frequency bands, although with occasional bands where no effect (or even an adverse effect) is observed. Among the three solutions, the sQRD with $N = 17$ seems to provide consistently better performance, an observation which is coherent with the SPL maps analyzed before.

Although the presented results seem promising, it must be said that further studies may be required in order to better optimize the correct shape of the barrier's surface, and thus to reach more pronounced effect in terms of attenuating the reflected sound levels in the lower placed region. In particular, it seems to be important to tackle the problem of adverse effects occurring for the 1000 Hz band in some configurations, since this is one of the dominant frequencies in traffic noise.

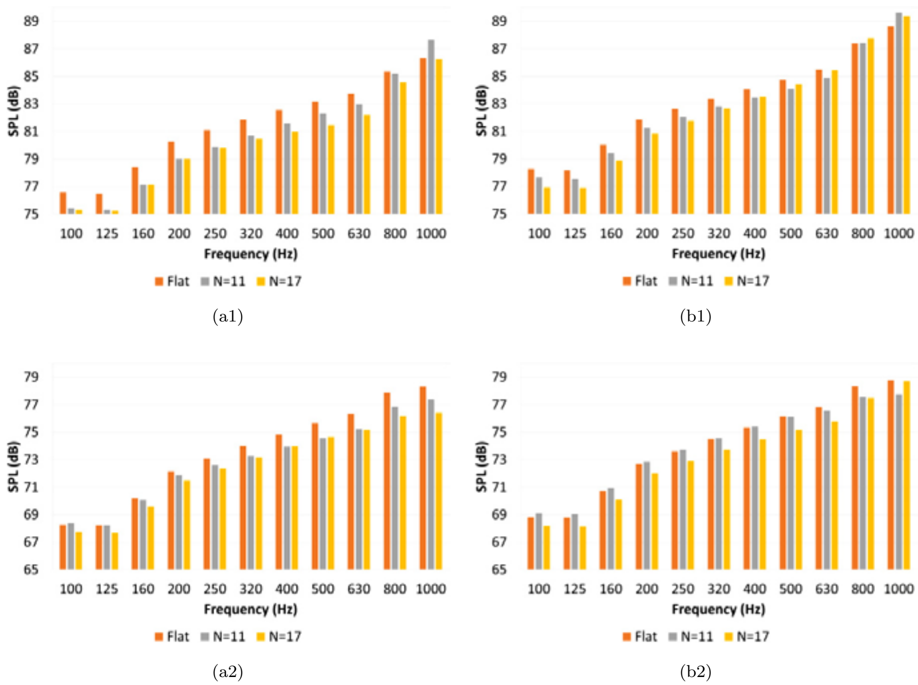


Fig. 17. Average SPL at the lower placed receivers, and considering receivers at $z = 0\,\text{m}$ ((a1) and (a2)) and at $z = 10\,\text{m}$ ((b1) and (b2)). Two source positions are considered, namely at $x = 5\,\text{m}$ (a) and $x = 3\,\text{m}$ (b).

6. Conclusions

The sound pressure field in an outdoor environment with a 3D sound source and linear acoustic barriers was here investigated. The aim of this work was mostly to computationally assess the possibility and the efficiency of using noise barriers with rigid but diffusive surfaces to help controlling the sound field generated when two such barriers are used in parallel. For this purpose, a 2.5D boundary element approach was used, synthesizing the 3D sound field as a discrete summation of simpler 2D problems.

The proposed barrier configurations result from a simplification of the well-known QRD diffusers, by removing the walls that delimit each well, resulting in a so-called sQRD design. Different orders N (17 and 11) and cross-sections of the acoustic sQRD panels were simulated and first compared with classic QRD solutions in a simpler 2D situation. Relevant differences were found, and, for similar geometries, the sQRD seems to exhibit performance peaks at higher frequencies than the classic QRD. The effect of considering the diffuser as a 3D structure was then analyzed, allowing to conclude that this effect can be quite important when long panels are used. According to the results obtained, the sQRD panels may reveal better performance within certain frequency bands depending on its frequency of design (400 Hz, 500 Hz and 1000 Hz were evaluated in this work). Besides, by changing the sQRD frequency design it is possible to change the effect to higher or lower frequency spectra. Our results indicate that using sQRD based on the classical QRD configuration obtained for a design frequency of 400 Hz or 500 Hz can maximize the diffusion effect at around 1000 Hz.

In what concerns the application of such panels in parallel acoustic barriers, some illustrative examples were presented, and allowed identifying the possible effects and benefits of their use. Indeed, the obtained results indicate that these structures, with $N = 11$ or $N = 17$, may allow some control over the reflected sound field that occurs between barriers, by breaking the original wavefronts into various waves with smaller amplitudes. The decay of energy within the space delimited by the barriers was also analyzed, evidencing some positive differences to the traditional flat barriers. However, perhaps the most important feature evidenced by the presented results is related to the capacity of the solution to allow establishing a more diffuse field between barriers, and even lowering the maximum amplitudes of the reflected field in a sensible manner.

It should be noted that the presented results were achieved only by numerical computation. While the BEM method used for the simulation has been demonstrated here and in preceding works to have very good precision when applied to acoustic problems, further research must be performed in order to confirm the possible benefits of such barriers with real measurements.

Acknowledgments

The work carried out was supported by the Portuguese Ministry of Education and Science — FCT and COMPETE under the project PTDC/ECM-COM/1438/2012. The authors also wish to thank the Government of Extremadura, the Regional Ministry of Economy, Trade and Innovation and the European Social Fund for funding the project.

