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ENVIRONMENTAL NOISE IN BOSTON NEIGHBORHOODS: A CASE STUDY

Noise pollution is a major determinant of quality of life, particularly in urban areas. Of the sources of noise pollution, environmental noise is typically the most significant in urban areas. This includes sources such as construction, heavy machinery, traffic noise, and transportation noise. It has been established in past studies that there is a correlation between the socio-economic quality of a neighborhood and the environmental noise experienced within it [1]. While likely due to several factors, historically underprivileged neighborhoods have experienced injustice in their built environment, with less investment in infrastructure and zoning laws that have zoned them closer to industrially zoned areas [2]. I propose to measure noise levels in two neighborhoods with vastly different demographics and socioeconomic standings that border Northeastern University, Roxbury and Fenway. To compare neighborhoods, two distinct areas in each neighborhood were measured during rush hour on weekdays. Areas were chosen based on recorded vehicular traffic levels, perceived pedestrian traffic levels, and proximity to Northeastern University. Recordings were manipulated and characterized in different ways to gain an understanding of the types of noise present in each area.

Literature on Perceived Noise and Socioeconomic Correlation:

In *Spatial and sociodemographic determinants of community loudness perception* by authors Nina F. Lee, Jonathan I. Levy, Marcos Luna, Erica D. Walker, the authors created a voluntary survey of perceived noise at the street and neighborhood scales. Their summary of positive and negative correlations of perceived noise can be seen in Figure 1. Roxbury has a higher number of auto body shops than Fenway with 8 inside the area of interest compared to Fenway's 0. There are also 2 police stations in the Roxbury area of interest, and 0 within the Fenway area of interest. Median household income in Roxbury is much lower than the average across the City of Boston. There are more police stations in Roxbury than Fenway, and Roxbury has a larger number of frequent bus lines going through it, particularly in the area of interest. Lee et al. also predicted restaurants and commercial activity as predictors of perceived neighborhood noise. Both Nubian Square and West Fenway have these in high proportion. From this data, it can be hypothesized that Roxbury, particularly Nubian Square, might have a higher degree of perceived neighborhood noise. To add to the growing idea of a socioeconomic coloring of environmental noise, [3] found that A-weighted environmental noise across the contiguous United States was statistically higher in Black, Latine, and impoverished communities. The results can be seen in Table 1.

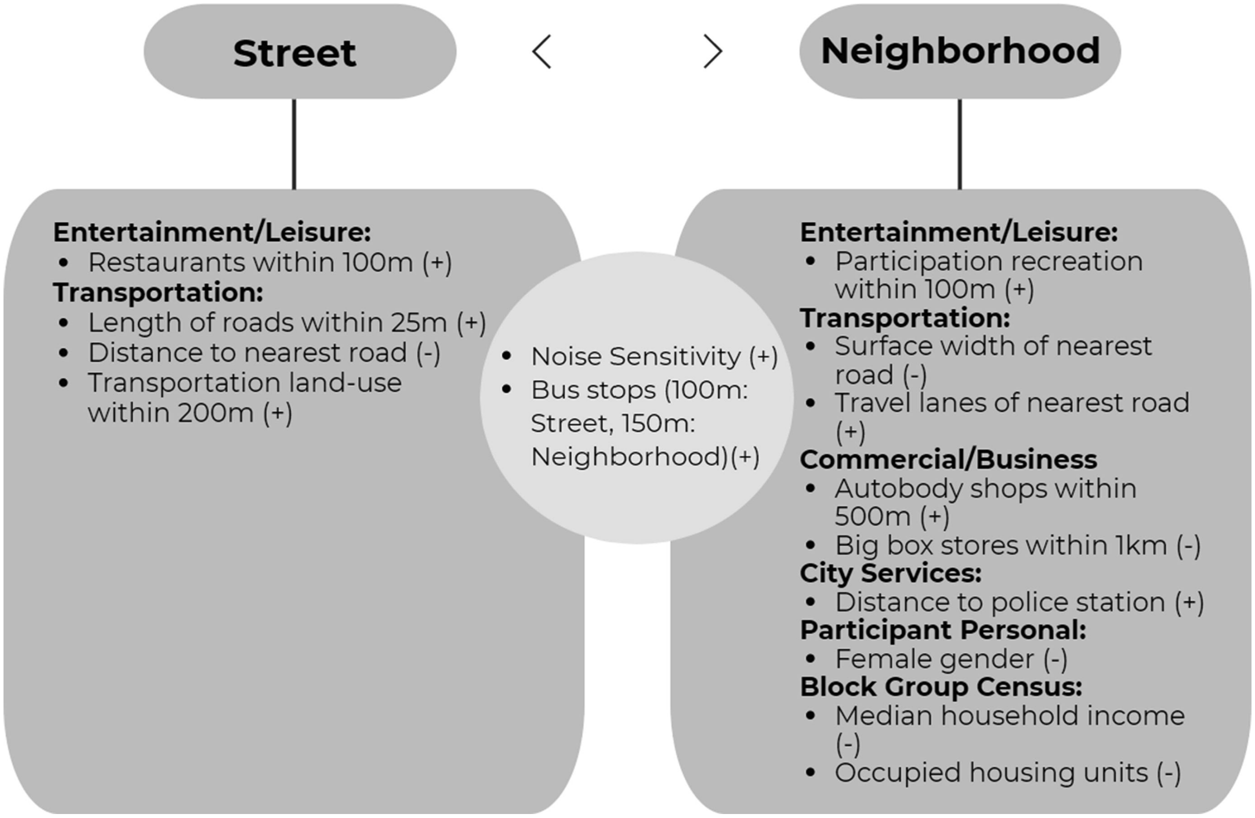

Fig. 1: Positive (+) and negative (-) correlations with noise perception [4].

Characteristic	Total, *n* (%)	Median (IQR) anthropogenic noise, dBA[a]		
		L_{50} nighttime	L_{50} daytime	L_{10} daytime
Race/ethnicity[b]				
Hispanic	44,095,827 (17.3)	45.6 (43.3–47.5)	49.5 (47.5–52.3)	54.1 (52.3–56.0)
Non-Hispanic				
American Indian	1,209,132 (0.5)	42.9 (37.9–45.7)	46.1 (37.8–49.7)	51.5 (44.8–54.4)
Asian	13,081,414 (5.1)	45.4 (43.9–47.1)	49.1 (47.4–51.1)	54.0 (52.4–55.7)
Black	32,935,749 (13.0)	45.6 (43.8–47.6)	49.7 (47.6–52.6)	54.2 (52.4–56.3)
White	157,730,767 (62.0)	43.6 (41.3–45.7)	47.1 (43.3–49.2)	52.3 (49.6–54.2)
Income ≤ poverty threshold	33,194,588 (13.3)	45.2 (42.8–47.5)	49.2 (46.6–52.2)	54.0 (51.7–56.1)
Income > poverty threshold[c]	216,181,346 (86.7)	44.2 (42.0–46.3)	47.9 (44.9–50.0)	52.8 (50.6–54.8)

Table 1: Distribution of anthropogenic L50 nighttime, L50 daytime, and L10 daytime noise among urban residents by race/ethnicity and socioeconomic characteristics at the block group level from the 2006–2010 American Community Survey [3].

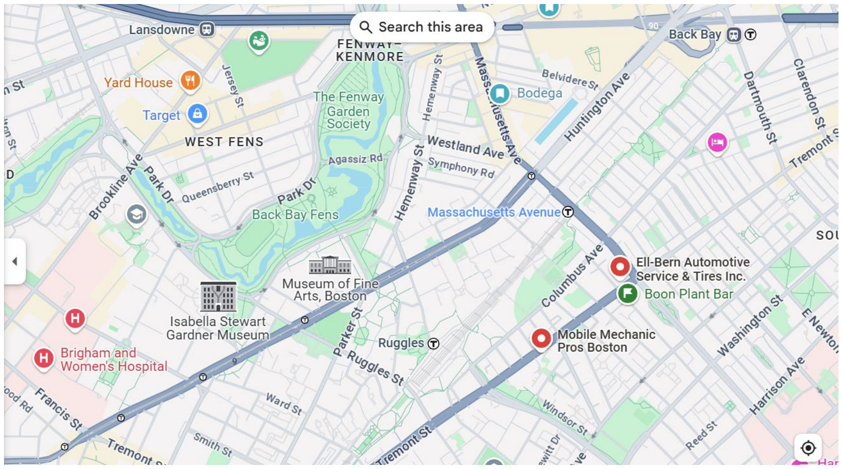

Fig. 2: A Google Maps search for auto shops in Fenway.

