LA Noise Array – planning and design lessons from a noise sensing network

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Abstract
The interaction between environmental noise and the built environment is an often-neglected area in the practice of urban planning and design. Most quantitative research is limited to single value loudness metrics and ignore the more complex spatial nuances of the noisescapе. Qualitative soundscape research, on the other hand, is difficult to generalize to the urban scale. We report on an exploratory noise sensing project in Los Angeles, CA that investigates both qualitative and quantitative aspects of the noisescapе. Using a novel noise sensor array mounted on city street lights we collected preliminary data that demonstrates the promising and revealing nature of spatially and temporally granular urban sound data. By analyzing sounds in various frequency bands at different resolutions we identify how aspects of urban design such as landscaping, material choice and building typologies impact the sonic environment. Our results reveal the spatio-temporal structure of low frequency noise in traffic-exposed areas; a phenomenon not captured by traditional a-weighted decibel metrics. Based on these results, we present a model predicting noise based on historic traffic data. These results provide insights for future methods that can be applied to long-term policymaking and planning decisions.

Introduction
In urban planning and design, the sensory aspects of the environment such as sound and light are often merely an afterthought. The ephemeral nature of these phenomena can be challenging to control and consider in the design process. Planners and policy makers treat the environmental soundscape mostly as a source of unwanted noise exposure, and to a far lesser extent, as a sensory modality that helps people to orient themselves in the environment, serves as a source of aesthetic experience, and provides a sense of place. The first aspect is recognized as a public health concern and in most places regulated to some extent. The second aspect is equally important for public wellbeing, but is considered a design concern that is not often addressed. The lack of attention can be attributed to the difficulty of measuring and assessing the soundscape in its spatial and temporal complexity and the lack of a nuanced spatial representation of the auditory environment. To account
for the complex interactions between the soundscape, human activity, and the built environment requires training and experience; most professionals are not equipped to account for the physical, physiological, psychological, and cultural aspects of the auditory domain.

We believe that a sensor network approach to ambient sound sensing can be useful to address both of these challenges. A dense network of identical calibrated measuring devices that capture a broad range of parameters facilitates the comparison of environmental sound across space and time. If the measured values are fine-grained enough to capture local specificities such as the interaction of sound with building facades or moving sound sources such an installation would also serve as a tool for planners to study the properties of sound from a design perspective. In this paper, we discuss the results of a prototypical Internet of Things project, a noise sensor network installed on LED street lights in the City of Los Angeles from August 2016 through January 2017, and discuss its implications for planners, urban designers, and architects. Instead of singular point measurements, the nodes within the sensing array are close enough to capture overlapping auditory regions, allowing the study of the spatial structure of the soundscape.

Noise as a public health concern and a source of environmental information

Environmental noise, described by the US Clean Air Act of 1963 as “unwanted or disturbing sound” (US Congress 1963) is a serious concern for public health. Among the scientific community as well as the public there is a broad consensus that noise can be both annoying and unhealthy. Epidemiological studies have shown that populations exposed to night-time aircrafts and road traffic noise (>65 dB) tend to suffer from elevated blood pressure (Jarup et al. 2008; van Kempen et al. 2002; Halonen et al. 2015; Recio et al. 2016). Chronic noise exposure also increases psychological stress, is detrimental to sleep quality, learning ability and general health, and is associated with higher morbidity (Stansfeld and Shipley 2015; Bialiatsas, van Kamp, Swart, et al. 2016; Klatte, Bergström, and Lachmann 2013; Hume, Brink, and Basner 2012; Hall et al. 2016). Beyond these general effects, parts of the population, including children, the elderly, and sufferers of a condition described as hyperacusis, are especially sensitive to environmental noise (Basner et al. 2014; Baguley and McFerran 2011). Furthermore, noise exposure often coincides with other forms of pollution and exacerbates environmental stress factors and conditions such as asthma and other respiratory diseases, which affect populations living along busy traffic corridors (Franklin and Fruin 2017).