References

1. A. Monzón and M. J. Guerrero, Valuation of social and health effects of transport-related air pollution in Madrid (Spain), *Sci. Total Environ.* **334–335** (2004) 427–434.
2. B. Berglund, T. Lindvall and D. H. Schwela, Guidelines for community noise, *World Health Organization* (1999).
3. A. Fyhri and G. M. Aasvang, Noise, sleep and poor health: Modeling the relationship between road traffic noise and cardiovascular problems, *Sci. Total Environ.* **408** (2010) 4935–4942.
4. C. Marquis-Favre, E. Premat, D. Aubrée and M. Vallett, Noise and its effects — A review on qualitative aspects of sound, Part I: Notions and acoustic ratings, in *Acta Acustica United with Acustica* **91** (2005) 613–625.
5. G. Mohammadi, An investigation of community response to urban traffic noise, *Iranian J. Environ. Health Sci. Eng.* **6** (2009) 137–142.
6. E. Öhrström, Longitudinal surveys on effects of changes in road traffic noise — Annoyance, activity disturbances, and psycho-social well-being, *J. Acoust. Soc. Am.* **115** (2004) 719–729.
7. M. Martins, L. Godinho and L. Picado-Santos, Numerical evaluation of sound attenuation provided by periodic structures, *Archives of Acoustics* **38** (2013) 503–516.

8. D. C. Hothersall, S. N. Chandler-Wilde and M. N. Hajmirzae, Efficiency of single noise barriers, *J. Sound Vibr.* **146** (1991) 303–322.
9. R. L. Wayson, A. MacDonald, A. El-Aassar and W. Arner, Continued evaluation of noise barriers in Florida, *Florida Dept. Transportation* (2002).
10. T. M. Barry and J. A. Reagan, FHWA highway traffic noise: Prediction model, Report FHWA-PD-77-108 and FHWA-PD-96-010. *Federal Highway, Administration, Washington DC* (Federal Highway Administration, Washington DC, 1978).
11. I. L. Vér and L. L. Beranek, *Noise and Vibration Control Engineering: Principles and Applications*, Second Edition (John Wiley & Sons, Inc., 2007), pp. 1–966.
12. C. E. Hanson, Federal Transit Administration's noise and vibration guidance manual — Updated after 10 years of experience (Minneapolis, MN, 2005).
13. Y. W. Lam, Using Maekawa's chart to calculate finite length barrier insertion loss, *Appl. Acoust.* **42** (1994) 29–40.
14. A. Muradali and K. R. Fyfe, A study of 2D and 3D barrier insertion loss using improved diffraction-based methods, *Appl. Acoust.* **53** (1998) 49–75.
15. T. Terai, On calculation of sound fields around three dimensional objects by integral equation methods, *J. Sound Vibr.* **69** (1980) 71–100.
16. P. Filippi and G. Dumery, Étude théorique et numérique de la diffraction par un écran mince, *Acustica* **21** (1969) 343.
17. Y. Kawai and T. Terai, The application of integral equation methods to the calculation of sound attenuation by barriers, *Appl. Acoust.* **31** (1990) 101–117.
18. C. A. Brebbia, J. C. F. Telles and L. C. Wrobel, *Boundary Element Techniques: Theory and Applications in Engineering* (Springer-Verlag, 1984).
19. T. Wu (Ed.), *Boundary Element Acoustics* (WIT Press, 2000).
20. F. J. F. G. Branco, L. Godinho and A. Tadeu, Acoustic insertion loss provided by rigid acoustic barriers of different shapes, *J. Comp. Acoust.* **11** (2003) 503–519.
21. L. Godinho, J. António and A. Tadeu, 3D sound scattering by rigid barriers in the vicinity of tall buildings, *Appl. Acoust.* **62** (2001) 1229–1248.
22. M. R. Monazzam and Y. W. Lam, Performance of profiled single noise barriers covered with quadratic residue diffusers, *Appl. Acoust.* **66** (2005) 709–730.
23. M. R. Monazzam and Y. W. Lam, Performance of T-shape barriers with top surface covered with absorptive quadratic residue diffusers, *Appl. Acoust.* **69** (2008) 93–109.
24. P. A. Morgan, D. C. Hothersall and S. N. Chandler-Wilde, Influence of shape and absorbing surface — A numerical study of railway noise barriers, *J. Sound Vibr.* **217** (1998) 405–417.
25. M. Baulac, J. Defrance and P. Jean, Optimisation with genetic algorithm of the acoustic performance of T-shaped noise barriers with a reactive top surface, *Appl. Acoust.* **69** (2008) 332–342.
26. M. Baulac, J. Defrance and P. Jean, Optimization of multiple edge barriers with genetic algorithms coupled with a Nelder–Mead local search, *J. Sound Vibr.* **300** (2007) 71–87.
27. D. Duhamel, Efficient calculation of the three-dimensional sound pressure field around a noise barrier, *J. Sound Vibr.* **197** (1996) 547–571.
28. D. Duhamel and P. Sergent, Sound propagation over noise barriers with absorbing ground, *J. Sound Vibr.* **218** (1998) 799–823.
29. A. J. B. Tadeu and L. M. C. Godinho, Three-dimensional wave scattering by a fixed cylindrical inclusion submerged in a fluid medium, *Eng. Anal. Bound. Elem.* **23** (1999) 745–755.
30. P. Jean, J. Defrance and Y. Gabillet, The importance of source type on the assessment of noise barriers, *J. Sound Vibr.* **226** (1999) 201–216.
31. M. Bouchon, Discrete wave number representation of elastic wave field in three-space dimensions, *J. Geophys. Res.* **84** (1979) 3609–3614.

