Assessing Environmental Impact of Transport Noise with Wireless Sensor Networks

Paul McDonald, Dermot Geraghty, Ivor Humphreys, and Stephen Farrell

Noise pollution from transportation systems devalues the environment and carries with it substantial social and economic costs. New legislation aims to reduce the impact of transport noise. This study outlines how wireless sensor networks can be used to assess accurately the socio-economic benefits of noise mitigation policies. Various economic methods of estimating the disamenity of noise are explored. Current practices for predicting the benefits of noise reduction strategies are examined, and the need for a long-term monitoring solution within the current system is observed. Sensor network with delay tolerance (SeNDT) units are presented as a wireless sensor networking device capable of monitoring environmental noise levels. Preliminary results from the SeNDT pilot study deployments are presented. These readings are used to estimate both the personally perceived and monetary gains resulting from the implementation of a new traffic policy that bans heavy goods vehicles in the city center of Dublin, Ireland. Initial calculations indicate that the ban will reduce the number of people annoyed by road traffic noise by approximately 8% and constitute a monetary saving of €77.50 ($105) per household in the area per year.

As the scale of transport systems has increased in recent decades, so too has the noise generated by these systems. Whether caused by road, rail, or air travel, the amount of noise pollution and also the number of people affected by it have grown dramatically. In recent years relevant authorities have begun to address this issue. Governments have drawn up legislation to combat noise pollution, efforts have been made to minimize the number of people exposed to noise from transport systems, and several studies have been conducted to try to help better understand the effects of noise exposure.

It is difficult to quantify noise pollution definitively. Certainly noise levels that damage one's hearing are harmful, but what about noise that does not physically harm people but simply annoys them? Again it is hard to define exactly what constitutes annoyance or what its consequences are. Whether it can be directly quantified or not, annoyance due to noise pollution has been shown to have several detrimental effects on people's health. Traffic noise has been shown to affect children's learning. Noise in the workplace leads to reduced productivity and lack of concentration. Noise during the night disrupts sleep patterns. Noise pollution results in elevated stress levels and can also increase the risk of cardiovascular and circulatory problems (*1*).

The pollution of auditory surroundings not only diminishes the quality of life but also devalues the environment as a whole.

VALUE OF THE ENVIRONMENT

One of the problems associated with assessing the impact of noise pollution is the relative nature of sound measurement. Apart from the fact that sound levels are measured on a logarithmic scale, noise intrusion can often be highly relative to the listener's surroundings. The impact of noise events is commonly compared with the background or ambient noise level and so is not solely dependent on the decibel level of the noise. As a result, it is difficult to quantify the personal or environmental impact of particular noise levels. A number of approaches have been adopted over the years that aim to put a value on noise reduction, either by gauging the annoyance to the public or by estimating the economic value of noise abatement. A recent study by a European Union (EU) working group of noise experts suggests a method based on dose–effect relationships for evaluating the number of people annoyed by noise from a given source (*2*). The dose–effect relationship is the relationship between the dose of harmful factors (i.e., noise) and the severity of their effect on exposed subjects.

This position paper (essentially an advisory paper for the European Council) uses the percentage of people annoyed (%A) and percentage of people highly annoyed (%HA) as metrics for noise-related annoyance in a community. The noise indicator used is L_{den}, as selected for noise annoyance in the EU noise directive (*3*). L_{den} is a noise-level reading that takes account of day, evening, and nighttime noise. Weightings are applied to the different periods to account for the fact that noise can be more annoying at different times of the day. The evening period (7:00 to 11:00 p.m.) carries a weighting of +5 dB, and nighttime noise (11:00 p.m. to 7:00 a.m.) carries a penalty of +10 dB. The L_{den} represents the yearly average noise level.

The use of dose–effect relationships produces results that are more comprehensible for the general public; not everyone is familiar with the L_{den} measurement but a useful measure of how annoying a particular noise source is can be easily understood. The working group proposed expressions for estimating the %A and %HA for a given source of transportation noise. The position paper also outlines possible mitigation strategies that may arise from the calculation of

P. McDonald, D. Geraghty, and I. Humphreys, Department of Mechanical and Manufacturing Engineering, School of Engineering, and S. Farrell, Department of Computer Science, Trinity College, Dublin 2, Ireland. Corresponding author: P. McDonald, pmcdonal@tcd.ie.