The most widely used measure for environmental noise power is the A-weighted decibel metric, suggesting a sustained level of 65 dB(A) as the threshold beyond which chronic health problems become noticeable. However, there are indications that this single measure is an insufficient descriptor of the many ways ambient noise affect humans and non-humans. Some dynamic phenomena are more disruptive than others. Low-frequency noise comprised of frequencies below 200 hz is prevalent in urban space, caused by the powerful engines found in ventilation systems and machinery, vehicles and aircrafts. Several studies have found this type of noise to be especially harmful and disruptive (Leventhall 2004; Bialiatsas, van Kamp, van Poll, et al. 2016; Roberts 2010). However, most regulatory frameworks do not consider this noise component, since the A-weighted metric used in these frameworks does not adequately represent it.

The dynamic qualities and frequency components of noise are especially important since sound is a crucial medium of information for most humans and animals. Human speech and animal communication rely on certain frequency bands, just as the auditory environment itself provides many cues important for spatial perception and orientation. In the case of human communication,
consonants are located above 4kHz in the frequency spectrum. High-frequency noise will therefore impact language intelligibility. By masking crucial frequencies and drowning relevant cues, environmental noise can disrupt communication and make urban space acoustically opaque and illegible. Since a single sound source can decrease the auditory quality of space for everyone else, the sonic environment is therefore to be understood as a commons, a limited resource that is accessible to everyone (Odland and Auinger 2009).

The soundscape, a term introduced by urban designer Michael Southworth and popularized by Canadian composer Murray Schafer, describes the immersive quality of the acoustic environment in its full complexity (Southworth 1969; Schafer 1977). The spatial qualities of urban soundscapes are still poorly understood and are difficult to model. Sound interacts with the built environment, bounces off flat facade surfaces, gets absorbed and diffused by vegetation, masked by fountains and other sources, is shaped by the spatial rhythms of buildings and streets (Blesser and Salter 2009; LaBelle 2010). It makes a big difference if a street is bounded by two tall, flat, and parallel facades on each side, if the facades have instead many elements such as balconies that diffuse the sonic reflections, or if one side of the street is unbuilt (Augoyard and Torgue 2006).

All of these phenomena have implications for urban designers, but are difficult to operationalize for their every practice. Most soundscape research used a qualitative approach, which requires training and skill in active listening — a skill still rare in the profession. However, humans are very skilled at recognizing auditory cues to locate and orient themselves in their surroundings, even if they are not aware of this skill or cannot articulate its process. Even untrained individuals are able to distinguish surface materials and are able to tell whether a door is closed or open in a room with sufficiently low background noise (Blesser and Salter 2009).

Noise regulation in the US & EU and its problem of measurement

To describe current noise regulations in the US as insufficient would be a euphemism. Environmental noise was first recognized as a form of pollution in title IV of the Clean Air Act of 1963, which established the Office of Noise Abatement and Control (ONAC) to study the public health effects of noise, and recommend appropriate policies. The Noise Control Act of 1972 authorized ONAC to set noise abatement standards and enforce them (US Congress 1972). However, in 1981 the office was defunded by the Reagan administration, shifting the responsibility to states and municipalities. As a result, the US has currently no coordinated federal noise policy, comprehensive infrastructures for data collection, and noise regulations.

In Europe, the European Environmental Agency promulgated the Directive on Environmental Noise (2002/49/EC), which ordered states and larger cities to map the level of noise exposure and make this information available in a public database. Further, the states are ordered to develop noise management action plans for cities and transportation infrastructure. While the new directive has spurred efforts to measure noisescapes at the urban and national scale, these efforts are hampered by a lack of tools to measure noise exposure adequately. Most noise maps are simulations extrapolated from a small number of point of measurements, and the results obtained from different software packages can vary considerably (Murphy and King 2014, 96). Although recent models take building geometry and surface materials into account, comprehensive 3d building data is not available for most cities. In terms of measurements, not only the spatial

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1 In the language of economics, rivalrous
resolution, but also the placement and altitude of a sensor can make a big difference. To enable a differentiated understanding of urban auditory phenomena requires a rich set of spatially and temporally dense measurements that go beyond the capture of single dB(A) value and capture a range of frequencies and dynamic aspects.

Effective urban design guidelines and policies require a nuanced understanding of the spatio-temporal nature and quality of the urban soundscape. Until now, such fine-grained measurements of ambient noise were not available, as noise measurements conducted by cities are too sparse to allow examining how the built environment and human activity influence the soundscape. Crowd-sourced sensing using smartphone microphones promises to increase the resolution of measurements, but is limited by unsystematic data collection and uncalibrated measurements. Furthermore, crowdsourced noise sensing rarely manages to engage the number of participants necessary to convey a coherent picture of the soundscape.