32. R. A. Phinney, Theoretical calculation of the spectrum of first arrivals in layered elastic mediums, *J. Geophys. Res.* **70** (1965) 5107–5123.
33. M. R. Monazzam and P. Nassiri, Performance of profiled vertical reflective parallel noise barriers with quadratic residue diffusers, *Int. J. Environ. Res.* **3** (2009) 69–84.
34. D. C. Hothersall, D. H. Crombie and S. N. Chandler-Wilde, The performance of t-profile and associated noise barriers, *Appl. Acoust.* **32** (1991) 269–287.
35. K. Fujiwara, D. C. Hothersall and C. H. Kim, Noise barriers with reactive surfaces, *Appl. Acoust.* **53** (1998) 255–272.
36. C. Cianfrini, M. Corcione and L. Fontana, Experimental verification of the acoustic performance of diffusive roadside noise barriers, *Appl. Acoust.* **68** (2007) 1357–1372.
37. P. A. Mendes and A. Tadeu, Wave propagation in the presence of empty cracks in an elastic medium, *Comput. Mech.* **38** (2006) 183–199.
38. A. Tadeu, P. A. Mendes and J. António, 3D elastic wave propagation modelling in the presence of 2D fluid-filled thin inclusions, *Eng. Anal. Bound. Elem.* **30** (2006) 176–193.
39. M. Guiggiani, Formulation and numerical treatment of boundary integral equations with hypersingular kernels, *Singular Integrals in Boundary Element Methods*, Advances in Boundary Elements Series (Computational Mechanics Publications, Southampton, Boston, 1998), pp. 85–124.
40. A. Tadeu, J. António, L. Godinho and P. Amado Mendes, Simulation of sound absorption in 2D thin elements using a coupled BEM/TBEM formulation in the presence of fixed and moving 3D sources, *J. Sound Vibr.* **331** (2012) 2386–2403.
41. A. J. B. Tadeu, L. M. C. Godinho and J. M. P. António, Benchmark solutions for 3-D scattering from cylindrical inclusions, *J. Comput. Acoust.* **9** (2001) 1311–1327.
42. T. J. Cox and P. D'Antonio, *Acoustic Absorbers and Diffusers: Theory, Design and Application* (Taylor & Francis, 2009).

DISCUSSION AND FINAL CONCLUSIONS

In this thesis there has been a depth study of the predictive capacity that different methodologies have for estimating long-term indicators from short-term measurements. Fundamentally, the contributions are addressed, compared to previous publications, to the following goals:

From objective 1: The capacity to estimate and approximate the real equivalent hourly noise level ($L_{Aeq,1h}$ - Eq.3) from the integration of a number of consecutive minutes less than 60 has been studied. From the presented results, it follows that there is a high variability in the Stabilization Time values (the Stabilization is a parameter closely related to the temporal variability of the sound pressure level and to the appearance of impulsive sound events) depending on the hour of the day, the error condition considered and the location of the measurement station (this distinction was made according to the types of roads indicated in other studies in which a statistically significant relationship was found between noise levels and the road type).

The ST values required for the last hour of the night period (6:00 to 6:59) and the first of the day period (7:00 to 7:59) are very different from the rest of the hours, significantly higher. Thereby, an adequate selection of the measurement hour can be very important in terms of the percent of values stabilized (50%, 80%, 90%, 95% and 100%) and the required uncertainty (±2, ±1 and ±0.5 dB) for estimating $L_{Aeq,1h}$ (Eq. 3).

From the analysis by percentiles and considering all evaluated measurement stations, it is concluded that 15 min of integration time may be an appropriate time to achieve confidence levels of 90% and ±2 dB uncertainties, confidence levels of 80% and ±1 dB uncertainties, or 50% confidence levels and uncertainties of ±0.5 dB.

In addition, a stratified analysis of the measuring points (taking into account the categorization method proposed) leads to the conclusion that, for an error condition of ±2 dB and 15 min of measurement time, the confidence level to achieve stabilization in the stratum A (major roads) is equal to 95%. For strata B (secondary roads), C (district roads) and D (pedestrian), the confidence levels are 90 %, 80 % and 50 %, respectively.

From objective 2: The impact that specific/anomalous sound events can have on standard sound indicators contained in international laws and regulations (see section "Normativas y referencias legislativas") has been observed and quantified. If these singular noisy events are present or absent during the monitoring of a place, then long-term noise indices can be overestimating or underestimating, respectively, the indices established by the European.

The results displayed in this work could be extrapolated, in similar circumstances, to many countries around the world since the analyzed data proceed from 24 measurement stations located in three Spanish cities (Madrid, Málaga and Cáceres) of different size, very far apart, with very different planning, over a full year.

It has been detected the existence of a measurable effect of anomalous events on the average annual indices, L_{den} and L_n. The effect of this particular anomalous sound event (2010 FIFA World Cup) on the average annual indices was greater than 0.5 dB for the L_n indicator for nearly 40% of the measuring points evaluated in the work, with a maximum increase of 4.4 dB. It was also greater than 0.5 dB for the L_{den} in more than 20% of the locations, with a maximum increase of 2.2 dB.

In addition, it has been measured the individual effect of:

- The 2010 FIFA World Cup quarterfinals in more than 20% of the measurement stations for the L_n index, with a maximum increase of 0.7 dB, and 17% for the L_{den} index, with an increase up to 0.4 dB.
- The 2010 FIFA World Cup semi-finals at nearly 40% of the measurement stations for the L_n index, with a maximum increase of 0.4 dB, and 17% for the L_{den} index, with a maximum increase of 0.3 dB.
- The 2010 FIFA World Cup final at almost 100% of the measurement stations for both indices L_{den} and L_n, with a maximum increase of 3.5 dB for the first index and 1.8 dB for the second one.

Therefore, this study suggests that there are singular noisy events that may have an appreciable effect on the mean daily, monthly, and even annual noise indices, implying that would not be adequately addressed in the noise maps that are being developed, both by measurements and by sound field propagation models.

