Noise monitoring and enforcement in New York City using a remote acoustic sensor network

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Abstract

The urban sound environment can have a profound effect on quality of life as indicated by the large majority of noise related complaints to New York Citys 311 information/complaints line. To effectively monitor and understand these spatially and temporally dynamic environments, a process of real-time, long term measurement and analysis is required. This paper discusses the use of a smart, static, low-cost acoustic sensor network for continuous urban noise monitoring. The paper discusses the implementation and use of a level based noise event detector to reveal an indication of a noise code breach. The system was used to study 11 months of calibrated sound pressure level data from a cluster of 17 sensor nodes in Manhattan, where it positively confirmed the presence of construction noise from 47 localized complaints where subsequent enforcement visits could not identify the offending source. Its use as a tool to aid city agencies in effective noise enforcement is discussed and its shortcomings in terms of false positives are summarized.

Keywords: noise mitigation, sensors, cyber physical systems, sensor network, urban noise

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1. Urban noise pollution and its enforcement

With its moniker of "The City That Never Sleeps", New York City (NYC) is famous for its high energy state and infamous for its high levels of noise. In 2016 the cities 311 information/complaints line [1] received an average of 48 noise complaints per hour. It has been estimated that around 90% of NYC residents are exposed to noise levels exceeding the Environmental Protection Agencies (EPA) guidelines on levels considered harmful to people [1]. NYC has tried to regulate sources of noise since the 1930s and in 1972 it became the first city in the U.S. to enact a noise code [2, 3]. As a result of significant public pressure, a revised noise code went into effect in 2007 [4]. This award-winning code, containing 84 enforceable noise violations, is widely-considered to be an example for other cities to follow. However, NYC lacks the resources to effectively and systematically monitor noise pollution, enforce its mitigation and validate the effectiveness of such action. Therefore, the purpose of this paper is to assess the effectiveness of the current noise monitoring and compliance approaches through a focused case study of construction noise in a small area of New York City through the use of a remote acoustic sensor network.

The process of noise enforcement is complaint driven, with an enforcement visit scheduled in response to complaints made via the cities 311 service. Typically, the most common complaints such as residential noise are routed to the New York Police Department (NYPD). The Department of Environmental Protection or DEP handle a wide range of complaint types including: construction and ventilation noise. DEP handled complaints made up 14% (58,493 or 160/day) of all noise complaints (420,285 or 1151/day) in 2016. DEP enforcement is carried out by a team of 53 enforcement officers who also handle air quality complaints. A typical enforcement visit will be carried out by at least 2 inspectors with acoustic measurements manually taken using a sound level meter (SLM) such as the B&K 2239A [5]. Whilst this meter is capable of generating Type/Class 1 [6] measurements, the DEP requires that their meters meet the slightly less accurate Type/Class 2 standard.

The NYC noise code is source focused when it comes to construction noise and individual tools and machines have separate rules applied. Jackhammers for example are not allowed to exceed 85 dBA at 50 ft. These rules establish a unique noise mitigation plan for each construction site, offering alternatives for contractors to continue their important construction tasks while having less noise impact on the surrounding environment. To use

[1] nyc.gov/311

street level construction as an example, an enforcement team would take an ambient level measurement at a time when the offending noise source is not active. An indication that the construction site is producing too much noise is found if its measured level exceeds the ambient by more than 10 dB at a distance of 15 ft. These measurements are taken using the A-weighted, slow setting of the SLM which uses a 1 s integration period. These are taken for durations of around 20 s to account for any short–term temporal level fluctuations. If this 10 dB threshold is exceeded, it provides a strong indication that there are tools being used that are in violation of the noise code and that necessary steps are not being taken to reduce noise spill out of the site. In the event of an on–site measurement showing a piece of equipment is producing too much noise, a construction site manager would be given a 3 business day cure period in which to make changes that result in a reduction of noise levels. The DEP inspector on–site will recommend ways in which to do this, such as: purchasing quieter jack–hammers, adding absorbent blanketing, erecting acoustic barriers around the site, closing machinery doors or keeping construction within the allowed weekday hours of 7AM–6PM. Another interesting method of complaint reduction is the brokering of an agreement with the construction manager that the noisier tools will only be used when the complainant is at work. If it is found that these recommendations have not been implemented and levels are still exceeding the code after this 3 day period, a violation is issued resulting in a court case usually involving heavy fines.