The LA Noisescape Experiment

The approach discussed here involves a dense array of networked noise sensors mounted on streetlight poles at the height of the light fixture or luminaire. This height was selected to avoid vandalism and simplify maintenance and mounting. The mounting height does pose some sound modeling challenges as it is of course high above typical human head level. Nevertheless, the practical benefits make it a worthwhile compromise. The prototypical deployment conducted by Philips Lighting in collaboration with the City of Los Angeles’ Bureau of Street Lighting involved around 30 sensors covering a small area of about 50 acres (0.2 km²) in East Hollywood. The selected location is characterized by mixed land use including industrial, commercial, and housing, a school and a home for the elderly. It contains side streets covered by a tree canopy as well as busy streets including Santa Monica Blvd. and North Virgil Ave.

The sensors were located in proximity to each other and configured to report at regular intervals, yielding a high spatial and temporal resolution. The sensors were mounted at heights of 25-30ft or about 7.5-9 meters. Each sensor measured different parameters, including the minimum, maximum and continuous equivalent (Leq) decibel values, both raw and A-weighted, using a sample window of 15 seconds. Besides noise power, the sensors measured three frequency components every 5 seconds: low frequencies ranging from 20–400 Hz, voice-range frequencies between 400–8000 Hz, and high frequencies of 8000 Hz and above. The aggregate decibel values were encoded as floating-point values, the frequency components as 8-bit integers (yielding a resolution of 256 steps). The number of captured parameters, its timing intervals and data formats were determined by the available bandwidth of the GSM modems used to transmit the data in real-time. Figure 1 provides an overview of the project deployment area.

Related work

In the wake of the smart city discourse, sensor networks for collecting environmental data such as air quality, temperature, noise, or light levels are increasingly deployed in the urban environment. Starting in 2009, Smart Santander, a project funded by the European Union, deployed around 750 sensor nodes, including 50 noise sensors distributed across the Spanish city of Santander (Sanchez et
al. 2014). The sensor readings\(^2\) are accessible in real time,\(^3\) and capture a single, A-weighted dB value. Several sensing projects were specifically initiated to monitor noise and create or update municipal noise maps. Noise sensors collecting a continuous, A-weighted dB value was deployed in the Spanish cities of Girona (a total of five sensors) and Alicante (15 sensors).\(^4\) In addition to noise indicators, some platforms collect and transmit compressed audio (Pham and Cousin 2013), or conduct signal analysis on location to identify events such as gunshots (Showen, Calhoun, and Dunham 2009).

Participatory sensing represents an alternative measurement strategy, which relies on crowd-sourced measurements conducted by citizen volunteers using dedicated smartphone apps (Maisonneuve et al. 2009; Walker 2015). Noise modeling also relies on indirect measurements, including citizen complaints submitted via 311 systems and data scraped from social media (Wang, Zheng, and Liu 2014; Zheng et al. 2014). Information acquired through participatory sensing and citizen requests can potentially produce large data volumes,\(^5\) a review of crowd-sourced noise measurement apps reveals however only a few active users who produce spatially and temporally sparse measurements. Additional issues are inherent biases due to self-reported reporting and data quality issues stemming from the use of uncalibrated devices and measurement protocols. Hybrid forms between infrastructural and participatory sensing approaches exist, as in the example of Chicago’s Array of Things, where sensor nodes are installed by the city, but the protocols, code, and data collected by these devices is made directly available to the citizens.\(^6\)

Most sensor-network based projects are concerned with noise measurement, in most cases collecting only a single A-weighted noise value. An exception NYU’s Citygram project, which tries to capture more detailed qualities of the soundscape, and the Sound Score project, which combines a survey instrument with participatory sensing covering different frequency bands (Park et al. 2012; Walker 2015).

Our project differs from other initiatives in several aspects. First, the noise sensors used in this project measure nine indicators, including minimum, average, and maximum decibel, both raw and A-weighted, as well as three different frequency components. Second, the use of lamp posts as a sensing infrastructure offers a higher spatial density compared to other projects, allowing the comparison of local conditions. Sonic events are registered at several adjacent sensors, offering the opportunity to study the diffusion of sound and potentially their interaction with the built environment. Third, our sensors are static and calibrated, allowing comparison across space and time. The use of light poles, however, also comes with a considerable limitation: the height at which the sensors are placed is several meters above the street, and therefore does not accurately capture the noisescape a pedestrian would encounter.