From objective 3: It conducted a systematic study of the capacity to estimate the annual indicator L_{den} from continuous measurements carried out during an arbitrary number of days randomly selected in the range from 3 to 60 days.

For this purpose, it has analyzed the capacity of estimation based on the use of two methods for obtaining the standard deviation. First, the value obtained from measurement data (it was used continuous measurements performed at 26 different stations located in Madrid -Spain- that were subject to different sound level conditions and variability throughout the days studied, using at least 95% of the days of the year), and second, the relation proposed in the literature.

From continuous measurement method, if it requires to obtain an estimate of annual L_{den} with a probability of success within a 90% confidence interval, it needs to take measurements for 9 days (on average) spread randomly throughout the year and it should use two standard deviations of the mean as an interval. If it requires a probability of 95%, the number of sampling days should be increased to 30–35.

From the mathematical relationship proposed in the literature for the estimation of annual L_{den}, contrasted with real data from our 26 measurement stations, suggests that it possible to achieve a probability of success of 90%. For 25–30 days and two standard deviations, the probability of success reaches 75%.

From objective 4: This work proposes a new analytical methodology in the study of temporal structure. The annual variability of noise levels associated with traffic has been studied in two Spanish cities (Madrid and Málaga) with very different geographic, urban planning and size features. By using the measurement stations of Madrid, a model has been proposed for estimating the long-term acoustic indicators from the continuous component A_0 (represents the linear average of the annual values) and mean amplitude values of the first and second highest harmonic component of the Fourier analysis.

The proposed model allows the transformation of a nonlinear problem (estimating the annual long-term parameters from daily values) into a linear problem (the estimation of the continuous or fixed component (A_0) of the Fourier harmonic series). The errors committed by the application of the model to both cities are, on average, less or equal than 1 dB for all acoustics indicators.

From objective 5: This work presents the first attempt to apply the categorization method (in order to classify streets into different groups based on their use as communication routes) to indicators obtained by long-term measurements, i.e. throughout the complete day.

First, it was conducted a stratification of the roads using the categorization method. Second, short and long-term measurements (approximately one week) were conducted at different sampling locations across different categories of streets.

Considering that linear noise sources are similar for short and long-term measurements, the sound power levels in the daytime indicate that short-term measurements are sufficient when an adequate number of long-term measurements cannot be conducted.

It was found a clear differentiation among the different categories with regard to the indices calculated from the long-term measurements. From these assumptions, it was surmise that the categorization method can be expected to sufficiently estimate the long-term indicators recommended in the European Directive. In addition, it was found that sound level variation behaves similarly throughout the day across the different categories. This finding implies that the city's sound is homogeneous across locations.

The ROC analysis that examined the predictive capacity of the categorization method in Plasencia (Spain) found overall sensitivities and predictive values higher than 85% with regard to the categorization method.

From objective 6: The present study shows that the categorization method is a suitable tool for assessment of the temporal and spatial noise, enabling the stratification of noise in cities. Hence, this method has advantages in terms of the reduction of sampling points and measurement time. The analysis of sound levels was registered over a year in 21 measurement stations located in Madrid (Spain) on roads with different functionality, implying the following results:

- A comparison of sound levels with the Kruskal-Wallis and Mann-Whitney U tests, shows that the differences among values of functional categories are statistically significant for a confidence interval of 95%.

- When analyzing the discrimination capacity of the categorization method using ROC curves, we found that all the pairs of categories presented AUC values above 0.94, indicating the high precision of the method. These values are the result of sensitivity and non-specificity close to 100% and 0% respectively. Also, ROC analysis indicates a good predictive capacity for non-measured values.
- The significant stratification of temporal variability in the different categories was mainly owed to the significant differences between average and low sound values (percentile Px – median Me). Also, the difference between diurnal and nocturnal sound levels (L_d - L_n) presented stratification in the three analyzed categories.
- The highly significant relation among types of range as a measurement of temporal variability and the success probability of average annual sound value corroborate the advantages from temporal perspective of the traffic roads stratification according to their functionality.

From objective 7: This work contributes to the body of knowledge regarding the physical and technical behavior of acoustic barriers. A 2.5D boundary-only numerical model is developed and implemented, and computational analyses are performed in order to compare different surface profiles of the acoustic barriers.

In addition, the sound pressure field in an outdoor environment with a 3D sound source and linear acoustic barriers was here investigated. The aim of this work was mostly to computationally assess the possibility and the efficiency of using noise barriers with rigid but diffusive surfaces to help controlling the sound field generated when two such barriers are used in parallel. For this purpose, a 2.5D boundary element approach was used, synthesizing the 3D sound field as a discrete summation of simpler 2D problems.

The proposed barrier configurations result from a simplification of the well-known QRD diffusers, by removing the walls that delimit each well, resulting in a so-called sQRD design. Different orders N (17 and 11) and cross-sections of the acoustic sQRD panels were simulated and first compared with classic QRD solutions in a simpler 2D situation. Relevant differences were found, and, for similar geometries, the sQRD seems to exhibit performance peaks at higher frequencies than the classic QRD.

According to the results obtained, the sQRD panels may reveal better performance within certain frequency bands depending on its frequency of design (400 Hz, 500 Hz and

1000 Hz were evaluated in this work). Besides, by changing the sQRD frequency design it is possible to change the effect to higher or lower frequency spectra. Our results indicate that using sQRD based on the classical QRD configuration obtained for a design frequency of 400 Hz or 500 Hz can maximize the diffusion effect at around 1000 Hz.

In what concerns the application of such panels in parallel acoustic barriers, some illustrative examples were presented, and allowed identifying the possible effects and benefits of their use. Indeed, the obtained results indicate that these structures, with N = 11 or N = 17, may allow some control over the reflected sound field that occurs between barriers, by breaking the original wavefronts into various waves with smaller amplitudes. The decay of energy within the space delimited by the barriers was also analyzed, evidencing some positive differences to the traditional flat barriers. However, perhaps the most important feature evidenced by the presented results is related to the capacity of the solution to allow establishing a more diffuse field between barriers, and even lowering the maximum amplitudes of the reflected field in a sensible manner.