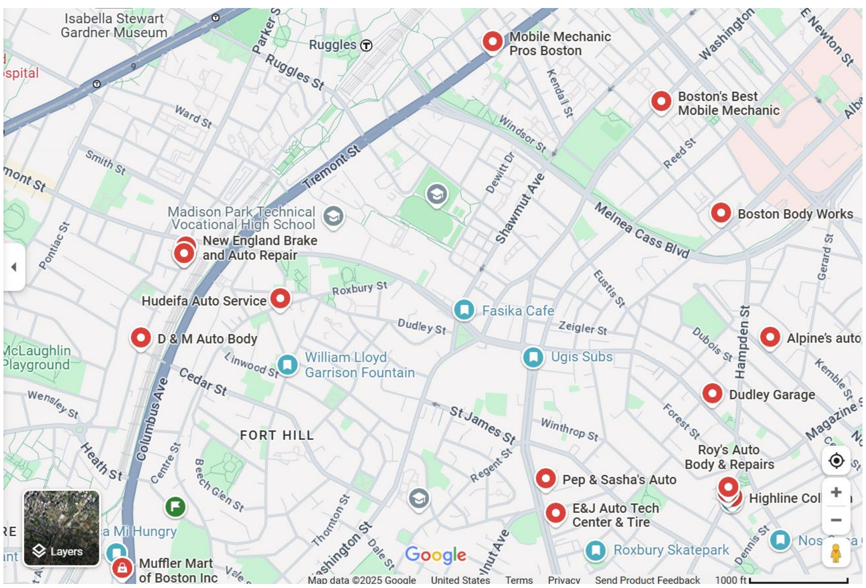

Fig 2: A Google Maps search for auto shops centered in Roxbury.

Brief Socioeconomic Consideration of Roxbury and Fenway

Despite being connected by the compact campus of Northeastern University, the neighborhoods of Roxbury and Fenway are socioeconomically distinct neighborhoods. In 2022, there was a significant educational disparity between Roxbury and Fenway, with Fenway having a 52% higher percentage of its population holding a bachelor's degree compared to Roxbury. The well characterized link between education level and income means it shouldn’t come as a surprise that in 2017, the median household income in Roxbury was $27,721, lower than $62,021 throughout Boston. While Fenway’s was $39,550, this does not factor in the large proportion of college students with a lack of a steady income in Fenway. Considering income from direct family, particularly family out of state, Fenway's household income is almost certainly higher. On the racial side, Roxbury's proportion of Black residents was 47% higher than that of Fenway's. Roxbury has an 18% higher Hispanic population as well. Overall, Roxbury's population is more racially diverse, socioeconomically disadvantaged, and even older than Fenway [5]. Given the previous literature on the link between an area's socioeconomic status and environmental noise, Roxbury likely hears more environmental noise than Fenway.

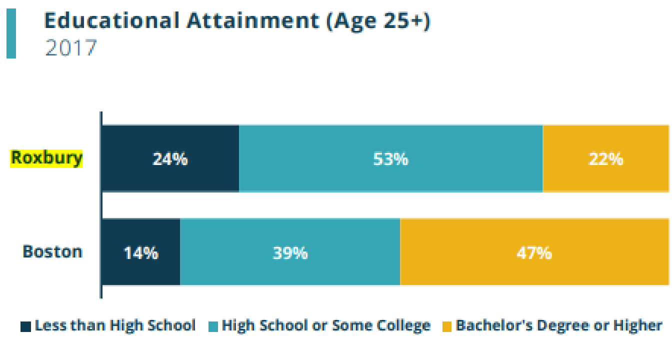

Fig. 3: Roxbury vs Boston Educational Attainment.

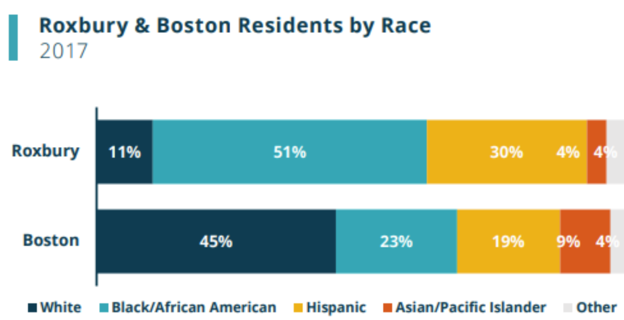

Fig. 4: Roxbury vs Boston Racial Composition.

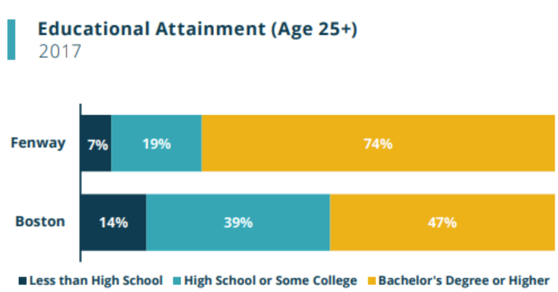

Fig. 5: Fenway vs Boston Educational Attainment.

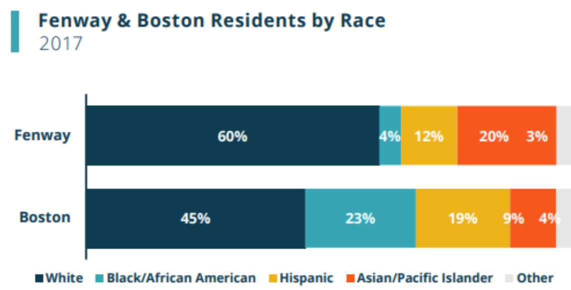

Fig. 6: Fenway vs Boston Racial Composition.

Proposal:

To study the environmental noise of each neighborhood, two street typologies were considered. The first category, Main Squares and Roads, are streets with heavy commercial activity and foot traffic. I considered commercial centers close to Northeastern University that students might patronize but likely wouldn't see students as the only traffic. This narrowed down the subdistricts to Nubian Square, Egleston Square, or Dudley/Blue Hill Avenue in Roxbury, and the West Fens in Fenway. The second category, Neighborhood Streets, were local, low traffic roads close to the highly trafficked area, approximately midblock to minimize noise from traffic traveling perpendicular to the street of interest. The streets and intersections considered are listed in Table 2. Fenway's Main Square and Road was selected to be the intersection of Kilmarnock Street and Boylston Street, near Fenway Park and neighborhood amenities such as grocery stores, restaurants, retail stores, and health centers. In Roxbury, the intersection of Warren Street and Dudley Street in Nubian Square was chosen. This intersection is in a neighborhood center with similar amenities, including a library and bus hub. Fenway's Neighborhood Street was Peterborough Street, a local road with dense mid-rise apartment buildings. In Roxbury, the equivalent was chosen to be Greenville Street, a street with a mix of mid-rise apartments and freestanding residential structures. The Main Square and Road intersections were chosen to have similar vehicular traffic throughput based on City of Boston traffic counts, which were not available for the neighborhood streets. Both Neighborhood Street locations were empirically observed to have low vehicle volumes and little pedestrian traffic during recording.

Neighborhood	Classification	Street(s)	Grand Total Traffic Throughput, Peak Hours

Roxbury	Main Squares and Roads	Blue Hill Avenue at Washington St	
Roxbury	Main Squares and Roads	Blue Hill Avenue at Seaver Street	
Roxbury	Main Squares and Roads	BHA @ Warren St	
Roxbury	Main Squares and Roads	Warren St @ Dudley St	22498
Roxbury	Main Squares and Roads	Washington St @ Malcolm X Boulevard	
Roxbury	Main Squares and Roads	Columbus Ave @ Washington St	
Roxbury	Main Squares and Roads	Dudley St @ Columbia Rd	
Roxbury	Main Squares and Roads	Ruggles St @ Tremont St	
Roxbury	Neighborhood Streets	Centre St	
Roxbury	Neighborhood Streets	Highland St	
Roxbury	Neighborhood Streets	Maywood St	
Roxbury	Neighborhood Streets	Waverly St	
Roxbury	Neighborhood Streets	Moreland/St James	
Roxbury	Neighborhood Streets	Waverly St	
Roxbury	Neighborhood Streets	Mt Pleasant Ave	
Roxbury	Neighborhood Streets	Greenville St	
Roxbury	Neighborhood Streets	Hammond St	
Fenway	Main Squares and Roads	Huntington @ Ruggles St	
Fenway	Main Squares and Roads	Huntington @ Mass Ave	
Fenway	Main Squares and Roads	Hemenway @ Westland Ave	
Fenway	Main Squares and Roads	Park Drive @ Boylston St	
Fenway	Main Squares and Roads	Boylston @ Kilmarnock St	21630
Fenway	Main Squares and Roads	Park Drive @ Beacon St	
Fenway	Neighborhood Streets	Symphony Rd @ St Stephen St	
Fenway	Neighborhood Streets	Gainsboro @ Hemenway	
Fenway	Neighborhood Streets	Burbank St	
Fenway	Neighborhood Streets	Peterborough St	

Table 2: Streets and intersections considered for study. Chosen areas are highlighted in red [6].