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\(^2\) For technical details see [http://www.libelium.com](http://www.libelium.com)

\(^3\) See [http://maps.smartsantander.eu](http://maps.smartsantander.eu)


\(^5\) Between 2010 and 2017, more than 16 million requests were submitted in New York City alone - [http://nycopendata.socrata.com/Social-Services/311-Service-Requests-from-2010-to-Present/erm2-nwe9](http://nycopendata.socrata.com/Social-Services/311-Service-Requests-from-2010-to-Present/erm2-nwe9)

\(^6\) See [https://arrayofthings.github.io](https://arrayofthings.github.io)
Research design

Our exploratory analysis focused on the potential to study the spatial structure of the soundscape, and sought to answer a number of questions. First, was the sensor set-up in terms of its measured parameters and its spatial, temporal resolution sufficient to capture the interaction between soundscape and the urban environment? For example, were street sections with closed building facades noisier than those with more open space? Did foliage and canopy have a noticeable effect? Second, was the sensor setup sufficient for identifying the auditory signatures of moving sound sources, for example follow the trajectory of an emergency vehicle via its siren? Our research was also interested in gaining insight into different qualities of noise. Would, for example, the sound profiles of busy streets significantly differ from those on quieter streets? Finally, we were also interested in comparing and matching the collected noise data with other urban data sources of the same area, including official traffic counts, citizen complaints, and historical weather data.

To investigate these questions, we used a mixed methods approach. To complement the quantitative analysis of the sensor data, we conducted qualitative observational studies in the deployment area, paying close attention to events in public space and the features of the urban environment. We also verified the accuracy of the sensors through manual noise recording on location.
Exploratory analysis of the sensor data

Basis of the analysis were measurements collected from 27 nodes over four months, between September and December 2016. We excluded six nodes from the analysis due to data artifacts and mis-calibration issues. We also limited our analysis to the period from August 26-October 6, since this was the only period during which all sensors were consistently active.

In an initial exploratory analysis, a clear spatial pattern emerges. Santa Monica Boulevard and North Virgil Avenue are consistently noisier than all other streets. The contour plot of interpolated loudness values reveals the intersection of the two streets as a location of peak noise intensity (Figure 1). This spatial pattern is stable across all hours of the day. The sensor data shows an average noise difference between either of the two streets and all other streets at about 10 dB(A), sometimes exceeding 20dB(A) during peak hours. While Santa Monica and North Virgil are the loudest streets in absolute terms, they have the lowest variance in loudness (Figure 1 in supplement).

Averaged across all sensors, the difference between weekdays and weekends is less pronounced than one might expect. Aggregated by street and hour of day, differences appear depending on locations and weekdays. The afternoon peaks remain relatively stable throughout the week, while the morning and evening levels differ by day and street. The hourly noise profiles aggregated by street show a common overall shape for weekdays: noise picks up around 5 am, reaches a first peak at
around 7 am followed by slight decline and then a higher peak at around 3 pm. Noise finally fades off in the evening after 8pm, falling back to its lowest value at around 3am (Figure 2).

The frequency composition reveals a distinct temporal pattern not visible in the loudness values. Mid-range frequencies maintain a relatively stable level of around 70db throughout the day between 7am and 10pm. The low frequencies, otherwise closely following the levels of the mid frequencies, seem to increase significantly during afternoon, peaking at around 5pm. It can be hypothesized that this low-frequency afternoon "bump" is connected to low-frequency noise emissions of the large diesel engines of trucks and busses, which are more frequently found on Santa Monica and North Virgil (Figure 3). These values have to be placed in perspective, considering that the sensors are mounted at heights of 7.5-9m above the road surface. Since loudness diminishes with distance from the source, measured values are expected to be lower than on street level.