BIBLIOGRAFÍA

Abbaspour M, Golmohammadi R, Nassiri P, Mahjub H. An investigation on time-interval optimisation of traffic noise measurement. Journal of Low Frequency Noise Vibration and Active Control 2006; 25: 267-273.

Alberola J, Flindell IH, Bullmore AJ. Variability in road traffic noise levels. Applied Acoustics 2005; 66: 1180-1195.

Ausejo M, Recuero M, Asensio C, Pavón I, López JM. Study of precision, deviations and uncertainty in the design of the strategic noise map of the macrocenter of the city of Buenos Aires, Argentina. Environmental Modeling and Assessment 2010; 15: 125-135.

Banerjee D, Chakraborty SK, Bhattacharyya S, Gangopadhyay A. Appraisal and mapping the spatial-temporal distribution of urban road traffic noise. International Journal of Environmental Science and Technology 2009; 6: 325-335.

Barrigón Morillas JM, Gómez Escobar V, Méndez Sierra JA, Vílchez-Gómez R, Vaquero JM, Trujillo Carmona J. A categorization method applied to the study of urban road traffic noise. Journal of the Acoustical Society of America 2005; 117: 2844-2852.

Beaumont J, Semidor C. Interacting quantities of the soundscape due to transport modes. Proceedings of the 2005 congress and exposition on noise control engineering (Inter-Noise), Rio de Janeiro, 2005, pp. 7p.

Bendtsen H. The Nordic prediction method for road traffic noise. Science of the Total Environment 1999; 235: 331-338.

Berglund B, Lindvall T. Community Noise. World Health Organization, Estocolmo, 1995.

Berglund B, Lindvall T, Schwela DH. Guidelines for community noise. World Health Organization, Geneva, 1999.

Birk M, Ivina O, Von Klot S, Babisch W, Heinrich J. Road traffic noise: Self-reported noise annoyance versus GIS modelled road traffic noise exposure. Journal of Environmental Monitoring 2011; 13: 3237-3245.

Björk EA. Community noise in different seasons in Kuopio, Finland. Applied Acoustics 1994; 42: 137-150.

Björkman M. Community noise annoyance: Importance of noise levels and the number of noise events. Journal of Sound and Vibration 1991; 151: 497-503.

Björkman M, Rylander R. Maximum noise levels in city traffic. Journal of Sound and Vibration 1997; 205: 513-516.

Bonvallet GL. Levels and spectra of noise in industrial and residential areas. Journal of the Acoustical Society of America 1949; 21: 463.

Botteldooren D, De Coensel B, De Muer T. The temporal structure of urban soundscapes. Journal of Sound and Vibration 2006; 292: 105-123.

Buss R. United Nations Conference on the Human Environment (UNCHE). June 5 to June 16, 1972. Stockholm, Sweden: United Nations, 2007.

Can A, Van Renterghem T, Rademaker M, Dauwe S, Thomas P, De Baets B, et al. Sampling approaches to predict urban street noise levels using fixed and temporary microphones. Journal of Environmental Monitoring 2011; 13: 2710-2719.

Comisión Europea. Libro Verde: Política futura de lucha contra el ruido. Vol 96. Bruselas: COM, 1996.

Craven NJ, Kerry G. A good practice guide on the sources and magnitude of uncertainty arising in the practical measurement of environmental noise: University of Salford, 2007.

Chakrabarty D, Santra SC, Mukherjee A, Roy B, Das P. Status of road traffic noise in Calcutta metropolis, India. Journal of the Acoustical Society of America 1997; 101: 943-949.

Chang TY, Liu CS, Bao BY, Li SF, Chen TI, Lin YJ. Characterization of road traffic noise exposure and prevalence of hypertension in central Taiwan. Science of the Total Environment 2011; 409: 1053-1057.

Da Paz EC, Zannin PHT. Urban daytime traffic noise prediction models. Environmental Monitoring and Assessment 2010; 163: 515-529.

De Coensel B. Introducing the Temporal Aspect in Environmental Soundscape Research. Faculty of Engineering. Ghen University, Ghent, Belgium, 2007.

De Muer T. Policy supporting tools for urban noise assessment. Vakgroep Informatietechnologie. University of Ghent, 2005.

Department of the Environment. Development Plans and Regional Planning Guidance. PPG12. HMSO, London 1992.

Di G, Liu X, Lin Q, Zheng Y, He L. The relationship between urban combined traffic noise and annoyance: An investigation in Dalian, north of China. Science of the Total Environment 2012; 432: 189-194.

Diniz FB, Zannin PHT. Noise impact caused by electrical energy substations in the city of Curitiba, Brazil. Science of the Total Environment 2004; 328: 23-31.

Doygun H, Kuşat Gurun D. Analysing and mapping spatial and temporal dynamics of urban traffic noise pollution: A case study in Kahramanmaraş, Turkey. Environmental Monitoring and Assessment 2008; 142: 65-72.

Embleton TFW. Tutorial on Sound Propagation Outdoors. Journal of the Acoustical Society of America 1996; 100: 31-37.

Environmental and Health Protection. Noise from fans and cooling systems in residential areas. Sweden, 1991.

European Parliament C. Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise. L 189, 2002, pp. 12-25.

Favre BM. Noise emission of road vehicles: Evaluation of some simple models. Journal of Sound and Vibration 1983; 91: 571-582.

Fothergill LC. The variation of environmental noise outside six dwellings between three seasons. Applied Acoustics 1977; 10: 191-200.