Substantial penalties can be incurred for producing noise outside of the allowed hours of 7AM–6PM, however, special permits can be obtained to allow for this in rare cases. It should be noted that the DEP rarely issues these permits, however certain construction related city agencies have the power to issue a variance for these out of hours periods.

A common problem experienced by DEP inspectors is the transient nature of the offending noise sources. An inspection visit often results in no action as the noise source is not present or functional at the time of the visit. Another issue is that building managers and construction workers are acutely aware of the DEPs noise enforcement procedures and their associated fines, resulting in well–timed downed tools during DEP inspection visits. This all makes for a time consuming process towards the eventual noise mitigation goal.

2. Examples of remote sensing for noise enforcement

Remote acoustic sensor networks allow for the collection of longitudinal acoustic data from a collection of static locations. The abilities of these networks are often dictated by their price points. High–cost commercially available static noise monitoring solutions such as the Bruel & Kjaer's Noise Sentinel system [7], provide highly accurate SPL measurements, wireless data transmission and a web portal for real–time data visualization. These have been used for the monitoring and reduction of air traffic noise around NYC airports with a deployment of 32 noise monitoring stations [8]. The cost of these networks limit their scalability and deployability, with each sensor costing upwards of $15,000 USD. Typically these networks are rented to a client at the cost of $105 USD per day. At these prices, a modestly sized network of 32 sensor locations as previously mentioned would result in an annual cost of around $1.23 Million USD. These networks are used to ensure that major airports are in compliance with local air noise codes.

A number of university research projects have developed and deployed small scale noise sensing networks [9]. The Life DYNAMAP Project [10] deployed 25 low–cost noise sensors across Rome and Milan for the period of 1 year to aid in the production of accurate noise maps for the cities. These networks were able to produce high temporal resolution, longitudinal noise data which resulted in more accurate noise maps than was traditionally possible using mainly prediction based sound propagation models. A sensor network developed by a team from Valencia, Spain approached this in a similar fashion, using low cost sensors to map and monitor road noise annoyance using low–cost remote sensors [11]. These research led solutions aim to inform policy with the production of accurate noise maps, however there is a scarcity of remote noise sensing initiatives that actually act to directly inform noise mitigation strategies and outcomes, possibly due to the need for long duration deployment periods that many of these studies lack. A wireless noise sensing network needs to be validated in terms of its application in urban noise reduction.

3. SONYC – The Sounds Of New York City Project

To begin to understand the cities noise condition, a network of 35 low-cost acoustic sensing devices were designed, built and deployed to capture long-term audio and objective acoustic measurements from strategic urban locations [12]. These $80 USD devices incorporate a quad–core single board computer (SBC) Raspberry Pi 2B [13] computing platform with Wi–Fi connectivity and a custom–made, digital and calibrated Microelectromechanical systems (MEMS) microphone for high accuracy sound pressure level (SPL) data acquisition allowing it to produce data at the Type 2 level used by city agencies.

The initial goal of this network is to provide the capability of capturing, analyzing and wirelessly streaming long–term, high–resolution environmental acoustic data [2]. SPL data is continuously logged at the 1 second resolution, as well as 10 second snippets of audio, randomly spaced in time, resulting in around 3 snippets per minute. These snippets are obtained rather than continuous audio sampling to maintain the privacy of people in close proximity to the sensor nodes.

As of July 2017 the operational sensor count stands at 38, with clusters of sensors across Manhattan and Brooklyn. By the end of Summer 2017, a further 62 sensors will be deployed in more diverse locations such as: Grand Central District (Midtown Manhattan), Jamaica (Queens) and Sunnyside (Queens). The more dense cluster is located around the Washington Square Park area of the New York University main campus. The sensors in this area were deployed progressively between the periods of May 2016 to January 2017, providing up–to 11 months of high resolution, calibrated SPL data. Sensors are typically mounted on external window ledges at roughly 4 m above street level.

4. Investigation into urban noise enforcement

4.1. Case study of localized noise complaints

In order to determine the ability of the SONYC sensor network to provide useful insights into localized noise conditions an area with a relatively dense node deployment of 17 was selected. A 100 m boundary was established around each node and merged to form the focus area. Noise complaints occurring within this area were gathered from the NYC 311 Open Data[3]. Complaints not handled by the DEP and those that occurred outside of the life–time of the within–range sensors were excluded. Duplicate complaints as identified in the 311 data were also excluded, e.g. complaints about the same instance in time of a noise source from the same complainant or from multiple localized complainants. The filtering process over the time span of interest with complaint counts at each stage is as follows: citywide total (389,821), citywide DEP handled (50,244), within focus area (162) and non–duplicates (92).