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these data. The following abatement and prevention measures are suggested:

- Elimination of unacceptable noise levels by imposing a legal limit in terms of L_{den}, possibly linked to the type of source;
- Preservation and extension of quiet areas both residential and natural; and
- Improvement of acoustic environment in areas where L_{den} is arbitrarily deemed to be too high (*2*).

Current EU policy aims to reduce the effects of transport noise on the general population and will no doubt continue to be so aimed for the foreseeable future. The success of these policies can only be quantified by the employment of useful methodologies and metrics such as the dose–effect relationship, provided that the underlying data accurately represent the situation. In order to fully evaluate the impact of noise pollution, or indeed noise prevention, accurate measurement of noise emissions from transport systems is necessary.

But what about the more indirect impacts of noise pollution? Quantifying annoyance is indeed useful and provides a means of describing noise in a way that is easy to understand. However, there is another metric that everyone can understand—money. What is the cost of environmental noise? In 1992 the French National Planning Office used dose–effect relationships to calculate a value of €137 ($187) per person annoyed per year (*4*). In addition to annoyance and other personal factors, noise pollution has several detrimental effects in an economic sense. During the 1980s and early 1990s numerous studies were carried out aimed at estimating the costs of traffic noise. They examined areas such as losses in property value, productivity losses, costs voluntarily incurred by the public, and government expenditure on abatement strategies. Soguel (*5*) estimated that the people of Neuchâtel in Switzerland were willing to pay approximately €710 ($970) per annum to reduce their exposure to traffic noise by half (*1*). A more recent study by Bjorner in Copenhagen, Denmark, estimated that at 65 dB the inhabitants were willing to pay €6 ($8) per decibel reduction per year (*6*).

These studies were compiled with the contingent valuation method, an economic and statistical tool used to estimate a monetary value for intangible things like "peace and quiet" by surveying the attitudes of the general public. This stated-preference approach involves questioning a representative sample of the population about how much they would be willing to pay for a reduction in noise exposure. Their willingness to pay (WTP) can refer to preventive measures such as home insulation or increased rent and house prices to live in a quieter area. Some researchers believe that a loss in property value can be seen as a marginal WTP by home owners for small changes in exposure (*7*).

One such survey was carried out by Feitelson et al. in 1996 (*8*) that dealt with the prices of houses affected by airport noise and used the contingent valuation method. Feitelson used a noise depreciation index (NDI) to estimate the loss in property value due to noise from air transport. The NDI is the percentage reduction in house price per decibel of noise exposure (usually assuming a given base level). They proposed an NDI of 1.5% loss of property value for houses in the area (*8*). This value was calculated by asking local residents how much they would be willing to pay for a house that was essentially the same as their own but free from airport-related noise pollution. They were also polled on how much they would pay for such a house subject to varying levels of noise (L_{den}). These values may have been slightly excessive, but they do give an indication as to the large amount of money people are willing to pay for a quieter environment.

Although they apparently provide a good insight into the attitudes of the public toward noise pollution, the results of these stated-preference surveys can be distorted by other factors. Responses can be biased by several influences; for example, a respondent might not fully understand the hypothetical scenario he or she has been asked to imagine. In the case of noise measurements there is even more chance of this lack of understanding; it must be made clear that a halving of noise exposure does not mean a 50% reduction in the decibel level but rather a drop of about 10 dB. The surveys must be carefully constructed to avoid any ambiguity. A respondent might take into account the fact that reduced traffic flow would also result in fewer carbon emissions and less congestion. This assumption could lead to a response that is not wholly related to noise reduction.

Another technique of measuring the cost of noise that takes account of market trends rather than public attitudes is the hedonic house price method, which is a revealed-preference approach, meaning that results are based on hard data from property markets and the possibility that personal biases might affect the outcome is eliminated. The aim is to analyze house prices in a given area and attempt to quantify the loss in property value attributable solely to transportation noise, assuming all other things are equal.