Fyhri A, Aasvang GM. Noise, sleep and poor health: Modeling the relationship between road traffic noise and cardiovascular problems. Science of the Total Environment 2010; 408: 4935-4942.

Gaja E. Contribución al estudio de un modelo matemático sobre el ruido emitido por el tráfico urbano y los niveles de molestia en el municipio de Valencia. ETSII Universidad Politécnica de Valencia, Valencia, 1984.

Gaja E, Giménez A, Sancho S, Reig A. Sampling techniques for the estimation of the annual equivalent noise level under urban traffic conditions. Applied Acoustics 2003; 64: 43-53.

García B, Garrido FJ. La contaminación acústica en nuestras ciudades. Barcelona: Fundación "La Caixa", 2003.

Griffiths ID, Langdon FJ. Subjective response to road traffic noise. Journal of Sound and Vibration 1968; 8: 16-28.

Guedes ICM, Bertoli SR, Zannin PHT. Influence of urban shapes on environmental noise: A case study in Aracaju - Brazil. Science of the Total Environment 2011; 412-413: 66-76.

ISO 1996-1. Acoustics. Description, measurement and assessment of environmental noise. Part 1: Basic quantities and assessment procedures. International Organization for Standardization, Switzerland, 2003.

ISO 1996-2. Acoustics. Description, measurement and assessment of environmental noise. Part 2: Determination of environmental noise levels. International Organization for Standardization, Switzerland, 2007.

ISO 9613-1. Acoustics. Attenuation of sound during propagation outdoors. Part 1: Calculation of the absorption of sound by the atmosphere. International Organization for Standardization, Switzerland, 1993.

ISO 9613-2. Acoustics. Attenuation of sound during propagation outdoors. Part 2: General method of calculation. International Organization for Standardization, Switzerland, 1996.

Jagniatinskis A, Fiks B, Mickaitis M. Statistical assessment of environmental noise generated by road traffic. Transport 2011; 26: 96-105.

Kihlman T, Abukhader S. Long-term noise abatement planning-case studies in Göteborg, Sweden. Inter-noise, The Hague, Holland, 2001.

Ley 37/2003. De 17 de noviembre, del Ruido. BOE num. 276 de 18/11/2003.

Li B, Tao S, Dawson RW. Evaluation and analysis of traffic noise from the main urban roads in Beijing. Applied Acoustics 2002; 63: 1137-1142.

Luquet P. Method for the objective description of an acoustic environment based on short Leq values. Applied Acoustics 1982; 15: 147-156.

Makarewicz R, Gałuszka M. Nonlinear uncertainty of the long term average level calculated from short term average sound levels. Noise Control Engineering Journal 2012; 60: 770-774.

Malchaire JB, Hortman SW. Community noise survey of Cincinnati, Ohio. Journal of the Acoustical Society of America 1975; 58: 197-200.

Marquis-Favre C, Premat E, Aubrédue D. Noise and its effects - A review on qualitative aspects of sound. Part II: Noise and annoyance. Acta Acustica united with Acustica 2005a; 91: 626-642.

Marquis-Favre C, Premat E, Aubrée D, Vallett M. Noise and its effects - A review on qualitative aspects of sound. Part I: Notions and acoustic ratings. Acta Acustica united with Acustica 2005b; 91: 613-625.

Maruyama M, Kuno K, Sone T. The minimum measurement time for estimating LAeqT of road traffic noise from the number of vehicle pass-bys. Applied Acoustics 2013; 74: 317-324.

Meister FJ. Traffic noise in West Germany, evaluation of noise levels and experience in noise control. Journal of the Acoustical Society of America 1956; 28: 783.

Mohammadi G. An investigation of community response to urban traffic noise. Iranian Journal of Environmental Health Science and Engineering 2009; 6: 137-142.

National Physical Planing Agency. Summary of the Fourth Report Extra on Physical Planing. Ministry of Housing, Physical Planing and Environment, The Hague, Netherlands, 1991.

Nelson PM. Introduction to transport noise. Vol 1. Butterworths, London, 1987.

Ng CH, Tang SK. On monitoring community noise using arbitrarily chosen measurement periods. Applied Acoustics 2008; 69: 649-661.

Öhrström E. Psycho-social effects of traffic noise exposure. Journal of Sound and Vibration 1991; 151: 513-517.

Öhrström E, Rylander R. Sleep disturbance by road traffic noise - A laboratory study on number of noise events. Journal of Sound and Vibration 1990; 143: 93-101.

Öhrström E, Skånberg A. Sleep disturbances from road traffic and ventilation noise-laboratory and field experiments. Journal of Sound and Vibration 2004; 271: 279-296.

Omiya M, Kuno K, Mishina Y, Oishi Y, Hayashi A. Comparison of community noise ratings by L50 and LAeq. Journal of Sound and Vibration 1997; 205: 545-554.

Onuu MU. Road traffic noise in Nigeria: Measurements, analysis and evaluation of nuisance. Journal of Sound and Vibration 2000; 233: 391-405.

Oyedepo OS, Saadu AA. Evaluation and analysis of noise levels in Ilorin metropolis, Nigeria. Environmental Monitoring and Assessment 2010; 160: 563-577.

Ozer S, Yilmaz H, Yeşil M, Yeşil P. Evaluation of noise pollution caused by vehicles in the city of Tokat, Turkey. Scientific Research and Essays 2009; 4: 1205-1213.

Purkis HJ. Transport noise and town planning. Journal of Sound and Vibration 1964; 1: 323-324.

Real Decreto 1367/2007. De 19 de octubre, por el que se desarrolla la Ley 37/2003, de 17 de noviembre, del Ruido, en lo referente a zonificación acústica, objetivos de calidad y emisiones acústicas. BOE num. 254 de 23/10/2007.