Figure 1 shows the bounded area containing a total of 92 complaints from May 20th 2016–April 26th 2017. The area is the Washington Square Park campus area of New York University (NYU) which contains a number of high rise residential buildings. Running vertically on the far right of the image is Broadway, which experiences heavy traffic flow and frequent roadworks. The complaint type counts are shown in Figure 2.

[2] wp.nyu.edu/sonyc

[3] `nycopendata.socrata.com/data`

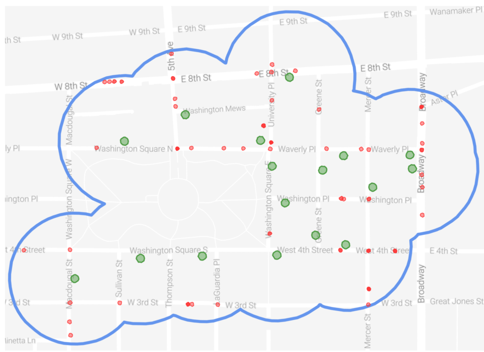


Figure 1: Focus area (large green circles = sensor nodes, small red circles = noise complaints, blue line = boundary area at 100 m from nodes)

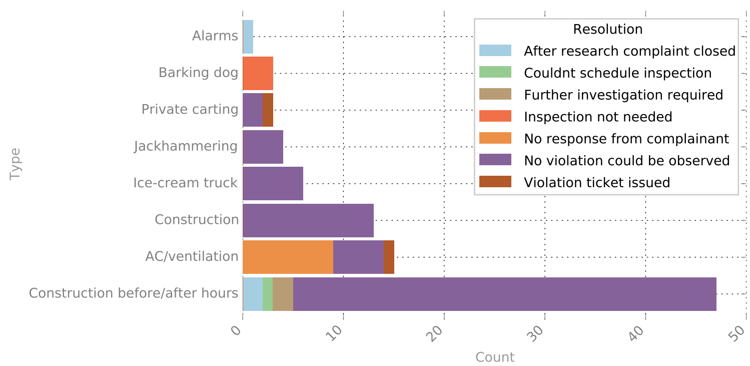


Figure 2: Complaint type with resolution breakdown

The distribution reveals the proliferation of building and improvement works in the city with construction noise making up 70% of total complaints in this area when combining all construction related complaint types. *"Construction before/after hours"* makes up the majority with 51%. Construction work is only authorized to occur between the hours of 7AM–6PM. Complaints created outside of these hours make up 49% of this sample, but it is worth noting that the created time may not necessarily correspond to the occurrence of the violating noise source as a complainant may make the complaint long after the noise event has occurred.

The resolution of each complaint is also logged and provides an insight into the challenges of noise enforcement in the city. Figure 2 shows this breakdown by complaint type, with the vast majority resulting in the outcome of *"No violation could be observed"* at 78% and only 2% of complaints resulting in a violation ticket being issued. This illustrates the transient nature of these noise sources and the difficulty that lies in observing a noise code infringement. For example, in 89% of *"Construction before/after hours"* enforcement visits, no violation could be observed.

4.2. Localized continuous acoustic monitoring of out–of–hours construction noise

Due to the high majority (51%) of *"Construction before/after hours"* complaints and the predominance of their enforcement outcomes as *"No violation could be observed"*, it was decided to focus on these in the following analysis using objective SPL data from the deployed sensor network.
A simple amplitude–threshold based excessive noise detection pipeline was developed to automatically identify excessive noise events in the long term SPL data. The detector firstly calculates the ambient background level as L_{90} using a moving window of length 2 hours with zero overlap between windows. This period was chosen as it allows for the adaptation to the variation of background level as it changes throughout the day and by sensor location. This is used to move along the time series of long–term SPL values to provide an adaptive baseline for the detection of a noise event. At each iteration of this ambient level calculation a smaller rolling window is passed along this 2 hour period, calculating $L_{AeQ:20min}$ to detect sustained periods of high noise activity above the ambient baseline. This detection is triggered by the exceeding of the threshold set out in the NYC Noise Code: *"Noise that exceeds the ambient sounds level by more than 10 decibels as measured from 15 feet from the source as measured from inside any property or on a public street is prohibited"*. The shorter 20 minute L_{AeQ} averaging period was selected to reduce the number of false positive event detections from short–term noise sources such as close proximity car horns and emergency vehicle sirens passing by sensor locations. Jackhammering for example would result in a number of detections due to its multiple repeated durations of hammering. The ability of the noise event detector to correctly identify out–of–hours construction noise complaints will be assessed in the following section.