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Measuring and Quantifying Noise:

A standard measure of noise in urban environments is the measure of equivalent sound pressure level over short time interval averages weighted using digital filters to produce the sound's response in the human ear. "Slow" response is considered 1 second averages of SPL, and ISO 9613-2 describes that the pressure level should be "A-weighted." On the purpose of A-weighting:

> The A-weighting is a general purpose model of the human response to noise and used for environmental noise and hearing damage risk assessment [7]

The ISO 9613-2 approximation of A-weighted noise over a given period is defined in Eq. 1. Different digital filters for weighted noise can be found in Figure 7.

$$L_{Aeq,T} = 10\log_{10}\left(\frac{1}{T}\int_0^T \frac{p_A(t)^2}{p_0^2}dt\right), p_0 = 20\mu Pa$$

Eq. 1: equivalent continuous A-weighted sound pressure level over period T. p(t) is is a-weighted instantaneous pressure.

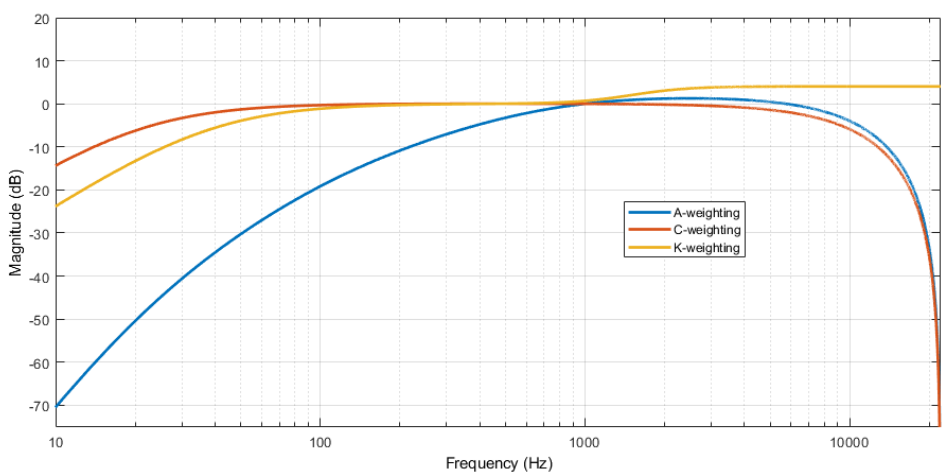

Fig. 7: Noise weighting digital filter implementation in MATLAB [8].

In addition, there is merit in examining different weighting of noise, along with frequency bands of noise. Different sources produce noise in different frequency ranges, and varying locations can have different sources of noise. Per [9], noise can be classified in four bins. Very low frequency noise (VLFN) is defined as the range ≤ 20 Hz; low frequency noise (LFN) is defined to be 25–125 Hz, medium frequency noise (MFN) is defined to be 160–500 Hz, and high frequency noise (HFN) is > 500 Hz. In [9], Leaffer et al. found that VLFN and LFN were negatively correlated with A-weighted noise, but positively correlated with C-weighted noise. LFN and VLFN have been shown to correlate to annoyance above 55 dB, likely due to their ability to shake the human body physically. They can cause chest wall vibrations, gag sensations, and post-exposure fatigue at levels below 145 dB [10]. Given the negative health effects of LFN and VLFN as described in literature review of Leaffer et al., analyzing recordings in the context of both A-weighted and C-weighted noise is worthwhile.

$$L_{eq}(f) = \sum_{i=1}^{n} 10 \log_{10}\left(10^{\frac{Li}{10}}\right)$$

Eq. 2: Equation to determine the average level of noise for a certain frequency range. Li is the 1-second level for a specific frequency bin, n is the number of 1-second time samples in the sampling period.

Methods Notes:

Recordings were made using the Zoom H4N Pro recorder, windscreen, and a camera tripod. While the Zoom H4N Pro is not a professional-grade, standard sound level meter, it has a relatively flat response across the human hearing range. The attenuation at 18 Hz means that C-weighted noise may not be as accurate in terms of dB levels. The frequency response of the Zoom H4N Pro can be seen in Figure 8. Recordings were made within 5 feet of active roadway surface, at least 1.5 feet above the sidewalk. Notes on environmental conditions and recording setups for each recording can be found in Appendix A. Recordings were preprocessed to remove setup and teardown sounds in Audacity, then analyzed in MATLAB 2024b. Scripts used to analyze recordings can be found in Appendix B**.** To calibrate the field recorder and ensure accurate SPL and L_{eq} values, an iPhone running the NIOSH Sound Level Meter application and recording apparatus were placed in the same location, where the recording apparatus was calibrated with a 1kHz, 94dB test tone. SPLs for recordings were then calculated by converting to SPL from dBFS, using the offset between measured dBFS and the iPhone SLM application measurement at 1 kHz, 94 dB.

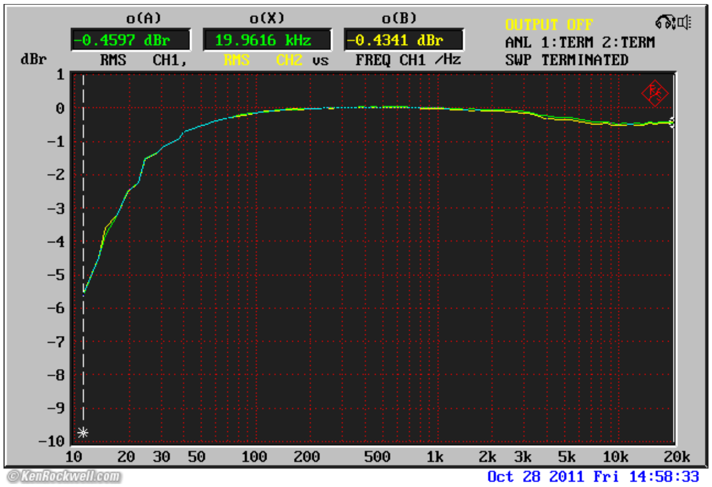

Fig. 8: Frequency Response of Zoom H4N Pro.

Results:

Figures 9-19 show various noise statistics processed from the tests. The average L_{eq} at Warren and Dudley was only 0.3 dBA higher than that of Boylston and Kilmarnock over the recording period. On average, Greenville Street was 3dBA louder than Peterborough Street, both of which were lower than both Boylston/Kilmarnock and Warren/Dudley in all noise metrics. This confirms the conclusion that Neighborhood Street typologies are much quieter than Main Squares, even the Main Squares in more economically advantageous areas. Boylston/Kilmarnock had much higher SPLs than Warren/Dudley at lower frequencies, which were subsumed by Warren/Dudley's higher SPLs at higher frequencies, particularly octaves past 2 kHz. HFN noise serves as audible annoyance, and this range is where Fletcher-Munson curves show the human ear as most sensitive to higher SPL [11]. The presence of HFN is a somewhat surprising result, considering that Leaffer et al. found VLFN and LFN to be more present in Roxbury than Everett over a long time scale.

With C-weighting, all study areas exceed daytime noise levels of 55 dBC, with much higher levels of VLFN and LFN than under A-weighting. A-weighted 5-minute average SPLs exceed the 55dBA limit in the Main Squares areas, and approach it in the Neighborhood Streets areas.

In Figures 16-19, it can be noted that transient events rather than continuous noise create the greatest loudness differences in higher frequencies. These can be observed as vertical lines across the frequency spectrum at a particular point in time. Additionally, in the range of 50-250 Hz, the dynamic range of the noise is much greater, whereas below 20 Hz and above 2500 Hz it is more constant. Further work on this subject will need to investigate the spectral nature of different types of environmental noise, possibly identifying unique spectral characteristics of different sources of environmental noise and using computational techniques to identify them in recordings. Due to the transient nature of periods of high SPLs in each recording, future work should focus on these transient events regarding the sources and characteristics of each.