Real Decreto 1513/2005. De 16 de diciembre, por el que se desarrolla la Ley 37/2003, de 17 de noviembre, del Ruido, en lo referente a evaluación y gestión del ruido ambiental. BOE num. 301 de 17/12/2005.

Rey Gozalo G, Barrigón Morillas JM, Gómez Escobar V. Urban Streets Functionality As A Tool For Urban Pollution Management. Science of the Total Environment 2013; 461-462: 453-461.

Rey Gozalo G, Barrigón Morillas JM, Prieto Gajardo C. Urban noise functional stratification for estimating average annual sound level. Journal of the Acoustical Society of America 2015; 137: 3198-3208.

Romeu J, Genescà M, Pàmies T, Jiménez S. Street categorization for the estimation of day levels using short-term measurements. Applied Acoustics 2011; 72: 569-577.

Romeu J, Jiménez S, Genescà M, Pàmies T, Capdevila R. Spatial sampling for night levels estimation in urban environments. Journal of the Acoustical Society of America 2006; 120: 791-800.

Sato T, Yano T, Björkman M, Rylander R. Road traffic noise annoyance in relation to average noise level, number of events and maximum noise level. Journal of Sound and Vibration 1999; 223: 775-784.

Schafer RM. The soundscape: our sonic environment and the tunning of the world. Rochester, Vermont, USA, 1994.

Shaw EAG. Noise Environments Outdoors and the Effects of Community Noise Exposure. Noise Control Engineering Journal 1996; 44: 109-119.

Skinner CJ, Grimwood CJ. The UK noise climate 1990-2001: Population exposure and attitudes to environmental noise. Applied Acoustics 2005; 66: 231-243.

Sommerhoff J, Recuero M, Suárez E. Community noise survey of the city of Valdivia, Chile. Applied Acoustics 2004; 65: 643-656.

Steele C. A critical review of some traffic noise prediction models. Applied Acoustics 2001; 62: 271-287.

Tang UW, Wang ZS. Influences of urban forms on traffic-induced noise and air pollution: Results from a modelling system. Environmental Modelling and Software 2007; 22: 1750-1764.

To WM, Ip RCW, Lam GCK, Yau CTH. A multiple regression model for urban traffic noise in Hong Kong. Journal of the Acoustical Society of America 2002; 112: 551-556.

Torija AJ, Ruiz DP. Using recorded sound spectra profile as input data for real-time short-term urban road-traffic-flow estimation. Science of the Total Environment 2012; 435-436: 270-279.

Torija AJ, Ruiz DP, Ramos-Ridao A. Obtaining of a factor to describe the anomalous sound events in traffic noise measurements. Proceedings of the 19th International Congress on Acoustics, Madrid, Spain, 2007.

Torija AJ, Ruiz DP, Ramos-Ridao A. Required stabilization time, short-term variability and impulsiveness of the sound pressure level to characterize the temporal composition of urban soundscapes. Applied Acoustics 2011; 72: 89-99.

Torija AJ, Ruiz DP, Ramos-Ridao A. Estimation procedure of the descriptor L Aeq, T from the stabilization time of the sound pressure level value. Noise and Vibration Worldwide 2012; 43: 11-18.

Van Renterghem T, Botteldooren D, Dekoninck L. Evolution of building façade road traffic noise levels in Flanders. Journal of Environmental Monitoring 2012; 14: 677-686.

Walerian E, Janczur R, Czechowicz M. Sound levels forecasting for city-centers. Part I: Sound level due to a road within an urban canyon. Applied Acoustics 2001a; 62: 359-380.

Walerian E, Janczur R, Czechowicz M. Sound levels forecasting for city-centers. Part II: Effect of source model parameters on sound level in built-up area. Applied Acoustics 2001b; 62: 461-492.

Wang JH, Chang C. Identification of the number and locations of acoustic sources. Journal of Sound and Vibration 2005; 284: 393-420.

WHO. El Ruido. Criterios de salud ambiental. World Health Organization 1983; 454 OPS/WHO, Ginebra.

Wolde TT. The EU Noise Policy and the Related Research Needs. Acta Acustica (Stuttgart) 2003; 89: 735-742.

Zannin PHT, Diniz FB, Barbosa WA. Environmental noise pollution in the city of Curitiba, Brazil. Applied Acoustics 2002; 63: 351-358.

Zannin PHT, Engel MS, Fiedler PEK, Bunn F. Characterization of environmental noise based on noise measurements, noise mapping and interviews: A case study at a university campus in Brazil. Cities 2013; 31: 317-327.

Zannin PHT, Sant'Ana DQ. Noise mapping at different stages of a freeway redevelopment project – A case study in Brazil. Applied Acoustics 2011; 72: 479-486.

ANEXOS

Apéndice 1: Factor de impacto y área temática de las revistas

ISSN	Full Journal Title	Subjetc Category	IF	5 year IF	J. Rank
0003-682X	Applied Acoustics	Acoustics	1,068	1,269	15/31
0137-5075	Archives of Acoustics	Acoustics	0,656	0,482	22/31
1230-1485	Polish Journal of Environmental Studies	Environmental Sciences	0,871	0,888	185/221
0167-6369	Environmental Monitoring and Assessment	Environmental Sciences	1,910	1,918	110/221
0048-9697	Science of the total Environment	Environmental Sciences	4,099	4,414	18/221
0218-396X	Journal of Computational Acoustics	Acoustics	0,852	0,664	18/31
0001-4966	Journal of the Acoustical Society of America	Acoustics	1,503	1,736	11/31

Apéndice 2: Justificación de la contribución del doctorando

Artículo I. Barrigón Morillas, J. M., Prieto Gajardo, C. (2013). "Uncertainty evaluation of continuous noise sampling," *Applied Acoustics 75*, 27-36.