4.2.1. Are these authentic noise complaints?

With 89% of out–of–hours construction enforcement visits in the focus area resulting in no observation of the offending noise source, one assumption could be that the complaint was spurious. It is more likely however that the complaint was in fact genuine, but the enforcement visit failed to observe a violation.
To investigate this, continuous SPL data was retrieved from each of the 17 sensors with all data outside of the "before/after hours" time range of

6PM–7AM excluded, making for data windows of 13 hours per day per sensor. This seemingly wide time range was chosen, as the time of complaint creation may not be the time that the noise event is occurring, for example a complainant may make a complaint in the morning about a noise heard during the preceding night. To further reduce this dataset, data windows from sensors further than 100 m from a complaint location were excluded. These remaining data windows were then only kept if their localized complaint time stamps fell within the data window time range or the following day. The noise event detector was then run across this filtered dataset resulting in a total of 324 detections, an average of ≈7 per complaint. A detected noise event such as jackhammering will likely be detected multiple times in a single construction period. These were selected for manual auditioning and identification of valid out–of–hours construction noise events. The relevant audio snippets for each detection were auditioned and it was found that 76% (246) of these were caused by construction noise events of these types: jackhammering (223), compressor engine (16) and metallic banging/scraping (7). The remaining 24% (78) consisted of emergency vehicle siren passes (74) and large vehicle engine idling noise (4).

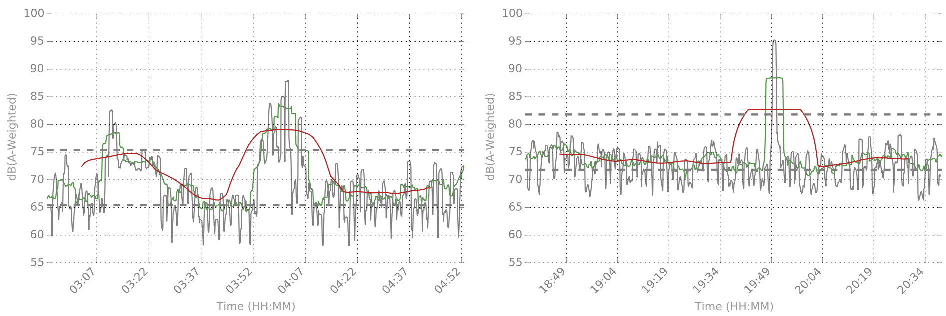
Out of the 47 out–of–hours complaints, 44 instances of construction noise was observed during 6PM–7AM, within 100 m of each of these complaints. The remaining 3 complaints with no observed noise events may have been due to a lower level or more impulsive source that did not produce extended levels that would result in an event detection. Despite this, the finding can confirm that 94% of these complaints were, in fact authentic. This is a promising indication that a deployed noise sensor network provides the ability to capture noise events that may otherwise be missed by enforcement visits.

4.2.2. Noise event profile: out–of–hours construction

To understand more about the acoustic characteristics of these events the following section discusses the possible reasons for false positive detections and details the correctly detected events. Figure 3 illustrates the time domain difference between an example period of jackhammering and a siren pass.

The high instantaneous level of the siren acts to bring up the $L_{AeQ:20min}$ value, resulting in a detection. Based on the auditioning of the audio snippets for these events, the siren passes also continue over a relatively long duration, possibly caused by slow traffic, further increasing the $L_{AeQ-20min}$ values calculated. The characteristics of the 246 construction noise events are summarized in Table 1.