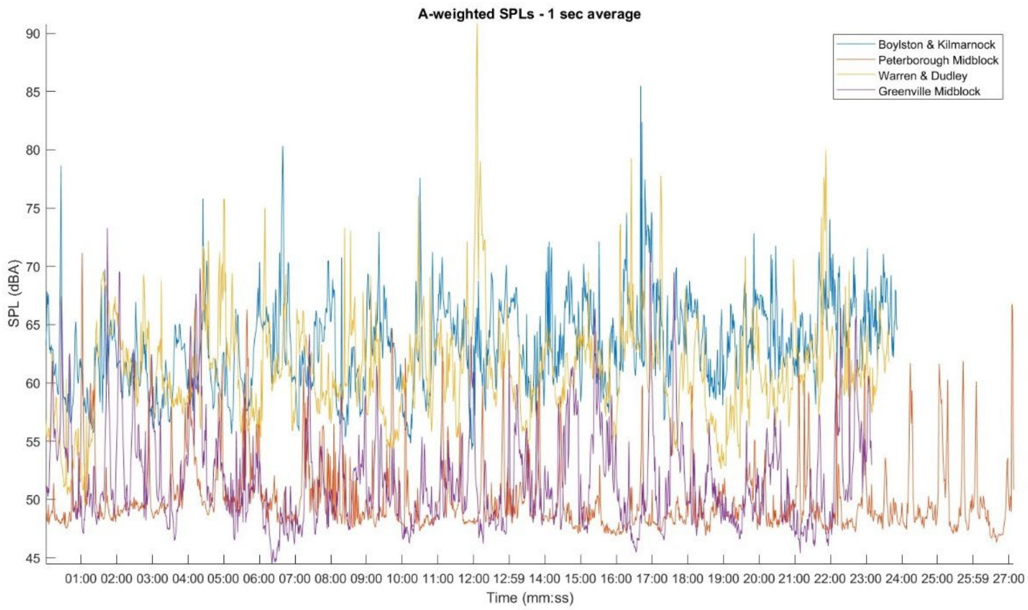

Fig. 9: A-weighted SPLs for recordings, averaged over 1 second

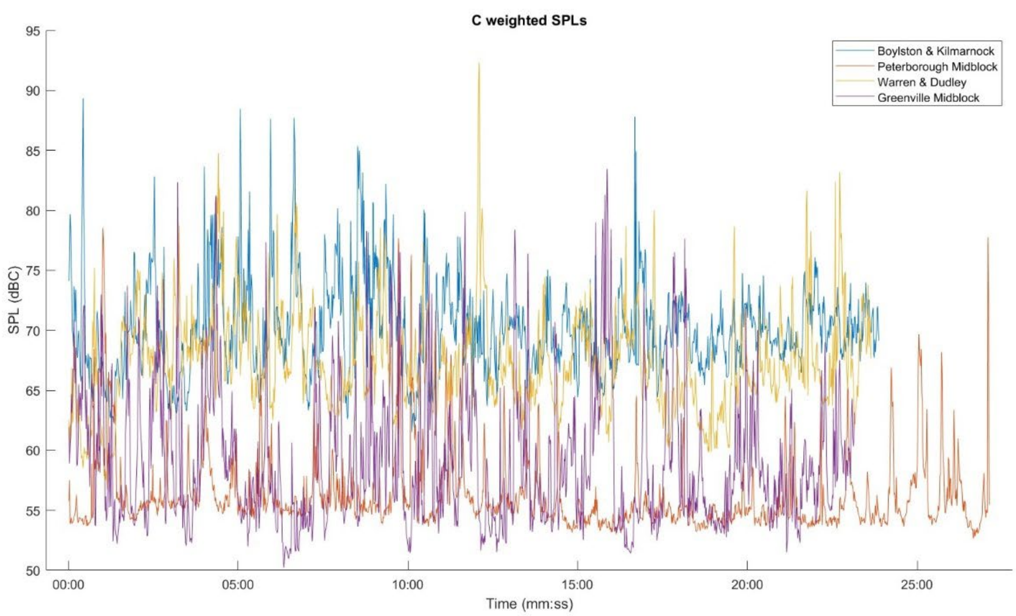

Fig. 10: C-weighted SPLs for recordings, averaged over 1 second.

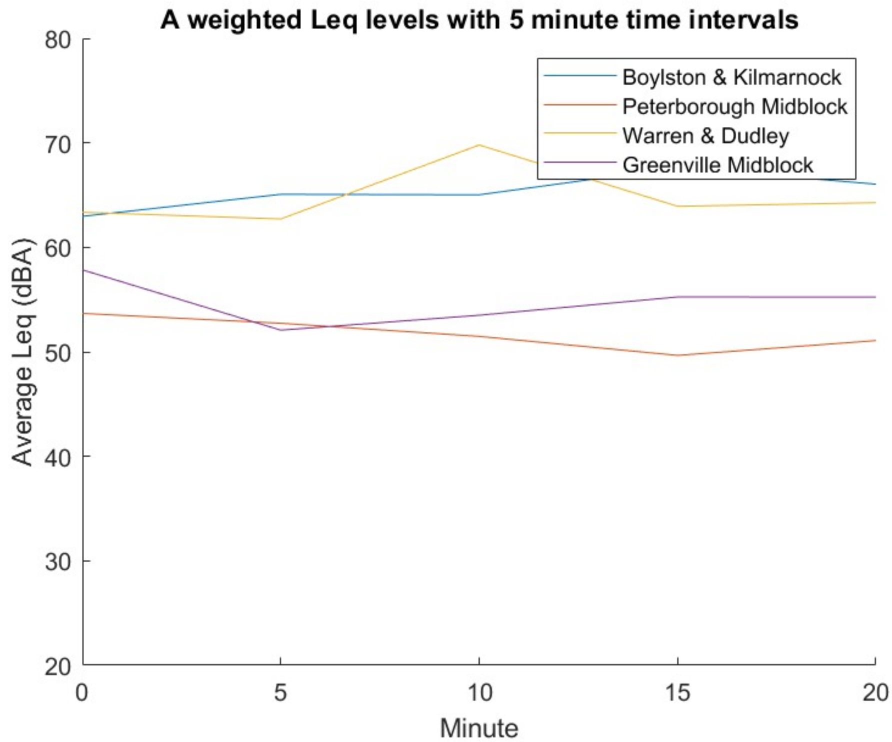

Fig. 11: A-weighted SPLs averaged over 300 seconds.

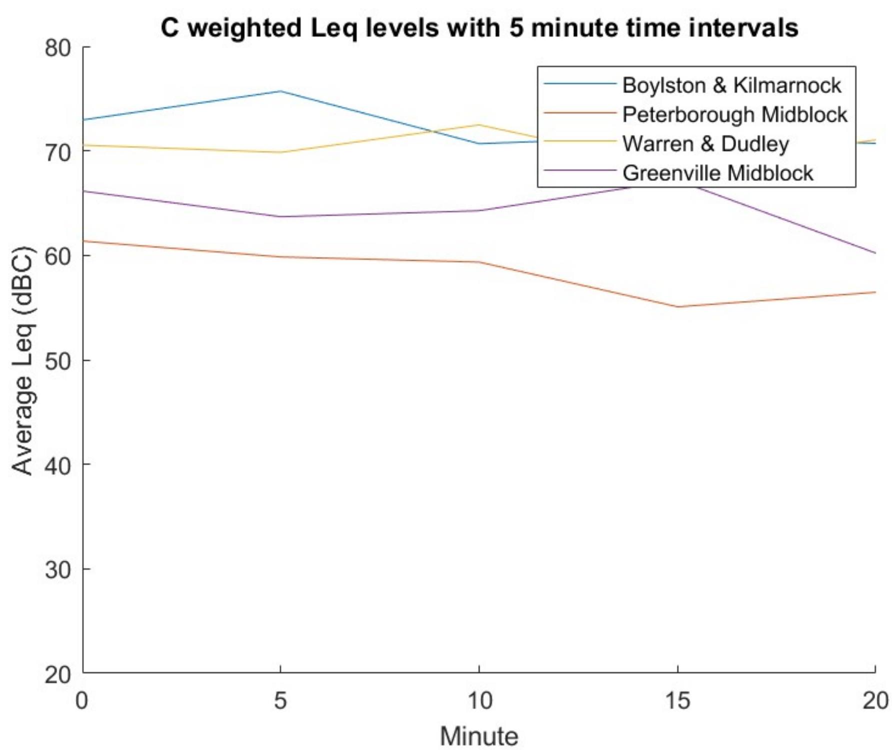

Fig. 12: C-weighted SPLs averaged over 300 seconds.

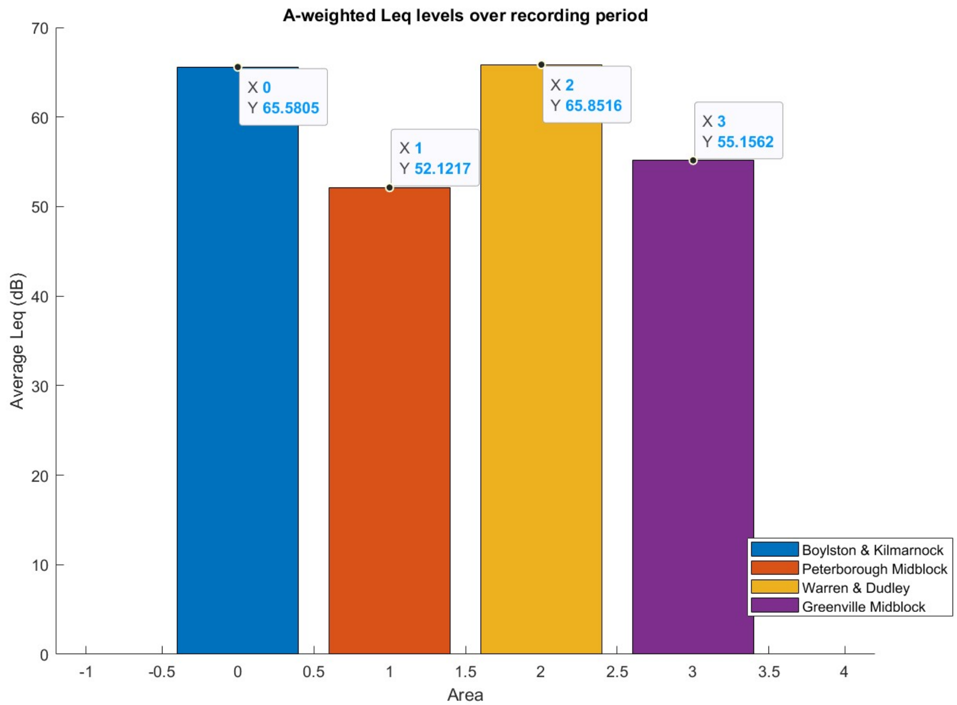

Fig. 13: A-weighted SPLs averaged over entire recording period.