Figure 2 Comparison of the loudness and frequency components of a single sensor on Santa Monica over one day. Note the bump in the low frequencies (dark red line) during the afternoon, which remains hidden in the average loudness (Leq dB(A) – middle blue line), which is the standard measure on most systems.
Modeling noise intensity based on historic traffic and weather data

Auditory space is a dynamic phenomenon that is shaped by numerous factors. These include not only the activities such as traffic or the physical shape of the environment, but also variables such as temperature, rain, and wind.

A considerable number of models for estimating environmental noise based on vehicle counts have been developed since the early 1950s (Murphy and King 2014; Garg and Maji 2014; Calixto, Diniz, and Zannin 2003; Steele 2001). Comprehensive traffic data for the area is scarce since the city does not store the data collected by the conductive loops of the ATSAC sensor system. As a proxy, we used five traffic count studies conducted between 2009 and 2014 by LA’s Department of Transportation inside or in proximity to the deployment area (LADOT 2017, Table 1). Data from these studies include the number of vehicles counted per hour in each direction, without distinguishing cars and trucks, however. Using data from these studies implies making a number of somewhat problematic assumptions: that the traffic volume has remained relatively stable over more than ten years; that single-day snapshots are representative for the temporal profiles of current traffic in the area; and that the traffic counts for a given street remain constant within a given radius.

Despite these limitations, the hourly profiles of historic traffic counts and measured loudness values are remarkably similar. Both show the same pattern of peaks and slopes, indicating that the temporal structure of traffic has remained relatively stable over the years (Figure 4). The number of

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7 For more information about the system, see http://trafficinfo.lacity.org/about-atsac.php
cars counted correlate highly with the loudness values measured at the respective streets on a weekday (r=0.9 for both S. Monica and N. Virgil). The scatter-plot indicates an exponential relationship between counted cars and noise dB(A), which is to be expected due to the logarithmic nature of the dB metric. A logarithmic transformation of the traffic count reveals a strong linear relationship with the measured loudness values, especially for voice frequencies and dB(A) values, to a lesser degree for raw dB values. However, above values around 72dB(A) or 1300 cars per hour, the linear relationship becomes weaker. A comparison of the temporal profiles reveals that the afternoon rush hour peak appears to have shifted over the years, registering about two hours earlier in the noise measurements than in the historic traffic count data (Figure 5).

Table 1 Historic traffic count dates and locations

<table>
<thead>
<tr>
<th>Count Date</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wed 2/28/07</td>
<td>Santa Monica / Vermont</td>
</tr>
<tr>
<td>Mon 3/27/09</td>
<td>N Virgil / Willow Brook</td>
</tr>
<tr>
<td>Tue 7/9/11</td>
<td>N Virgil / Lexington</td>
</tr>
<tr>
<td>Tue 8/19/14</td>
<td>Santa Monica / Hoover</td>
</tr>
<tr>
<td>Tue 8/20/14</td>
<td>Santa Monica / Vermont</td>
</tr>
</tbody>
</table>

Figure 4 Historic traffic counts by primary street and hour of day (LADOT 2017).
A series of four linear regression models predicting loudness in dB(A) based on the logarithm of the traffic count (1) yields adjusted $R^2$ values between 0.89 and 9.93 for each traffic count episode (Table 2).

Equation 1

$$L_{dB(A)} = \alpha + \beta \cdot \log_{10}(V)$$

$V$ traffic volume in vehicles per hour

Table 2 Regression results

<table>
<thead>
<tr>
<th>Individual Regressions</th>
<th>Dependent variable:</th>
<th>$L_{eq dB(A)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(1) 2/28/07 S. Monica</td>
</tr>
<tr>
<td>log10(cars)</td>
<td>12.400***</td>
<td>8.763***</td>
</tr>
<tr>
<td></td>
<td>(0.328)</td>
<td>(0.227)</td>
</tr>
</tbody>
</table>
Especially the coefficients for the N Virgil models show similarities to the WADC noise model (2), one of the earliest estimation models for traffic noise (WADC 1952). The most notable difference is the higher constant value in the historic model, which corresponds to the assumed background noise level.

Equation 2

$$L_{50} = 68 + 8.5 \times \log_{10}(V) - 20 \times \log_{10}(D)$$

$V$ traffic volume in vehicles per hour, $D$ distance from the traffic lane, in feet.

