Personal Exposure to Noise and Air Pollution in the Queen Street valley (PENAP) – Final Report

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The PENAP study was completed with the collaborative support of the Auckland Council Research, Investigations and Monitoring Unit (AC/RIMU), the National Institute of Water and Atmospheric Research (NIWA), the University of Auckland (UoA) and the Auckland University of Technology (AUT), and with funding support from the City Centre Targeted Rate (CBD Advisory Board) and Heart of the City.

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Executive Summary

The “PENAP” project (Personal Exposure to Noise and Air Pollution) is an observationally-based study of air quality and noise in downtown Auckland. It brings together expertise from NIWA, the University of Auckland, AUT and Auckland Council to study our environment at the scale that matters to people and is relevant to initiatives in the City Centre Masterplan.

Prior to this study, Auckland Regional Council have been conducting air quality monitoring in Queen Street since 1975. However, it has not previously been known to what degree that dataset actually represents air quality across the whole CBD. Previous screening monitoring by ARC has indicated that Auckland’s regional background air (beyond the city’s periphery) is very clean but with the potential for localised but significant hot-spots of poor air quality in the CBD.

The observational study took place in winter and spring of 2013. Samplers at 62 sites revealed spatial variation in levels of the traffic-related air pollutant nitrogen dioxide over 6 weeks. In total, 22 intensive pedestrian surveys of ultrafine particles and carbon monoxide from vehicle exhaust, and noise were made during the morning rush hour and afternoon periods in 7 CBD streets. Detailed sound recordings were also made and 200 questionnaires regarding street soundscapes were answered *in situ* by members of the public. As a long-term legacy, Auckland Council’s air quality monitoring site in Queen Street was augmented with New Zealand’s first continuously-operating ultrafine particle monitor.

The PENAP results show that air quality, noise and the perception of noise in the CBD vary substantially from street to street in a mosaic of relatively clean/pleasant and polluted spots. These locations are broadly correlated with traffic volumes, with slightly worse air quality near intersections. Levels of traffic-related air pollutants on CBD streets with moderate to heavy traffic can be double the levels of those found in adjacent low-traffic shared spaces, indicating the substantial improvements in air quality that can be gained or lost through traffic management. Inner city soundscapes were assessed to be dominated by machine noise and, to a much lesser extent, people noise. It was evident that inner city street soundscapes were largely evaluated negatively, especially when compared to Albert Park.

The highest levels of air pollution were observed along and around Customs Street, despite it being less than 200 m from the open space and good dispersion of the waterfront. This study suggests that levels of nitrogen dioxide on many of our busier CBD streets may exceed the WHO Ambient Air Quality Guideline, especially Customs Street, despite Auckland having the rare natural advantage of almost zero levels at the city’s edge and a relatively windy climate. Auckland Council’s long-term air quality monitoring site in Queen Street appears to be broadly representative of the CBD as a whole. However, it under-estimates concentrations in the most polluted parts of the CBD but also does not represent the substantially lower concentrations in low-trafficked or better ventilated parts of the CBD.

Average sound levels observed during morning and afternoon periods exceeded 65 dBA L_{eq} in every street sampled, which would be classified by the OECD as a ‘black acoustic area’ if sustained across a 24-hour period. Furthermore, pedestrians are, on occasion, also exposed to excessively intense short duration sounds - levels above 120 dB L_{peak} were observed in all streets except Elliott Street. While exposure is not continuous and unlikely to result in noise-induced hearing loss, it will be nonetheless unpleasant.

On a long-term basis, air quality was substantially better in the shared spaces of Elliott Street, Lorne Street, and in the more open Kitchener Street compared to street canyons with more traffic. However, during some periods, air quality in Elliott Street was worse than Customs Street. This counter-intuitive result is likely related to the combination of shifts in wind direction and sheltering of other buildings and indicates that further research is required before the results for Elliott Street can be considered to apply generally to any shared or zero traffic street.

Elliott Street had the lowest machine noise of the inner city streets, and highest nature sound content. Of the three inner city streets samples, Elliott Street's soundscape was perceived to be the least stress-inducing, and more harmonious/melodious.

Whilst this report provides data on levels of air and noise pollution which give cause for concern, it also reveals the complexity of the interplay between traffic, buildings and street design and local meteorology. This makes it challenging to predict how air and noise pollution would change in response to changes to the city's form or management of streets.

This project has delivered a large database which can support further research. Project members plan to conduct further detailed analysis which will be submitted to peer-reviewed international scientific journals. In the near future, the database will be opened to other researchers for further exploration.

In addition, further research is recommended to expand the knowledge base and understanding about the city's downtown environment. Specifically, this includes:

- Further analysis into the influence of vehicle fleet mixes and movement.
- Analysis and dissemination of the ultrafine particle data from the new Queen Street monitor.
- Re-analysis to investigate the implications for pedestrians on the move.
- Investigation of correlations between noise and air quality.
- Further observational studies focussing on
    - The Customs Street, Britomart and waterfront areas
    - Elliott Street and other shared spaces
    - "before-and-after" intervention studies of forthcoming changes to streets
    - Influence of the Port and shipping

1.0 Background

1.1 Purpose and scope of this report

The “PENAP” project (Personal Exposure to Noise and Air Pollution) is an observationally-based study of air quality and noise in downtown Auckland. This Report has been prepared in February 2014. It covers the main results of observational campaigns conducted in Aug-Sep 2013.