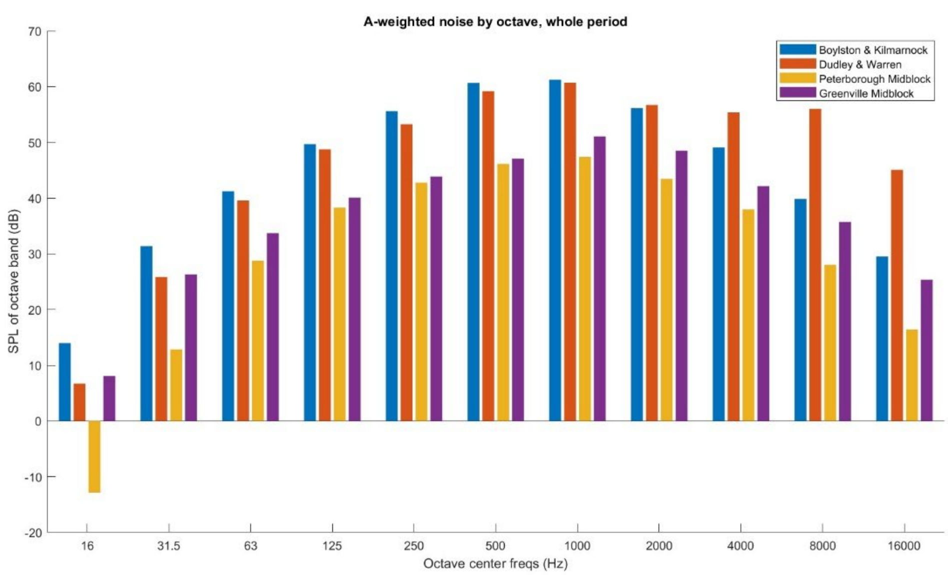

Fig. 14: Average A-weighted noise by musical octave over the recording period for each recording.

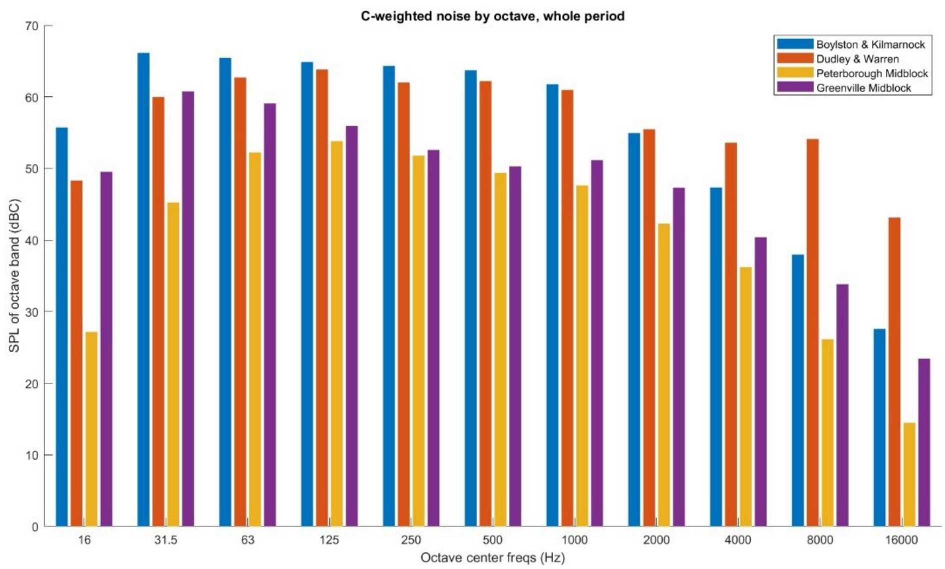

Fig. 15: Average C-weighted noise by musical octave over the recording period for each recording.

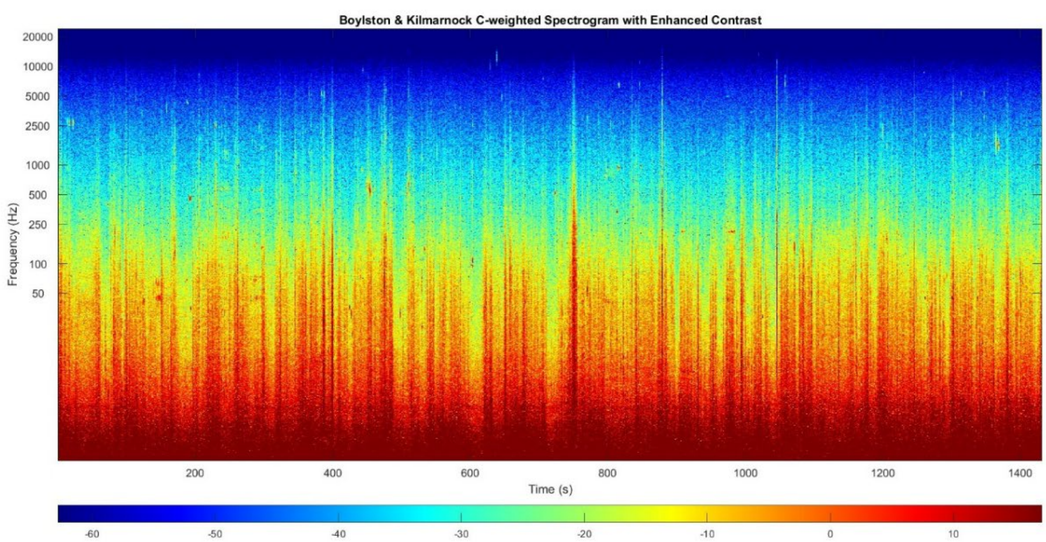

Fig. 16: C-weighted spectrogram, Boylston & Kilmarnock. Contrast is enhanced to show differences more dramatically.

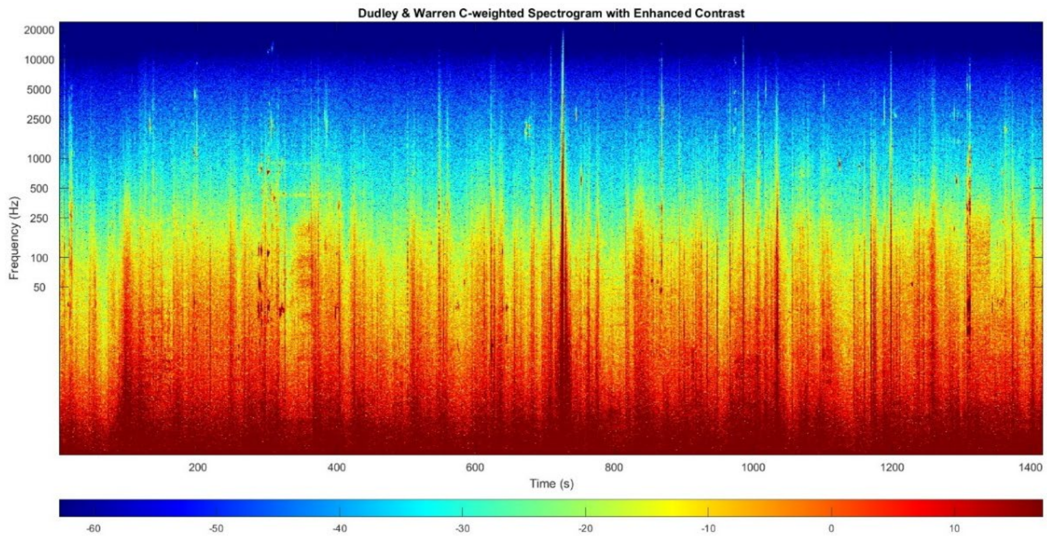

Fig 17: C-weighted spectrogram, Dudley & Warren.