The primary metric used in the hedonic pricing technique is the NDI. A number of studies carried out in Europe and the United States regarding transport noise, particularly traffic-related noise, assigned appreciable devaluation of property to noise pollution. In 1978 Nelson estimated an NDI of 0.88% for Washington, D.C. (*9, 1*). Proposed values ranged as high as 1.3% of house prices per decibel in Basel, Switzerland (*1*). A survey by the Center for Social and Economic Research into the Environment (CSERGE) and Environmental Friendly Technology (EFTEC) in 1994 suggested an average NDI of 0.67% (*10, 1*); however, it should be noted that this estimate assumes that the characteristic results of different studies are transferable between countries and cities. Although the data used in this survey are more than 20 years old and more up-to-date studies may be more accurate and representative, this finding still indicates that in general, property value losses amounting to billions of dollars can be attributed to noise pollution.

Governments and local authorities in both Europe and the United States are now charged with developing noise action plans. An action plan is concerned with the implementation and effectiveness of noise-reducing measures. Policy makers must be able to determine both the feasibility and environmental benefits of these plans. To do so, they will require a detailed cost–benefit analysis. Decision makers will then be able to directly assess, in monetary terms, the rewards of noise mitigation strategies. A full cost–benefit analysis requires that a monetary value be assigned to a reduction in noise levels. A position paper published by the EU Working Group on Health and Socio-Economic Aspects recommended a value of €25 ($34) per household per decibel per year (*11*). The value was based on a study conducted by Navrud in 2002 (*12*) and is a suggested value to be used by EU member states in the absence of more localized figures. According to that study, one can now put an approximate price on noise: a decibel is worth €25. But to be able to actually count the cost of noise pollution, the exact noise level due to transportation sources must be known. This area is where a reliable monitoring system to gauge the actual noise impact of transportation schemes is needed. Estimates cannot be made of the economic or personally perceived gains of noise reduction plans without being able to accurately measure their effect on environmental noise levels.

NOISE MONITORING

In 2002 the European Commission published the European noise directive (*3*). Its goal is to harmonize noise assessment throughout its member states. It also aims to provide a framework for local authorities to maintain a high level of health and environmental protection. The document lays out several guidelines for assessing noise pollution and for relating those data to the public. It specifies L_{den} as the noise indicator for gauging annoyance and L_{night} for evaluating disruption to sleep patterns. Under the terms of the directive, member states are obliged to produce strategic noise maps for all major cities and transportation networks, specifically

> agglomerations with more than 250,000 inhabitants and for all major roads which have more than six million vehicle passages a year, major railways which have more than 60,000 train passages per year and major airports within their territories. (*3*)

These maps will then be used in the formation of noise action plans.

Noise maps may take several forms, such as tabulated data or data in electronic form, but the most common format is a graphical representation of the noise levels in an area. Color-coded contour plots show the areas subject to the highest noise levels and link areas of equal noise exposure. Figure 1 shows a sample noise map of the Trinity College Dublin campus (*13*); dark areas located in the center and at the peripheries of the map represent quiet zones (<50 dB) and areas on the major roadways represent the noisiest zones (70 to 75 dB).

Current noise-mapping techniques employ predictive software that estimates the noise level in an area from a particular source given several governing factors, such as speed of traffic flow, number of light and heavy vehicles, road surface and gradient, and building topology. The common indicator is L_{den}. The software calculates the predicted sound level accounting for all these factors. According to the EU directive, the first set of maps for the areas mentioned earlier were deliverable by June 2007 and must be re-evaluated every 5 years thereafter. These maps will be used in the development of noise action plans and will provide a means of disseminating data to the public.

