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Pervasive wireless sensors: A new monitoring tool for road traffic noise evaluation

Shadman Marouf[a,*], Margaret Carol Bell[a], Paul Goodman[a], Anil Namdeo[a], Jeffery Neasham[b]

[a] School of Engineering, Newcastle University, Cassie Building, Claremont Road, Newcastle upon Tyne NE1 7RU, United Kingdom
[b] Stephenson Building, Claremont Road, Newcastle upon Tyne NE1 7RU, United Kingdom

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ABSTRACT

Noise pollution is estimated to affect 170 million citizens in Europe, causing serious public health problems [1]. The World Health Organisation claims that at least one million healthy life years are lost per year in Europe due to road traffic noise [2]. Effective management of noise requires an understanding of its causes. This understanding is limited by traditional monitoring methods, which employ expensive equipment and are labour intensive. This paper presents the results of a comprehensive programme of correction and validation of a low-cost device referred to as an eMote for pervasive monitoring and is the first to quantify the accuracy of inexpensive noise systems that use microphones typically costing about one Euro.

Pervasive wireless noise sensors (eMotes) were validated by co-location with precision sound level meters in controlled indoor, and at roadside outdoor environments. Strong linear relationships between the eMotes and the precision systems, across a noise range between 55 dBA and 94 dBA were observed and exhibited consistent bias compared to the precision measurement. Therefore, a generic, corrective relationship was derived and validated in three contrasting outdoor traffic noise environments, employing both short-term attended, and long-term unattended measurements, which were carried out during day and/or evening and/or night periods.

The eMotes were shown to respond consistently to *white* and *pink* generated noise during the evaluation of the accuracy process, and the generic correction algorithm for *white* noise delivered better than 3 dBA accuracy in comparison to precision data at a one-minute averaging resolution. The correction algorithm improved the concordance correlation coefficient (ccc) and coefficient of determination (R^2) of the eMote measurements against those of the precision instrument. Removal of short-duration, excessively loud events (e.g. sirens), which represented 2% of the total data, improved the ccc and R^2 values further typically to 0.74 and 0.60 respectively, which is considered good, given the limitations of the experimental procedure. The research provides scientific evidence that whilst not acceptable for compliance monitoring to standards for noise exposure, the eMote is a valuable system to screen for excessive exposure; to understand the causes of traffic related noise in urban areas; to provide an indication of the spatial and temporal variation in noise levels and the knowledge to design appropriate solutions, in turn this will lead to more effective abatement. The continued monitoring allows the impact to be quantified giving confidence that intervention measures are worthwhile, delivering added value compared to current measurement methods.

1. Introduction

Noise, or “unwanted sound”, has been declared a pollutant since 1972 by the World Health Organization (WHO) [3,4]. Noise pollution is a major environmental problem in Western Europe, with traffic being one of the major sources. In the UK urban road traffic noise dominates, with approximately 12 million people exposed to levels sufficient to cause disturbance [5]. In EU countries, more than 40% of citizens have been estimated to be exposed to road traffic noise levels exceeding 55 dBA during day time, whilst at night the figure is 30% [1]. It is estimated that 170 million citizens in Europe live in areas where noise levels cause serious health impacts during the daytime [6]. Whilst, the number of peolple exposed to noise pollution is much higher in developing countries, the long-term effects are the same in both [7]. There are several studies showing that environmental noise affects health and well-being through causing annoyance, sleep disturbance and cardiovascular diseases, such as hypertension and ischaemic heart disease [1]. The evidence presented by the WHO identifies the serious impact of

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* Corresponding author.
E-mail addresses: s.s.marouf@ncl.ac.uk (S. Marouf), margaret.bell@ncl.ac.uk (M.C. Bell), paul.goodman@ncl.ac.uk (P. Goodman), anil.namdeo@ncl.ac.uk (A. Namdeo), jeff.neasham@ncl.ac.uk (J. Neasham).

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environmental noise on public health throughout the world, estimating that at least one million healthy life years are lost per year in Europe due to road traffic noise [2]. The same report concludes that traffic noise annoys one in three individuals during the daytime and disturbs one in five at night.

These facts, along with growing evidence of the levels of noise and their health effects prompted the WHO in 1999 to publish guidelines for community noise [8]. These guidelines present noise threshold values and health effects when values exceed specific limits. For example, to protect the majority of residents from *moderate* and *serious* annoyance the day time outdoor noise L_{Aeq} should not exceed 50 and 55 dBA respectively, and the levels should be lower by 5 and 10 dBA for evening and night period respectively. At night time [9] advocates that outdoor L_{Aeq} above 40 dBA should be mitigated against suggesting 55 dBA as an interim target for the countries where the achievement is not feasible in the short term. The first round of noise mapping was delivered in 2007 and the second round was due for submission in October 2012, but as yet in 2017 maps are not available to the general public.

Current noise maps are mostly created using noise prediction models [1], which are based mainly on data from transportation planning or traffic assignment models with composition, speed and flow estimates representing peak periods of typically 2 or 3 h duration. These often fail to provide accurate estimates of noise pollution levels which need hourly levels over 24 h periods of the day. If monitored data is available the input variables are usually averaged for each hour over the day across a measurement period but at one location on a link. Data is available for typically 50–100 locations across a city. However, these isolated measurements are assumed to be representative of the entire length of road leading to noise estimates which fail to capture the variability of, and change in levels of noise along the length of a road and in close proximity to, and at, junctions.