En este primer trabajo, el doctorando Carlos Prieto Gajardo participó de una manera fundamental en el planteamiento inicial y posterior del trabajo, la elaboración de la revisión bibliográfica, el diseño, utilización y creación de la base de datos con los niveles sonoros anuales de las 26 estaciones de medida evaluadas, el análisis de los datos y la búsqueda de las relaciones entre los niveles anuales reales y los estimados mediante muestreo de días aleatorios. Así mismo, participó en la redacción del artículo y en las correcciones requeridas por los editores de la revista.

Artículo II. Rey Gozalo, G., Barrigón Morillas, J.M., Gómez Escobar, V., Vílchez-Gómez, R., Méndez Sierra, J.A., Carmona del Río, F.J. & Prieto Gajardo, C. (2013): "Study of the Categorisation Method Using Long-Term measurements". *Archive of Acoustics 38(3)*, 397-405.

La contribución del doctorando en este segundo trabajo fue la colaboración en la ubicación y estratificación de las calles de la ciudad de acuerdo al "Método de Categorización" desarrollado por el Laboratorio de Acústica de la Universidad de Extremadura, el tratamiento de los datos obtenidos de las medidas para la posterior aplicación del "método" sobre los indicadores acústicos de larga duración, la colaboración en el análisis y obtención de los resultados y, por último, la colaboración en la redacción y revisión del trabajo.

Artículo III. Prieto Gajardo, C., Barrigón Morillas, J.M., Gómez Escobar, V., Vílchez-Gómez, R., Rey Gozalo, G. (2014): "Effects of singular noisy events on long-term environmental noise measurements". *Polish Journal of Environmental Sciences 23(6)*, 2007-2017.

La contribución del doctorando en este tercer trabajo fue la colaboración en el planteamiento inicial y posterior del trabajo, la elaboración de la revisión bibliográfica, la utilización y creación de la base de datos con los niveles sonoros de las 24 estaciones de medida evaluadas, la observación y cuantificación de la contribución de los eventos sonoros puntuales o anómalos sobre los índices anuales establecidos en la directiva europea, el análisis y discusión de los resultados y la búsqueda de las relaciones entre los niveles anuales teniendo en cuenta tales sucesos y sin ellos. Así mismo, se responsabilizó de la redacción del artículo, colaboró en las correcciones requeridas por los editores de la revista e hizo la presentación y discusión de los resultados en congreso de ámbito internacional.

Artículo IV. Prieto Gajardo, C., Barrigón Morillas, J.M. (2014): "Stabilisation patterns of hourly urban sound levels". *Environmental Monitoring and Assessment 187(1)*, 1-16.

La contribución del doctorando en este cuarto trabajo fue la colaboración en el planteamiento inicial y posterior del trabajo, así como en la elaboración de la revisión bibliográfica, la adquisición y creación de la base de datos con los niveles sonoros obtenidos durante 5 años en las 12 estaciones de medida evaluadas en la ciudad de Málaga, la ubicación y estratificación de las calles de acuerdo al "Método de Categorización", el análisis estadístico de los datos y la búsqueda de las relaciones entre la estabilidad de los periodos horarios y las diferentes categorías. Así mismo, se responsabilizó de la redacción del artículo, y participó en las correcciones requeridas por los editores de la revista y en la presentación y discusión de los resultados en congreso de ámbito internacional.

Artículo V. Barrigón Morillas, J.M., Ortíz-Caraballo, C., Prieto Gajardo, C. (2015): "The temporal structure of pollution levels in developed cities". *Science of the Total Environment 517*, 31-37.

La contribución del doctorando en este quinto trabajo fue la colaboración en el planteamiento inicial y posterior del trabajo, así como en la elaboración de la revisión bibliográfica, la adquisición y creación de la base de datos con los niveles sonoros de las 27 estaciones de medida evaluadas en las ciudades de Madrid y Málaga, la ubicación y estratificación de las calles de acuerdo al "Método de

Categorización", la implementación de la metodología analítica en el software de análisis matemático y la búsqueda de las relaciones entre las estaciones de las diferentes categorías y la estructura temporal. Así mismo, se responsabilizó de la redacción del artículo y participó en las correcciones requeridas por los editores de la revista.

Artículo VI. Prieto Gajardo, C., Godinho, L., Amado-Medes, P.A., Barrigón Morillas, J.M. (2015): "Numerical Analisis of Acoustic Barriers with a Diffusive Surface Using a 2.5D Boundary Element Model". *Journal of Computational Acoustics 23(3).*

La contribución del doctorando en este sexto trabajo fue la elaboración de la revisión bibliográfica y estado del arte así como el planteamiento posterior del trabajo, la colaboración en el diseño e implantación del código para la simulación de barreras acústicas diseñadas mediante difusores QRD y la obtención de los resultados mediante software de análisis matricial. Así mismo, se responsabilizó de la redacción del artículo, y participó en la elaboración de las correcciones requeridas por los editores de la revista y en la presentación y discusión de los resultados en congresos de ámbito internacional.

Artículo VII. Rey Gozalo, G., Barrigón Morillas, J.M., Prieto Gajardo, C. (2015): "Sound Variability Stratification for Estimating Average Annual Sound Level". *Journal of the Acoustical Society of America 137(6),* 3198-3208.

Por último, la contribución del doctorando en este séptimo trabajo fue la colaboración en el planteamiento inicial del trabajo, la creación y diseño de la base de datos con los niveles sonoros anuales de las 21 estaciones de medida ubicadas en Madrid, la colaboración en la ubicación y estratificación de las calles de acuerdo al "Método de Categorización" y la colaboración en el análisis y discusión de los resultados. Así mismo, participó en la redacción del artículo y en las correcciones requeridas por los evaluadores de la revista.