But what are the shortfalls of these maps? The plots are estimates based on the assumption that the contributory factors remain more or less constant over the course of a year. It is generally seen as infeasible to base noise maps solely on noise-monitoring data because a prohibitively large number of sampling points would be needed. However, in Madrid, Spain, the City Council has done just that (*14*). Data are logged by using a number of mobile monitoring units, and this information is fed into the mapping software. As far as the authors are aware, Madrid is the only city in which this approach has been adopted. So maps are usually just predictions. Accordingly, it is necessary to calibrate and subsequently validate these maps with real data. And since L_{den} is a yearly average it is reasonable to conclude that any real monitoring data should be taken over a long period rather than take a discrete sample.

One of the fundamental concepts referred to throughout the directive is that data must be made readily available to the public in a manner that is clear and accessible. Noise maps, however, could be misleading since they only display noise from a single source. This restriction is certainly necessary in order to attribute the correct level of noise to a particular transport mode, but it does

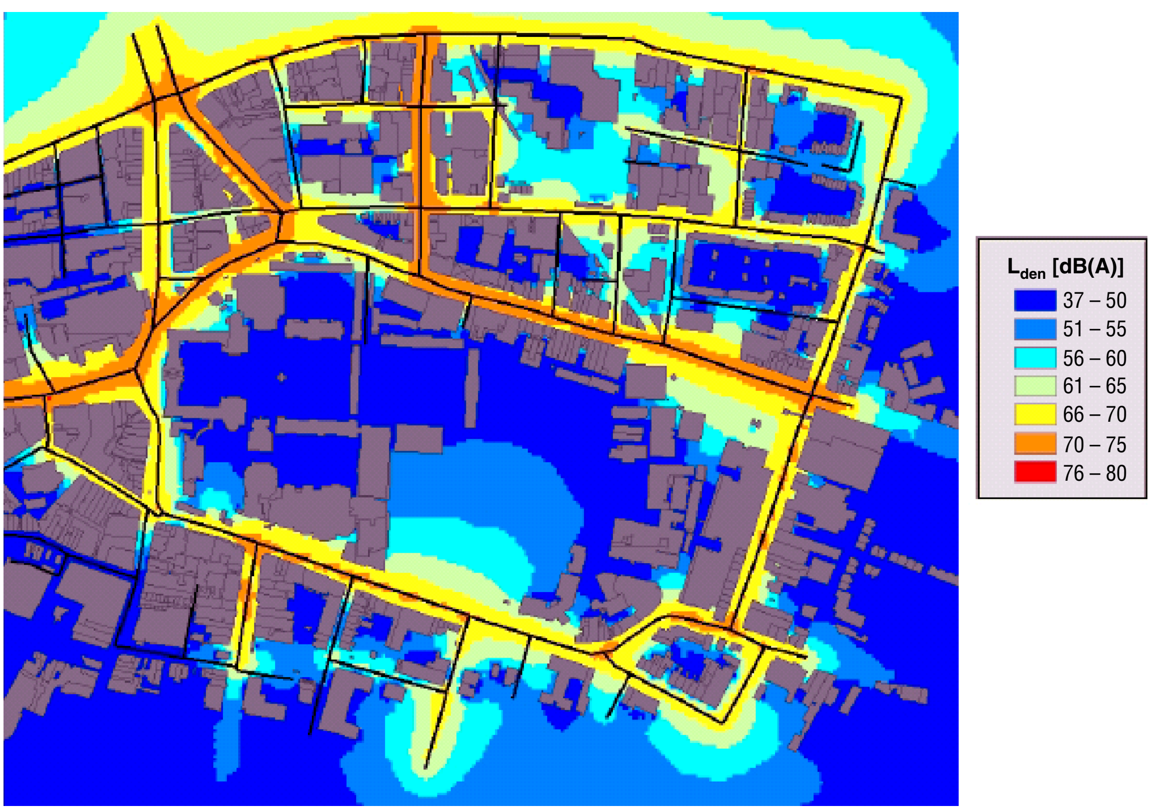

FIGURE 1 Noise map of Trinity College Dublin, Ireland.

not present a clear overall picture. King and Rice (*15*) addressed the issue, saying:

> It is clear that measurements must be taken to supplement the predicted noise maps and provide public assurance. These measurements will then account for various aspects outside the control of the prediction model. (*15*)

Real data can then be used to increase public confidence in mapped data and to provide a more complete representation of noise levels in an area. Measured data could possibly be linked to amalgamated noise maps, which would give a more realistic view of transport noise.