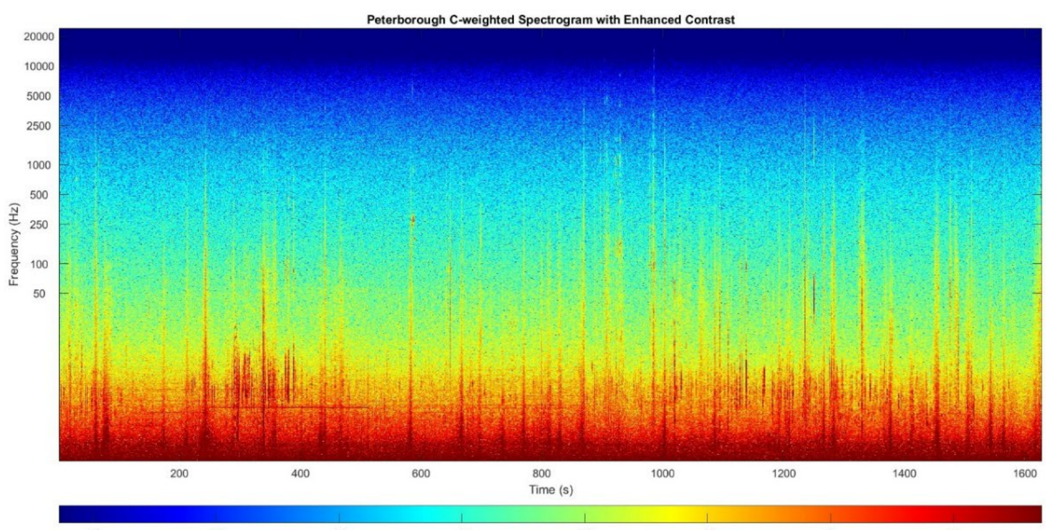

Fig. 18: C-weighted spectrogram, Peterborough Street.

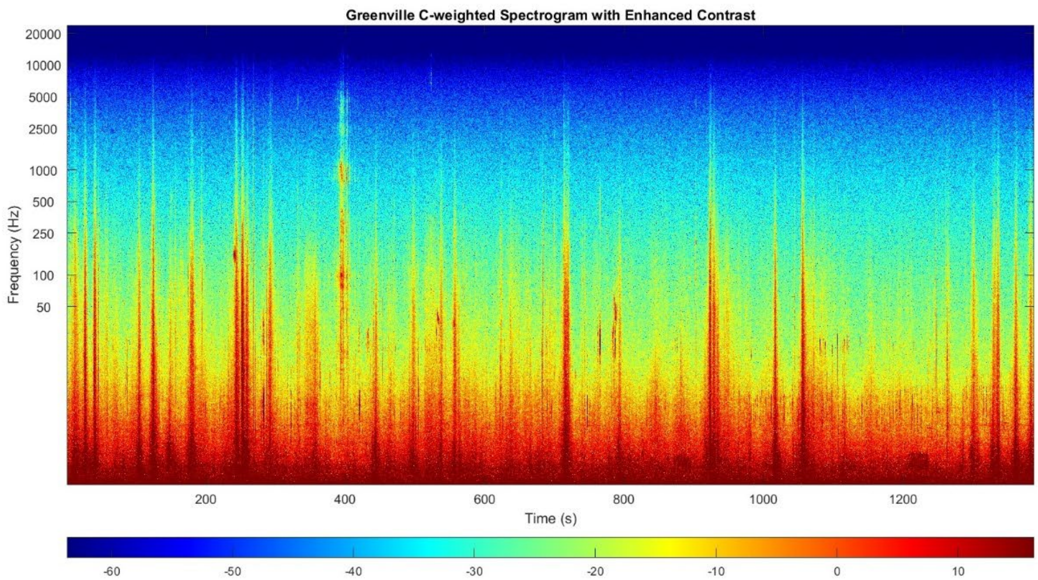

Fig. 19: C-weighted spectrogram, Greenville Street.

Conclusions

Overall, across many methods of data presentation, Roxbury experiences greater noise levels than Fenway across both street typologies. The C-weighted noise octave measurements show that Greenville Street experiences more HFN and far more LFN than Peterborough Street, bringing environmental noise into the ongoing discussion on socioeconomic disparities between neighborhoods. The geographical proximity and socioeconomic characteristics of Roxbury and Fenway showcase that even on a hyper-local scale, discrepancies in noise are tied to socioeconomic conditions.

Future Directions

Once sources of transient noise spikes can be identified, techniques should be developed to mitigate the high pressure levels of transient events. Given the extensive literature detailing the harm of different types of environmental noise, strategies should be employed to reduce the intensity and frequency of transient noise events. In urban environments like those considered, passive strategies can include careful selection of building materials for greater acoustical absorption, the addition of street-level greenery, which is understood to reduce negative automobile related externalities including road noise, and policy change on a broad scale to disincentivize noisy environments. Active strategies might include active noise cancellation on a vehicle or road level. The trend of higher noise levels in Main Square areas begs the question of urban development patterns and equity, especially considering the trend of large scale multifamily residential development in both Roxbury and Fenway's Main Square areas shown in Figures 20 and 21.

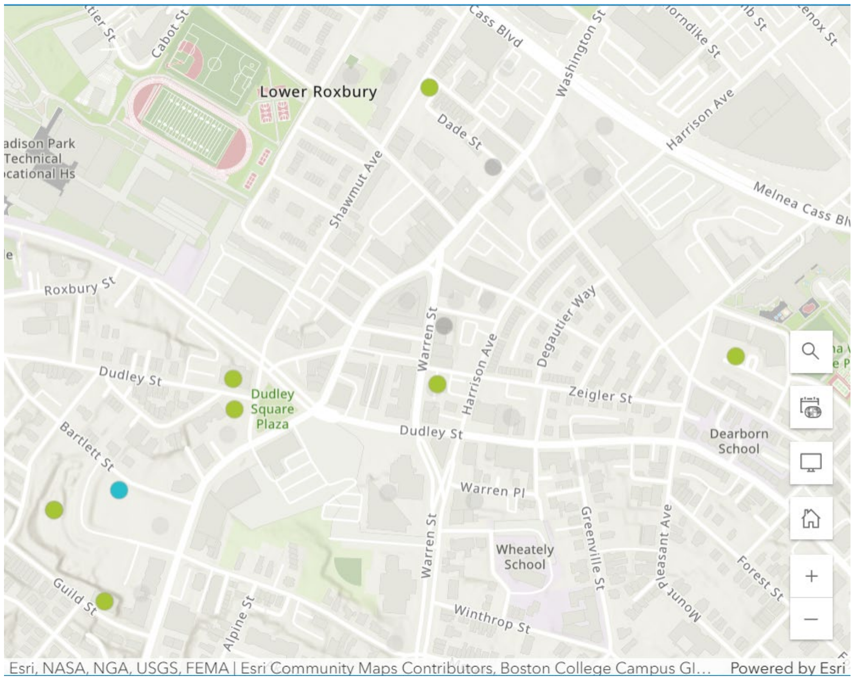

Fig. 20: Boston Planning Department approved projects in Nubian Square. Greyed out dots are primarily mixed-use developments approved before the usage of "Project Use" tag to describe developments [12].

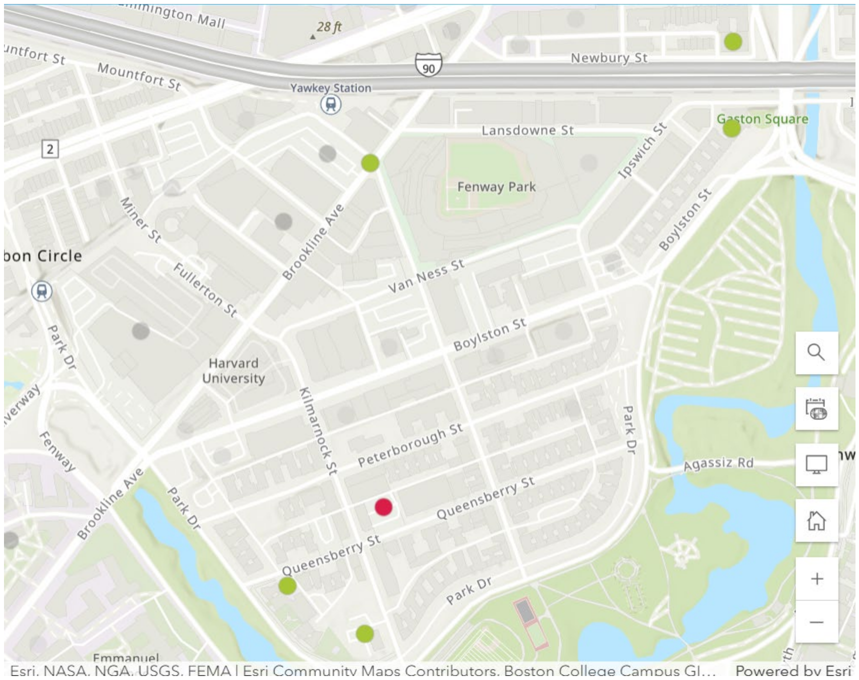

Fig. 21: Map of Boston Planning Department residential developments in the West Fens. Greyed out dots are primarily mixed-use developments approved before the usage of "Project Use" tag to describe developments [12].