Besides traffic, weather was another factor potentially influencing the ambient noisescape of the environment. Unfortunately for the analysis, the weather was very consistent throughout the pilot phase — rain and strong winds were almost entirely absent. Higher wind speeds registered as higher noise levels in the sensors, but with significant differences depending on exposure and location of the sensor. On average, an increase in wind speed of 1 mph registers as an 0.8 dB(A) increase in measured loudness.

The local environment and the soundscape

Each sensor shows a distinct profile in terms of magnitude and frequency distribution over time. These differences are caused by different local conditions that include many factors, including intensity and composition of traffic on nearby streets, the configuration, shapes and materials of the surrounding architecture and landscape, the effect of trees and vegetation, and activities taking place in proximity. To get a better sense of these local conditions, we conducted on-site field research while the sensors were operational.

Events and activities

The pilot was installed is a mixed-use area, including a considerable number of apartment buildings and single-family homes, retail, and industrial facilities. Furthermore, the area contains two major streets and moderate traffic exposure. The capacity to measure citizens perception of noise exposure is limited since the 311-citizen complaint system of Los Angeles does not offer a category for noise. A review of the issues discussed at the East-Hollywood Neighborhood Council in the project area,

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8 See https://www.lacity.org/myla-311/myla-311-service-request
reveals that traffic noise is discussed less than the noise from human activity, notably the activities of street vendors and the noisy environment at swap meets.\footnote{See \url{http://www.easthollywood.net/meetings}}

Within the project area Willow Brook street is home to an elementary school, and the noise of children coming to school in the morning is clearly visible in the noise data captured by proximate sensors. Another event that left its signature in the sensor recordings was the municipal garbage collection on Westmoreland street that took place during the fieldwork. Its characteristic signature on Thursday morning was also visible in the measurements collected during the following weeks.

Other signatures of environmental noise sources identified in the recorded data in combination with the on-site fieldwork included idling trucks and roadworks activities. Their step-like sonic signature was also a useful marker for investigating the propagation of noise across space as captured by adjacent lamp posts, with the noise intensity diminishing with increasing distance. It was also interesting to observe that different frequencies diminished at different rates, with high frequencies falling quicker with distance from the noise source (Figure 6).

We investigated the capacity of the sensor array to detect moving sound sources across adjacent sensors, but unfortunately the 5 and 15 second intervals were too long to capture fast sources such as moving emergency vehicles. It was however, possible to identify the noise peaks generated by waste collection. Once the pattern was matched in the observational study, it could be identified in the data of the following weeks.

![Figure 6 Noise signature of an idling truck, diminishing over adjacent sensors (distances between sensors are not equal). Note how the high frequencies drop of quicker than the lower frequencies (the second sensor from the left did not report frequency values and is missing from the upper row).](image)

**Plants and Trees**

Plants can be effective noise barriers — the leaves diffuse high frequencies, while soil and roots dampen low frequencies. Literature reports a difference of 5dB for a 10m wide vegetation belt close to the road (Huddart 1990; Peng, Bullen, and Kean 2014). Unfortunately, the results obtained remain anecdotal and would require a modified research design. The trees in the study area do not
shed their foliage during winter, therefore their effect on noise propagation cannot be directly observed. One sensor located underneath a dense, street-covering canopy had to be excluded from our study due to calibration issues. An effect was observable at the locations on two other sensors on Westmoreland and Willow Brook, both covered by a tree canopy—the sensors reported lower noise values than neighboring sensors, but due to the various differences in the local conditions between the two locations we do not consider this result to be significant.

Facades and architecture

Building facades reflect sound and therefore increase the perceived and measured loudness. Again, due to the small study area and the impossibility to control for all possible confounding factors, the results are anecdotal. On Westmoreland street, a sensor was located right in front of a tall, flat facade, while the adjacent sensor was freestanding on the opposite side of the street. The sensor in front of the facade produced on average 5 to 10 dB higher readings than the free-standing sensor, but more research is needed to overcome the limitations of the exploratory study.