Commonly used noise monitoring equipment enables highly reliable and precise noise measurements to be made, but measurements are often limited to few sites due to the high cost of instruments (up to 30,000 euros) [10]. Also, such measurements are labour intensive, especially when noise levels need to be measured at numerous points across a study area [11]. Because of security issues, precision monitors cannot be realistically deployed on the roadside for extended periods. Hence, data collection periods may be short, potentially introducing errors and biases caused by unrepresentative short-term effects. Murphy and King [1] claimed that at least 14 days of continuous noise monitoring is needed to give a useful description of the noise environment. Such assessment is expensive and impractical especially for cities with limited budgets [12]. Another issue with precision measurement is that, given limited equipment availability, monitoring can only ever capture noise levels at a few, discrete positions at a time, resulting in asynchronous noise readings at different locations [13]. High-precision monitoring may be required across large areas, with the number or distribution of monitoring points not matching available resources [12,14]. Noise level maps can only be verified and validated by the direct measurement of the spatial and temporal variations of noise levels across an urban area, but given the fact that precision sound level meters are so expensive and labour intensive, validation of maps is severely restricted to a few sites only.

In the last decade, to overcome the shortfalls of precision monitoring systems, scholars [10,15–21], have researched alternative more cost effective and convenient approaches to monitoring noise. This led to the development of low cost pervasive sensor systems, that deploy wireless networks, to monitor noise along roads, at dwellings, or in sensitive locations.

The UK Engineering and Physical Sciences Research Council (EPSRC) funded the project MESSAGE (Mobile Environmental Sensing System Across Grid Environments) which led to the development of pervasive sensor prototypes [18,22]. These were commercialised as eMotes (electronic Mote) by Envirowatch Ltd.. In general, such acoustic networks consist of a number of autonomous, low cost, self-powered single processor sensors referred to as ‘nodes’ within a network. Other examples of pervasive sensor systems include: Tmote-Sky [19] CiNet [21,23], IoT [24], TmI and RPi [20], ELECTRET1, ELECTRET4, TYPEII, MEMS1 [15] and CinetNoise sensor node [10]. The cost of an electret microphone used with the sensor systems typically ranges from one to a few hundred Euros or pounds sterling. Given their low cost, large numbers of sensor systems may be deployed over wide areas to monitor variation in road traffic noise spatially and temporally, enabling both real-time and long-term data collection, with a minimal amount of maintenance. The nodes within the network communicate using multi-hop routing protocols and typically provide the equivalent A-weighted sound pressure level over a specific time period ‘T’, symbolized by $L_{Aeq,T}$ [20]. The noise level data are transferred co-operatively from an individual node’s memory to a central ‘sink’ node more often referred to as a ‘gateway’. The latter acts as an external connector, which has an internal clock to provide an accurate time stamp to the data captured in the network, and sends the data wirelessly to a remote central server for data synchronisation and storage either using 3G/GPRS modem or WiFi connection. The server, or client systems, may provide additional facilities for the post-processing and visualisation of the collected data.

Measurements of road traffic noise with different Wireless Sensor Network systems have been demonstrated and published in the literature [15,16,20,21,25]. Generally, the authors asserted the possibility to deploy the wireless noise sensors, on street furniture along roadsides. However, none of the published projects, except [15], have mentioned both long-term data collection along with co-location of the precision sound level meter, to check the accuracy of the measurements, considering the within-hour and day-to-day variability in noise levels from road traffic.

Van Renterghem et al. [15] deployed eight different types of microphones, ranging from low to high price in an outdoor environment for six months, to assess the microphone performance under different weather conditions. The microphones, installed on a bar at height equal to 1.7 m, faced a busy trafficked viaduct at about 150 m distance. The average noise level was 65 dBA during the day, and 50 dBA at night. The study demonstrated the high correlation between (5 out of 7) inexpensive wireless microphones tested and the reference microphone. This was a Brüel and Kjær type 4189 microphone capsule, connected to the dedicated noise measurement hardware system, Bruel and Kjaer PULSE software system, with front end type 3560C. However, the study only derived the coefficient of determination, which measures how close the data are to the fitted regression line, but failed to report any departure from the true line with a slope and intercept equal to 1 and 0 respectively as was the case for Segura-Garcia et al. [20].

In the field trial [21] five low cost sensors were deployed in a line perpendicular to a motorway, with 10 m separation between the units. A precision Cesva SC-20c SLM was systematically co-located with each sensor in turn giving simultaneous 5 min samples. The results showed on average a difference of less than 2 dBA between the measured and reference levels. However, the measurement period of 5 min especially at a sampling rate of 1 Hz, given the huge variability in the levels of road traffic noise prevailing during the day and night, is considered to be insufficient to appropriately evaluate the accuracy.

In 2009, the MESSAGE project designed, developed and deployed prototype low cost pervasive sensors at various sites in England (Leicester, Leeds, Gateshead and London) to measure noise, as well as air pollution (carbon monoxide, nitric oxide and nitrogen dioxide), temperature and humidity. A deployment of 50 wireless sensors was made in Leicester, UK, covering an area of approximately 1 km^2, which included different types of roads and acoustic scenarios in the vicinity of a busy signalised junction. These early prototype eMotes were validated by co-location with a precision monitor. The results highlighted the consistency of measurement across all eMotes and insensitivity of the low cost microphones to short-term peak noise events, and to levels below 45 dBA [26] and concluded that the accuracy of measurement was ~3 dBA [25]. However, the response of the microphone across the