The summarized ambient values reflect the high variability in ambient



(a) Jackhammer (b) Emergency siren

Figure 3: Event detection time series examples where: upper dashed line = threshold, upper dashed line = L_{90}, solid gray line = $L_{AeQ:1min}$, green line = $L_{AeQ:5min}$, red line = $L_{AeQ:20min}$

Characteristic	**Min.**	**Max.**	**Mean**	**Std.**
Ambient ($L_{90:2hr}$)	62.4	78.2	69.0	8.2
dBAS $L_{AeQ:5min}$	62.1	97.4	83.9	7.2
Maximum dBAS	84.5	112.2	104.4	4.0
dB > threshold	1.4	17.6	6.8	4.2
Max. dB > threshold	7.4	35.8	25.3	3.9
Event dBCS - dBAS	0.1	7.4	1.8	1.2
Ambient dBCS - dBAS	0.9	7.8	3.0	1.1

Table 1: Out of hours construction noise event characteristic summaries

background level at different stages of the out–of–hours focus period justifying the use of a relative threshold of 10 dB above ambient in the NYC noise code. The $L_{AeQ:5min}$ dBAS values reveal cases of noise events at the 97.4dBAS level for periods of up–to 5 minutes. Maximum dBAS values observed show very high levels of noise at 112.2 dBAS with a mean at 104.4 dBAS, although its important to note that these may be instantaneous in nature and therefore less perceptually annoying. Mean levels of 6.8 dB above the threshold reveal an average increase above ambient of 16.8 dB caused by this sample of construction noise. This can be loosely equated to a 3.2 times increase in perceived loudness above the ambient background level. The dBCS - dBAS characteristic is commonly used to determine the low frequency energy of urban noise conditions due to the C–Weighting filters greatly reduced roll off at low frequencies. The higher values of low frequency energy in the ambient calculations suggest that the noise events contain more high frequency energy which would exhibit itself in the more sensitive auditory frequency range from 100–4000 Hz, resulting in an expected increase in annoyance and eventually complaints. This is also reflected in the frequency composition of the audio snippets where the construction noise sources of jackhammering and compressor engines all exhibit distinct spectral peaks within the range of 100–2000 Hz.

4.3. Lessons learned utilizing noise sensor data to aid enforcement

A common problem for noise inspection officers is in the actual observation and measurement of a noise code violation. Workmen will often recognize a DEP official approaching a site and stop using more noisy power tools such as jackhammers and piling machines while they are present. Continuous monitoring of urban noise via remote sensor networks can provide these measurements to aid in the validation of noise complaints and the identification of noise events that may eventually result in a complaint.

The major limiting factor of the presented approach to noise event detection is the manual auditioning required to confirm a correct noise event is of the type of interest. As the NYC Noise Code is source specific when it comes to compliance, knowing the source of the noise event is key in determining a correct violation. The detection of false positive noise events such as long duration sirens is also of note as these events are difficult to distinguish from construction type noise events when utilizing time series SPL data. Further time domain techniques such as the exclusion of siren events using the events onset characteristic may be a worthy approach to remedy this. The automatic identification of noise sources would also contribute to overcoming this drawback and is briefly introduced in the Section 5.

5. Future work

Whilst the gathering of accurate SPL data in–situ is crucial to the monitoring of noise in urban settings, identifying the source of these noise events is of great importance, especially as the NYC Noise Code specifies compliance based on the source of the noise. The sensor's powerful processing unit means there is the capability of performing additional analysis of the audio signal. Considerable efforts have been employed on machine listening algorithms for the automatic identification of urban sound sources [14, 15] to enable noise code violations to be accurately determined in–situ. With this improvement in violation detection the presented sensor network could be used to immediately inform the DEP of a breach in the code. An automated system could be conceived that would automatically check for existing electronically accessible permit records for out–of–hours construction. In the event of a positive violation detection, information on suggested mitigation information/strategies could be automatically sent out to the manager of the construction site in violation of the code. This could go some way towards the goal of self mitigation of construction noise. With extended deployments, the effects of noise mitigation strategies by city agencies can also be quantified, by measuring changes in localized SPL after an agency enforcement visit. This, coupled with richer data from the DEP on the detailed actions taken on enforcement visits could provide a deeper study into the effects of agency intervention in noise situations.

6. Conclusions

The city agencies tasked with noise mitigation will benefit from a reliable stream of high resolution noise data that can contribute to a more effective noise mitigation strategy, especially in terms of enforcement scheduling and empirical real–time on–site intelligence. The presented sensor network will provide a low–cost and scalable solution to large scale calibrated acoustic monitoring, and a richer representation of acoustic environments that can empower a deeper, more nuanced understanding of urban noise and its characteristics across space and time. The city agency tasked with enforcing the award wining NYC Noise Code are key collaborators on the presented initiative and have stated that this kind of longitudinal noise data collection can result in more effective noise mitigation for the city to improve quality of life for millions of people.

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