Although relating information to the general public is an important theme throughout the directive, the main reason for noise mapping is to assist relevant authorities in the formulation of noise action plans. These noise abatement policies will include traffic planning, technical measures at noise sources, and measures for the reduction of sound propagation. They must also provide financial information, such as budgets, cost-effectiveness assessments, and cost–benefit analyses (*3*). This information cannot be calculated by using predictions and estimates alone. In order to accurately assess the effect of any noise reduction strategies, it will be necessary to take real measurements to indicate the real changes in noise levels. It is not enough to apply the noise reduction properties of, say, a barrier to a model. The effect must be measured at the location where the noise is perceived, that is, at the home or property affected (*12*).

Although prediction software may give an indication of noise levels in an area, in situ noise monitoring is needed to provide a reliable before-and-after picture of transport-related noise. Accurate hard data will allow planning authorities to directly quantify the effectiveness of noise mitigation policies and, by using the methods outlined earlier, measure in monetary terms the benefits of their actions.

WIRELESS SENSOR NETWORKS

Wireless sensor network (WSN) research is an area that has progressed rapidly in the past decade. The idea of "smart environments" has emerged as the vision and goal of many advocates of the technology. By developing and deploying sensors to passively monitor one's surroundings, one can gather and transfer data with an ease that was previously impossible.

The general concept behind WSNs is that a number of wireless (radio-equipped) devices are deployed in an area of interest to monitor some pertinent parameter. The data are collected automatically and subsequently transferred through the network to a data repository for postprocessing. This overview is a very simplified one, but the general principle can be applied to most WSN scenarios. There are a vast range of possible applications for WSNs, for instance, zebra tracking in Kenya, countersniper systems, and volcano monitoring (*16*–*18*). One field in which the technology is particularly suitable is environmental monitoring. The wireless nature of the devices means that data can be acquired and later accessed in locations where no intelligent transportation infrastructure or facilities are available. Many environmental monitoring applications require the sensing units to be capable of logging for extended periods of time or surviving in relatively harsh conditions.

Sensory Networks with Delay Tolerance

Trinity College Dublin has developed a data acquisition system capable of meeting the demands of long-term environmental noise-level monitoring, sensory networks with delay tolerance (SeNDT). Designed as a platform for delay tolerant networking (DTN) applications, the units are both physically and functionally robust. DTN protocols were originally developed for deep space communications in which an end-to-end path between communicating entities would almost never exist. The terrestrial incarnations of the technology assume that sensor nodes will be operating in locations or conditions where there may not always be a link to a network. Data are transferred only when the chance arises, either through opportunistic or scheduled contacts. SeNDT units were designed with these possible scenarios in mind and so possess several qualities that make them ideally suited to long-term environmental monitoring.

Compared with more commonplace sensor platforms (e.g., motes), the units are relatively high powered and high performance. Many envisaged sensor network scenarios tend toward dense deployments of small sensing units with limited power and range (~10 m). One of the main problems associated with this approach is the cost, approximately $130 per unit (*19*). Although these small sensor platforms will no doubt in time become cheap enough to allow large-scale installations, at the moment they are simply too expensive to permit the deployment of enough nodes to achieve the coverage needed for a situation like urban noise monitoring. The extra power consumption of SeNDT units is balanced by increased communications range and sensing capability.

SeNDT nodes are built around an Intel XScale 255 processor, supplied as part of the Triton XXS processor board. The processor has 64 MB of SDRAM, and the Triton board has 32 MB of onboard flash memory. The XScale includes digital signal processing (DSP) extensions specifically aimed at the real-time processing of audio signals. The Triton board is attached to the main SeNDT input–output (I-O) board, which is equipped with numerous communication and sensory interfaces. The primary communication system is the 802.11b wireless link. The nodes also have USB and RS232 ports (*20*). In addition to the Triton's onboard flash memory, the units include a Personal Computer Memory Card International Association compact flash card with up to 4 GB of storage capacity. Audio data are acquired through the high-performance analog front end. The nodes have four input channels, simultaneously sampled by a 16-bit analog-to-digital converter. Each of the channels is equipped with a low-cost electret microphone that converts changes in acoustic pressure to electrical signals. The signals are sampled at a rate of 49 kHz, more than sufficient for the capture of high-quality audio data.