Appendix A: Recording Notes

Date	Location	Name	Microphone Orientation	Temperature	Wind/Humidity	Time Start	Time Stop	Distance from Roadway
4/14	42.343947, -71.099799	Boylston St @ Kilmarnock St, SE Leg	Pointing directly up	67 degrees	Partly cloudy, windy	5:23PM	5:48PM	36" Length, 19" Height
4/14	42.343915, -71.096417	Peterborough St Midblock	Pointing up, 10 degrees from direct	67 degrees	Partly cloudy, windy	5:53PM	6:18PM	24"L, 26"H
4/16	42.328562, -71.083852	Warren St @ Dudley St, SW Leg	Pointing directly up	62 degrees	Sunny, slightly windy, rain at end of recording	5:20PM	5:48PM	60"L, 36"H
4/17	42.3284480, -71.0834400	Warren St @ Dudley St, SW Leg	Pointing directly up	50 degrees	Partly cloudy, gusts up to 29 MPH	5:38PM	6:00PM	30"L, 34"H
4/17	42.3277713, -71.0807604	Greenville St Midblock	Pointing directly up	50 degrees	Partly cloudy, gusts up to 29 MPH	6:03PM	6:27PM	20"L, 36"H
4/17	42.329089, -71.085591	Washington @ Malcolm X	Pointing directly up	47 degrees	Partly cloudy, slightly windy	7:20PM	7:45PM	30"L, 36"H

Appendix B: MATLAB Scripts

acoustics_final_analysis.m

```
close all



%% Import and process a-weighted and c-weighted SPL
if ~exist("by_aweight", "var")
    [by_aweight, Fs, ~, by_len, by_a_sig] =
SPLCalc('../recordings/boylston_upright.wav', 111.84, "a");
end
if not(exist("by_cweight", "var"))
    [by_cweight, ~, ~, ~, by_c_sig] = SPLCalc('../recordings/boylston_upright.wav',
111.84, "c");
end

if not(exist("dw_aweight", "var"))
    [dw_aweight, ~, ~, dw_len, dw_a_sig] =
SPLCalc('../recordings/dudley_warren_correct.wav', 111.84, "a");
end
if not(exist("dw_cweight", "var"))
    [dw_cweight, ~, ~, ~, dw_c_sig] =
SPLCalc('../recordings/dudley_warren_correct.wav', 111.84, "c");

end
```

```
if not(exist("pb_aweight", "var"))
    [pb_aweight, ~, ~, pb_len, pb_a_sig] =
SPLCalc('../recordings/peterborough_upright.wav', 111.84, "a");
end
if not(exist("pb_cweight", "var"))
    [pb_cweight, ~, ~, ~, pb_c_sig] =
SPLCalc('../recordings/peterborough_upright.wav', 111.84, "c");
end

if not(exist("gv_aweight", "var"))
    [gv_aweight, ~, ~, gv_len, gv_a_sig] = SPLCalc('../recordings/greenville.wav',
111.84, "a");
end
if not(exist("gv_cweight", "var"))
    [gv_cweight, ~, ~, ~, gv_c_sig] = SPLCalc('../recordings/greenville.wav', 111.84,
"c");
end

%% Plot a-weighted SPLs
figure
% subplot(2,2,1)
hold on
plot(duration(0,0,1:length(by_aweight), 'Format', 'mm:ss'), by_aweight)
plot(duration(0,0,1:length(pb_aweight), 'Format', 'mm:ss'), pb_aweight)
plot(duration(0,0,1:length(dw_aweight), 'Format', 'mm:ss'), dw_aweight)
plot(duration(0,0,1:length(gv_aweight), 'Format', 'mm:ss'), gv_aweight)

axis tight
title('A-weighted SPLs - 1 sec average')
xlabel('Time (mm:ss)')
ylabel('SPL (dBA)')
legend('Boylston & Kilmarnock', 'Peterborough Midblock', 'Warren & Dudley',
'Greenville Midblock')

%% Plot c-weighted SPLs
figure
hold on
plot(duration(0,0,1:length(by_cweight), 'Format', 'mm:ss'), by_cweight)
plot(duration(0,0,1:length(pb_cweight), 'Format', 'mm:ss'), pb_cweight)
plot(duration(0,0,1:length(dw_cweight), 'Format', 'mm:ss'), dw_cweight)
plot(duration(0,0,1:length(gv_cweight), 'Format', 'mm:ss'), gv_cweight)

title('C weighted SPLs')
xlabel('Time (mm:ss)')
ylabel('SPL (dBC)')
legend('Boylston & Kilmarnock', 'Peterborough Midblock', 'Warren & Dudley',
'Greenville Midblock')

%% Compute Leq values with minute intervals and average across entire interval

by_LeqA_300s = Leq_dB(by_aweight, 300);
pb_LeqA_300s = Leq_dB(pb_aweight, 300);
dw_LeqA_300s = Leq_dB(dw_aweight, 300);
gv_LeqA_300s = Leq_dB(gv_aweight, 300);
```

```
figure
hold on
plot(5.*(0:length(by_LeqA_300s) - 1), by_LeqA_300s)
plot(5.*(0:length(pb_LeqA_300s) - 1), pb_LeqA_300s)
plot(5.*(0:length(dw_LeqA_300s) - 1), dw_LeqA_300s)
plot(5.*(0:length(gv_LeqA_300s) - 1), gv_LeqA_300s)

title('A weighted Leq levels with 5 minute time intervals')
xlabel('Minute')
ylabel('Average Leq (dBA)')
legend('Boylston & Kilmarnock', 'Peterborough Midblock', 'Warren & Dudley',
'Greenville Midblock')
ylim([20,80])

by_LeqC_300s = Leq_dB(by_cweight, 300);
pb_LeqC_300s = Leq_dB(pb_cweight, 300);
dw_LeqC_300s = Leq_dB(dw_cweight, 300);
gv_LeqC_300s = Leq_dB(gv_cweight, 300);

figure
hold on
plot(5.*(0:length(by_LeqC_300s) - 1), by_LeqC_300s)
plot(5.*(0:length(pb_LeqC_300s) - 1), pb_LeqC_300s)
plot(5.*(0:length(dw_LeqC_300s) - 1), dw_LeqC_300s)
plot(5.*(0:length(gv_LeqC_300s) - 1), gv_LeqC_300s)

title('C weighted Leq levels with 5 minute time intervals')
xlabel('Minute')
ylabel('Average Leq (dBC)')
legend('Boylston & Kilmarnock', 'Peterborough Midblock', 'Warren & Dudley',
'Greenville Midblock')
ylim([20,80])


by_Leq_overall = Leq_dB(by_aweight, length(by_aweight));
pb_Leq_overall = Leq_dB(pb_aweight, length(pb_aweight));
dw_Leq_overall = Leq_dB(dw_aweight, length(dw_aweight));
gv_Leq_overall = Leq_dB(gv_aweight, length(gv_aweight));

figure
hold on
bar(0, by_Leq_overall)
bar(1, pb_Leq_overall)
bar(2, dw_Leq_overall)
bar(3, gv_Leq_overall)
title('A-weighted Leq levels over recording period')
xlabel('Area')
ylabel('Average Leq (dB)')
legend('Boylston & Kilmarnock', 'Peterborough Midblock', 'Warren & Dudley' ,
'Greenville Midblock')

%% Compute LeqA(f)
[by_Leq_bands, cfs] = Leqf('../recordings/boylston_upright.wav', 111.84, "bandType",
"octave", "weighted_signal", by_a_sig);
```

```
[dw_Leq_bands, ~] = Leqf('../recordings/dudley_warren_correct.wav', 111.84,
"bandType", "octave", "weighted_signal", dw_a_sig);
[pb_Leq_bands, ~] = Leqf('../recordings/peterborough_upright.wav', 111.84,
"bandType", "octave", "weighted_signal", pb_a_sig);
[gv_Leq_bands, ~] = Leqf('../recordings/greenville.wav', 111.84, "bandType",
"octave", "weighted_signal", gv_a_sig);


%%
figure
hold on
x = 1:length(by_Leq_bands);
bar(x, [by_Leq_bands, dw_Leq_bands, pb_Leq_bands, gv_Leq_bands], "grouped",
"LineStyle", "none")

xticks(x)
xticklabels(num2cell(cfs))
title("A-weighted noise by octave, whole period")
legend("Boylston & Kilmarnock", "Dudley & Warren", "Peterborough Midblock" ,
"Greenville Midblock")
xlabel("Octave center freqs (Hz)")
ylabel("SPL of octave band (dB)")

%% Compute LeqC(f)
[by_LeqC_bands, cfs] = Leqf('../recordings/boylston_upright.wav', 111.84, "bandType",
"octave", "weighted_signal", by_c_sig);
[dw_LeqC_bands, ~] = Leqf('../recordings/dudley_warren_correct.wav', 111.84,
"bandType", "octave", "weighted_signal", dw_c_sig);
[pb_LeqC_bands, ~] = Leqf('../recordings/peterborough_upright.wav', 111.84,
"bandType", "octave", "weighted_signal", pb_c_sig);
[gv_LeqC_bands, ~] = Leqf('../recordings/greenville.wav', 111.84, "bandType",
"octave", "weighted_signal", gv_c_sig);

%%
figure
hold on
x = 1:length(by_LeqC_bands);
bar(x, [by_LeqC_bands, dw_LeqC_bands, pb_LeqC_bands, gv_LeqC_bands], "grouped",
"LineStyle", "none")

xticks(x)
xticklabels(num2cell(cfs))
title("C-weighted noise by octave, whole period")
legend("Boylston & Kilmarnock", "Dudley & Warren", "Peterborough Midblock",
"Greenville Midblock")
xlabel("Octave center freqs (Hz)")
ylabel("SPL of octave band (dBC)")

%% Compute spectrogram for places
window_length = 8192;

[~, f_by, times_by, power_by, ax_by] = makeSpectro(by_c_sig, Fs, window_length);
% aci = sum(abs(diff(power,1,2)),2) ./ sum(power_by,2);
title(ax_by, "Boylston & Kilmarnock C-weighted Spectrogram with Enhanced Contrast")
```

```
[~, f_pb, times_pb, power_pb, ax_pb] = makeSpectro(pb_c_sig, Fs, window_length);
title(ax_pb, "Peterborough C-weighted Spectrogram with Enhanced Contrast")
% aci = sum(abs(diff(power,1,2)),2) ./ sum(power_by,2);

[~, f_dw, times_dw, power_dw, ax_dw] = makeSpectro(dw_c_sig, Fs, window_length);
title(ax_dw, "Dudley & Warren C-weighted Spectrogram with Enhanced Contrast")

[~, f_gv, times_gv, power_gv, ax_gv] = makeSpectro(gv_c_sig, Fs, window_length);
title(ax_gv, "Greenville C-weighted Spectrogram with Enhanced Contrast")

% change color limits to highlight differences to median dB value

median_val = median(10*log10([power_dw,power_by,power_pb, power_gv])+111.84, 'all');

clim(ax_by, [median_val-40 median_val+40]);
clim(ax_pb, [median_val-40 median_val+40]);
clim(ax_dw, [median_val-40 median_val+40]);
clim(ax_gv, [median_val-40 median_val+40]);
```