Conclusion, Design and Policy Recommendations

The results of this exploratory study have several implications for noise policy, architecture, and urban design. First, the project demonstrates the importance of a more nuanced understanding of noise that distinguishes between noise qualities. The measurement of noise frequencies revealed a temporal structure: a peak of low frequencies in the afternoon, which is not captured by the dB(A) metric. This is important because low frequency noise, typically generated by the powerful engines of trucks, aircrachts and ventilation systems, are experienced as especially disruptive and annoying. These results add to the evidence that the A-weighted loudness value alone is an inadequate metric for urban noise regulation and that a qualitative treatment of noise created by different vehicle types is beneficial. Beyond frequency composition, noise qualities also include temporal dynamics — the noise of cars differs from air conditioning units, trucks, or motorcycles. The sensor array captures the spatial, temporal, and frequency components that make an adequate investigation of noise qualities possible.

Second, the high spatial resolution of noise sensors attached to streetlights allow a more accurate investigation of the spatial aspects of the soundscape. The range of temporal noise profiles across space show that the urban soundscape is rich and nuanced, and that the local conditions, its building typology, vegetation, and activities are important. The results are not always conclusive due to the spatial and temporal limitations of the study and show the need for future work. The results, however, indicate that the sensor array is able to capture the interactions between sound sources, architecture, and vegetation at the scale of the whole city.

This has implications for the architecture and urban design disciplines, which are concerned with the visual appearance of streets and buildings, but less with how they sound like. We attribute this imbalance to a lack of adequate tools and methods. Mitigating noise pollution requires designers to consider the auditory qualities of different materials, surfaces and geometries, and the sensor array provides a test bed for observing their auditory effects at the urban scale. Architectural projects could be evaluated based on another set of criteria beyond their visual qualities. As mentioned with lighting early on in this paper, it is the ephemeral qualities of an environment that often drive people’s subjective sense of comfort and ease. Sound data could add a valuable aspect to evaluating urban design—not to mention in cities undergoing rapid upheaval through new construction.
Among the potential unexpected outcomes might be the way these data could be appropriated by the private sector. Real estate developers, for example, often select qualitative differentiators to distinguish one neighborhood from another. As cities like LA aim to make as much data public as possible it is important to consider the possible impacts on urban dynamics. The LA Open Data Policy\textsuperscript{10} describes how the city imagines stimulating entrepreneurial activities with ready access to non-personally identifiable data. It is likely that continuous sound data would provide a powerful additional source of inspiration for the same target community. It may, however, also have unintended consequences such as increasing the rate of gentrification or driving up real estate prices. Data governance models for these types of data are currently actively discussed.

The comparison with traffic counts data reveal a surprising historical continuity of traffic patterns while highlighting its changes over time. Our statistical models are largely consistent with simplified traffic noise models and show that fine-grained noise data can be used to estimate traffic and vice versa. This stability of the observations across time also allows the use of noise data as a proxy for traffic counts if the sensor data is calibrated with respect to the local environmental and urban conditions.

Methodologically, the pilot study demonstrates that quantitative sensor measurements can support qualitative inquiries into the geography of the urban soundscape, and therefore offer a simple and scalable alternative to traditionally qualitative studies, which are time and cost intensive while limited in scope. A mixed methods approach combining observational studies is especially powerful for studying the sonic signatures of urban phenomena.

Finally, the collected data indicates a rich sonic landscape that underscores the need for a more holistic and continuous urban design practice beyond noise mitigation. Instead of considering noise a substance that can simply be disposed of, noise is a necessary consequence and reflection of human activity. Streets and regulations can be designed in a way to make cities sound better and make them more legible.

Related to this final insight, relying on continuous data has significant implications for master planning as well. Instead of taking a snapshot in time and then rolling out a plan over 10 years some cities are taking a more iterative approach. Vienna, for example, used its Masterplan Licht (lighting masterplan) in a continuous way rather than as an absolute. In domains such as construction and infrastructure development this approach also allows cities to apply the latest technologies rather than remain wedded to past specifications.

For urban researchers examining the visual aspects of the city, a wide array of tools is available ranging from remote sensing infrastructures to tools such as Google Street View and crowd-sourced data sources. Methods and infrastructures for studying the soundscape, on the other hand, are still underdeveloped. Current auditory tools and infrastructures are largely limited singular point measurements that do not represent spatial qualities or crowdsourced data collection with its inherent biases and omissions. We have demonstrated that a dense array of noise sensors offers new opportunities towards a better understanding of the soundscape and the development of sonic design competencies for planners and architects.

\textsuperscript{10} See http://www.lamayor.org/garcetti_directs_city_departments_to_collect_data_for_open_data_initiative
References