Once the data are sampled, they are passed through a digital A-weighting filter. This filter is one that assigns weightings to certain frequency components of an audio signal, to account for the fact that the human ear is more sensitive to some frequencies than others. The filtered data are then converted to sound pressure levels and used to calculate the desired noise level measurements. Figures 2 and 3 show a SeNDT noise-monitoring unit and a populated I-O board, respectively.

The initial pilot study of the technology was conducted with the help of Dublin City Council and the Irish National Roads Authority. SeNDT units were deployed at a number of urban and motorway locations around Dublin to monitor traffic noise levels. The sites chosen were subject to high volumes of both commercial and commuter traffic and qualified as mandatory points for noise mapping. In the case of the motorway locations the noise can be directly attributed to traffic noise alone, since there are no other sound sources in the vicinity. At the urban sites there may be noise contributions from other transport modes. As suggested earlier, it is more useful to have this overall picture that is fully representative of the actual noise

FIGURE 2 SeNDT noise-monitoring unit.

levels at the location rather than just one constituent part thereof. When information is provided to the public, it is necessary to present data that give a real indication of the noise levels. Although a particular transport mode may not in itself constitute a noise problem, it may well increase noise levels in an area to an unacceptable level. It is certainly necessary then to understand the contribution of individual transport modes to overall noise levels, but these must be amalgamated when the data are disseminated to the public at large. It is for this purpose that a sufficiently widespread and cost-effective noise-monitoring network is needed.

Example

On the February 19, 2007, Dublin City Council introduced a city center ban on heavy goods vehicles (HGVs) with five or more axles. The ban is in place from 7:00 a.m. to 7:00 p.m. and was brought into force to try to reduce the amount of heavy commercial traffic around the inner city and on the Dublin quays. The aim was to make the city

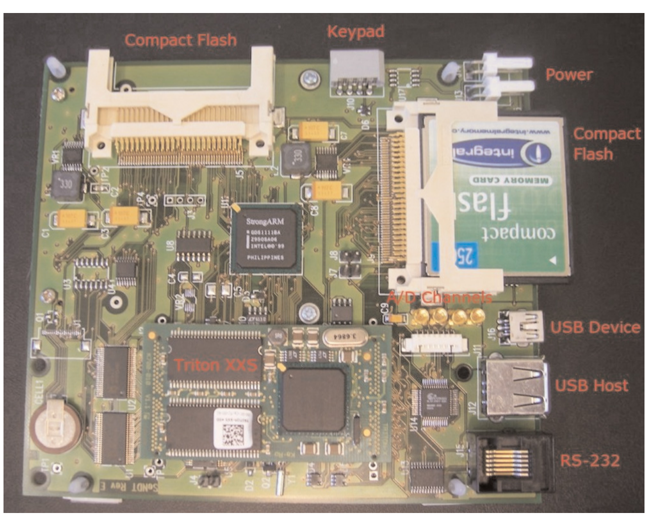

FIGURE 3 Populated SeNDT I-O board.

center less congested and safer for pedestrians and cyclists and to lower air pollution and, of course, reduce noise levels.

By installing a long-term noise-monitoring system in strategic locations, local authorities such as Dublin City Council can calculate the actual savings and monetary gains brought about by their policies and decisions.

Figures 4 and 5 show representative samples of A-weighted noise levels on the Dublin quays before and after the ban, respectively. The quays are heavily populated, with a large number of apartment buildings facing the river. This is an area of ongoing development with several more residential properties planned in the coming years.