monoWeighting.m

```
%% Converts a soundfile into a mono signal with weighting according to input
arguments. Default weighting: c
function [mono_weighting_out, Fs, bitDepth, n_samp] = monoWeighting(soundfile_path,
weighting)
    arguments
        soundfile_path {exist(soundfile_path,"file")}
        weighting string = "c"
    end;

    audio_info = audioinfo(soundfile_path);

    audio_signal = audioread(soundfile_path);

    Fs = audio_info.SampleRate;
    bitDepth = audio_info.BitsPerSample;
    n_samp = audio_info.TotalSamples;

    % Apply weighting filter
    if weighting == "c"
        weightFilter = weightingFilter("C-weighting", Fs);
    elseif weighting == "a"
        weightFilter = weightingFilter("A-weighting", Fs);
    else
        weightFilter = weightingFilter("K-weighting", Fs);
    end

    weighted_signal = weightFilter(audio_signal);

    % High-pass filter to reduce wind noise < 25 Hz
    d = designfilt('highpassiir', FilterOrder=3, PassbandFrequency = 25, SampleRate =
Fs);
    fw_signal = filter(d, weighted_signal);

    % if stereo signal, convert to mono
    if audio_info.NumChannels == 2
```

```
        fw_signal = mean(fw_signal, 2);
    end

    mono_weighting_out = fw_signal;
end
```

splCalc.m

```
%% Converts a recorded soundfile into a-weighted noise values in time-averaged
windows
function [dB_SPL, Fs, bitDepth, n_samp, weighted_signal] = SPLCalc(soundfile_path,
dB_offset, weighting)

    arguments(Input)
        soundfile_path string {exist(soundfile_path,"file")}
        dB_offset {isnumeric}
        weighting string = "c"
    end

    arguments(Output)
        dB_SPL double
        Fs double
        bitDepth double
        n_samp double
        weighted_signal double
    end
    [weighted_signal, Fs, bitDepth, n_samp] = monoWeighting(soundfile_path,
weighting);

    % reshape signal into 1-second windows per ISO 1996-1:2016
    window_size = Fs;
    n_windows= floor(length(weighted_signal)/window_size);
    weighted_signal = weighted_signal(1:n_windows*window_size);
    windows = reshape(weighted_signal, [window_size, n_windows])';

    % Take RMS values for 1-s windows
    rms_windows = rms(windows, 2);
    % using the calibration offset, we calculate SPL decibel values
    dB_SPL = 20*log10(rms_windows) + dB_offset;
end
```

Leq_dB.m

```
function LeqNS = Leq_dB(dB_array, n_secs)
    rem = mod(length(dB_array), n_secs);
    if rem < 0.5*n_secs
        dB_array = dB_array(1:length(dB_array) - rem);
    else
        dB_array = padarray(dB_array, n_secs - rem, "symmetric", "post");
    end

    % Number of data points to generate
    n_levels = floor(length(dB_array)/n_secs);
    LeqNS = zeros(n_levels, 1);
```

```
    %If there are fewer than 2 data points, only do the equation for the
    % length of time desired starting from the beginning
    if n_levels > 1
        for k = 0:n_levels - 1
            LeqNS(k + 1) =
10*log10(mean(10.^(dB_array(k*n_secs+1:min(length(dB_array), (k+1)*n_secs +
1))/10)));
        end
    else
        LeqNS = 10*log10(mean(10.^(dB_array(1:n_secs)/10)));
    end
end
```

Leqf.m

```
function [f_bands, centerFreqs] = Leqf(soundfile_path, dB_offset, NameValueArgs)
    arguments
        soundfile_path string
        dB_offset double
        NameValueArgs.weighting string = "c"
        NameValueArgs.bandType string = "octave"
        NameValueArgs.weighted_signal double = []
        NameValueArgs.showFig logical = true
    end

    %apply monoification and weighting to signal
    if isempty(NameValueArgs.weighted_signal)
        [weighted_signal, Fs, ~, n_samp] = monoWeighting(soundfile_path, weighting);
    elseif ~isempty(soundfile_path)
        Fs = audioinfo(soundfile_path).SampleRate;
        n_samp = length(NameValueArgs.weighted_signal);
        weighted_signal = NameValueArgs.weighted_signal;
    else
        error('soundfile_path must not be empty!')
    end

    if strcmpi(NameValueArgs.bandType, "octave")
        centerFreqs = [16, 31.5, 63, 125, 250, ...
            500, 1000, 2000, 4000, 8000, 16000];

    else
        centerFreqs = [25, 31.5, 40, 50, 63, ...
            80, 100, 125, 160, 200, ...
            250, 315, 400, 500, 630, ...
            800, 1000, 1250, 1600, 2000, 2500, ...
            3150, 4000, 5000, 6300, 8000, 10000, 12500, 16000];

    end

    %create array for frequency bands
    f_bands = zeros(length(centerFreqs), 1);
    for i = 1:length(centerFreqs)
        if strcmpi(NameValueArgs.bandType, "octave") % Octave case
            f1 = floor(centerFreqs(i) / sqrt(2));
            f2 = floor(centerFreqs(i) * sqrt(2));
```

```
        else % 1/3 octave case
            f1 = floor(centerFreqs(i) / (2^(1/6)));
            f2 = floor(centerFreqs(i) * (2^(1/6)));
        end

        if f2 > Fs/2
            f2 = Fs/2 - 1;
        end
        % Design Chebyshev Type I filter for bandpass
        [B,A] = cheby1(2, 1, [f1, f2]/(Fs/2), "bandpass", "ctf");
        wf_signal = filtfilt(B,A,weighted_signal, "ctf");
        window_size = Fs;
        num_windows = floor(n_samp / Fs);
        wf_signal = wf_signal(1:num_windows * window_size)';
        windows = reshape(wf_signal, window_size, num_windows)';
        rms_windows = rms(windows, 2);
        dB_SPL = 20*log10(rms_windows) + dB_offset;
        f_bands(i) = 10*log10(mean(10.^(dB_SPL/10)));
    end
end
```

makeSpectro.m

```
function [s,f,times,power, ax] = makeSpectro(signalIn, Fs, windowSize, NameValueArgs)
%MAKESPECTRO makes environmentally relevant spectrogram
%   Detailed explanation goes here
arguments
    signalIn(:,1) double
    Fs(1,1) double
    windowSize double = 1024
    NameValueArgs.windowType = "hann"
    NameValueArgs.nOverlap = windowSize / 2
end
    if strcmpi(NameValueArgs.windowType, "hann")
        win = hann(windowSize);
    end
    % compute spectrogram
    [s, f, times, power] = spectrogram(signalIn, win, NameValueArgs.nOverlap,
windowSize, Fs, 'yaxis');



    % no 0 freq
    f(1) = f(1) + 1;
    figure

    % make imagesc
    imagesc(times, log10(f),10*log10(power)+111.84);
    set(gca, 'YDir', 'normal')

    % useful y-ticks
    yticks = [50 100 250 500 1000 2500 5000 10000 20000];
    set(gca, 'YTick', log10(yticks), 'YTickLabel', yticks)

    % relevant yrange
```

```
    ylim(log10([20,20000]))

    axis tight;
    xlabel('Time (s)');
    ylabel('Frequency (Hz)');
    colorbar('southoutside');
    colormap(jet);


    ax = gca();
end
```

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