The L_{eq} is the average sound level over a given period. The L_{10} is the sound level exceeded 10% of the time; this measurement concerns peak noise events that would otherwise be averaged out. The L_{95} reading is the noise level exceeded 95% of the time, which is essentially the background noise level. Calculations of the L_{den} values were made by using the equation below, as defined by the EU (*3*):

$$L_{\text{den}} = 10\log\left[\frac{12 * 10^{\text{day}/10} + 4 * 10^{\text{evening}+5/10} + 8 * 10^{\text{night}+10/10}}{24}\right]$$

In the foregoing equation the day, evening, and night terms refer to the long-term A-weighted L_{eq} for the specified time period. A preliminary analysis based on all available readings (approximately 1 month before the ban and 3 months after) indicates a drop of 3.1 dB(A) in noise levels. It should be pointed out that a proper evaluation of these before-and-after conditions should make use of a much larger data set, for example, 1 year, to accurately calculate L_{den}. However, by using the available data some initial observations can be made.

The EU working group suggests the following polynomials for calculation of the percentage of people annoyed (%A) and highly (%HA) annoyed because of road traffic noise (*2*):

$$\%\text{A} = 1.795 * 10^{-4}\left(L_{\text{den}} - 37\right)^3 + 2.11 * 10^{-2}\left(L_{\text{den}} - 37\right)^2 + 0.5353\left(L_{\text{den}} - 37\right)$$

$$\%\text{HA} = 9.868 * 10^{-4}\left(L_{\text{den}} - 42\right)^3 - 1.436 * 10^{-2}\left(L_{\text{den}} - 42\right)^2 + 0.5118\left(L_{\text{den}} - 42\right)$$

With these expressions and the calculated value of L_{den}, one can estimate the benefits of the HGV ban. There is a reduction of 8.89% in the number of people annoyed by road traffic noise and a reduction of 8.33% in the number of people highly annoyed. In addition to the personally perceived advantages of the policy, the financial impact can be assessed. With the value suggested by the EU working group (*11*), initial calculations indicate a monetary benefit of €77.50 ($105) per household per annum for the HGV ban. Given the large numbers of residential properties in the area, this value represents significant savings.

DISCUSSION AND FUTURE WORK

Real data are necessary to accurately assess the effectiveness of changes brought about by noise reduction policies. Predictions cannot account for all factors governing noise pollution. The results reported here indicate how a WSN can be used to gather long-term environmental noise data. This system can be left unattended for months at a time and data subsequently collected in a simple manner. WSNs can provide a reliable and feasible method of long-term environmental noise monitoring. The results presented here are an example

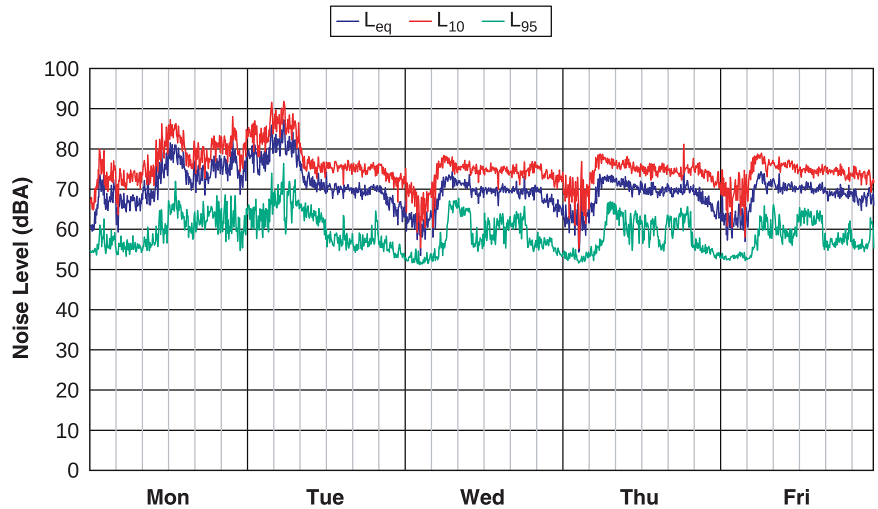

FIGURE 4 Noise levels on Dublin quays, January 15–19, 2007.

of how real data can be used to directly assess the socioeconomic gains of noise reduction methods.

The value of 3.1 dB(A) was slightly lower than expected (3 dB is about the limit of perceptible changes in sound levels). This result is most likely due to the fact that the elimination of HGVs from the city center has reduced congestion and traffic is faster-moving. Also, after 7:00 p.m. many HGVs use city center routes that are by then free-flowing. A large proportion of vehicle noise is due to tire–road interaction, and smaller volumes of fast-moving traffic can often be louder than larger yet slower volumes. This fact may account for the seemingly small reduction in noise levels, although a longer data set will reveal a clearer picture when available.

It should also be noted that the noise levels shown in these results are overall noise levels. Although the monitoring point was not in the vicinity of any other sources of transport noise, there may be some influences other than road traffic alone. It is planned to increase the signal processing capabilities of SeNDT units to allow them to distinguish between noise sources. With sufficient spectral analysis it will be possible to identify noise sources from a particular transport mode such as rail or aircraft. The data sets can then be amalgamated to form an overall picture of transport noise or used individually to validate noise maps.

Further ongoing improvements to the SeNDT nodes include fully automating data collection by using mobile nodes. A mobile node in the form of a municipal vehicle, for example, a garbage truck, will be instrumented as a data mule. A data mule is a mobile unit that collects data automatically from stationary monitoring points as it travels along a certain route. By using the delay-tolerant capabilities of SeNDT, data collection can be fully automated with guaranteed reliability.

CONCLUSION

In recent years there has been an increasing amount of time and resources dedicated to investigating the effects of environmental noise. By far the most prevalent source of noise pollution is transportation.

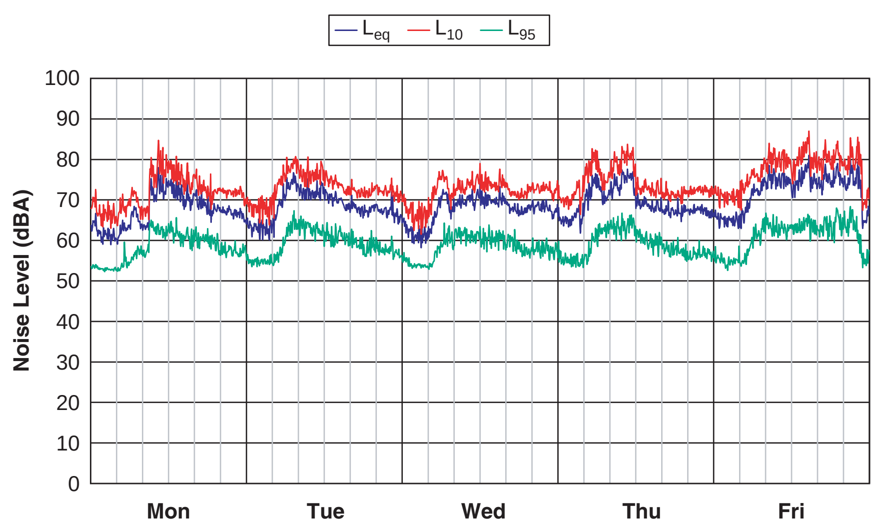

FIGURE 5 Noise levels on Dublin quays March 12–16, 2007.

The systems and modes that are employed worldwide every day pollute the acoustic environment on a vast scale. Research has shown that this noise pollution has detrimental effects on both a personal and an economic level. The health of the individual can be harmed and substantial money lost as a result of excessive transport noise.

Governments are now beginning to address these issues by enacting legislation aimed at protecting the general public and the environment from the effects of noise pollution. To be successful in this, those responsible must be able to quantify the noise impact of transportation systems and identify areas where change is needed. Various methods exist for assigning monetary and personal value to noise reduction. But for these methods to be usefully employed the data regarding the levels of noise pollution must be accurate and fully representative of the scenario at hand. The use of a widespread monitoring system will allow policy makers to accurately assess the effectiveness of their noise mitigation strategies. For such a widely distributed system to be practical, data collection must be simple and reliable. A useful noise-monitoring system must be capable of collecting data for extended periods of time with little or no human interaction. WSNs are the solution to this problem.

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