1.2 Project background

The Auckland Plan sets an ambitious vision for Auckland to be the world’s most liveable city. The plan looks to dramatically increase the prospects of Auckland’s young people, strongly commit to environmental sustainability and action, and radically improve the quality of urban living.

A vibrant and successful city centre is part of this vision. The city centre is required to have a strong sense of place, heritage and character and will be a place where an increasing number of people live, work and play.

Queen St already has the highest pedestrian counts in the region. Along with adjacent streets, it is also where high volumes of cars and diesel buses converge. Slow moving traffic, particularly diesel buses, can produce particularly high levels of air pollution which, along with noise, have huge effects on public health, amenity and subjective wellbeing.

Efforts are currently being implemented across European cities to minimise residential noise exposure and preserve or restore quiet areas in urban contexts. Such efforts are driven by a desire to improve urban living environments that are at high risk of becoming unsustainable, and emerging scientific evidence detailing both the adverse (i.e., noise) and promotional (i.e., sound) aspects of an individual’s acoustic environment on their health and wellbeing. No such unified noise policy exists in the New Zealand context, and instead environmental noise limits recommended by various New Zealand standards (e.g., NZS6801:2008 and NZS6802:2008) are selectively incorporated into individual district plans or applied to activities requiring planning approval via the Resource Management Act. Beyond these activities there is little motivation for regulatory authorities to engage with the acoustic environments contained within their territories. As such, the PENAP study represents an important step forward in the way the New Zealand regional councils approach sound and noise.

Commonly, the impact of environmental sound is managed using noise level metrics such as the decibel. Indeed, the application of basic ‘noise numbers’ to the management of environmental noise is intrinsic to New Zealand’s environmental noise standards. However, while such an approach provides an acoustic description of the environment, it does not provide a measure of sound quality, which is based on human factors. Thus, when evaluating the sound qualities of public spaces, a holistic approach analysing a triad of dimensions should be employed: 1) the acoustic energy in the environment; 2) the ‘lived’ sound (i.e., perception and interpretation), and; 3) the ‘represented’ sound (i.e., the social and cultural contexts in which the sounds occur). Such a combined analysis at the acoustical, individual and group levels of description, is consistent with the concept of the ‘soundscape’, defined as “the acoustic environment as perceived and understood, by people, in context”. The soundscape can be considered the auditory equivalent of a landscape, and represents an alternative ‘listener-orientated’ approach to the management of an acoustic environment that contrasts the ‘stimulus-oriented’ models adopted by the New Zealand environmental noise standards. Both the scope and objectives of the PENAP study are compatible with the soundscape approach.

Battles to implement air pollution mitigation have generally been won where irrefutable scientific evidence has been available, which would not have been the case without pollution monitoring. The existence and deployment of monitoring technologies determines which problems can be solved. Previously, monitoring has been deployed primarily to address the problems of regional-scale airshed management. However, the CBD-specific problems inherent in the City Centre Masterplan and City Centre Future Access Study (for instance) address a different scale and range of outcomes, and require a different approach to monitoring.

In the past and currently, Council, NIWA and the Universities of Auckland and Canterbury have worked in partnership to study air quality in the city and across the region. The universities (AUT, the University of Auckland and The University of Otago) have also worked together on a number of projects looking at various sources of environmental noise across New Zealand, such as roads, wind turbines and airports, and the impact these have on human health and well-being. The PENAP study build on these foundations and, for the first time, concentrates this capability into one highly-detailed high-quality study which substantially increases the air quality and noise pollution knowledge base for NZ urban environments, and is sufficiently robust to inform future decisions on city centre projects.

1.3 Project objectives

1. Characterise levels of traffic-related air pollutants in the Queen Street valley
2. Determine the contribution of bus and car emissions to levels of traffic-related air pollutants in the Queen Street valley
3. Characterise the nature of the noise in the Queen Street Valley (sound levels, frequency content, intermittency) at different locations within the valley
4. Assess people’s perceptions of the urban soundscape and its contributors
5. Assess people’s perceptions of how the soundscape can be improved to make Queen Street a more vibrant street

1.4 Project participants

The project is a collaboration between Auckland Council (RIMU), The University of Auckland, Auckland University of Technology and NIWA. The Project is directed by **Greg McKeown** (Heart of the City) on behalf of the CBD Board.

Other key personnel are:

Ian Longley (NIWA): Co-Principal Investigator (Air), report editor

Jennifer Salmond (The University of Auckland): Co-Principal Investigator (Air)

Kim Dirks (The University of Auckland): Co-Principal Investigator (Air/Noise)

David Welch (The University of Auckland): Co-Principal Investigator (Noise)

Daniel Shepherd (AUT): Co-Principal Investigator (Noise)

Stuart Grange (The University of Auckland): Project Manager

2.0 Air Quality in the Queen Street valley

2.1 Background

Prior to this study, Auckland Regional Council has been conducting air quality monitoring in Queen Street since 1975, with the current Auckland Council station having operated continuously since 1982, producing hourly data from 1998. However, it has not previously been known to what degree that dataset actually represents air quality across the whole CBD.

Previous screening monitoring by ARC has indicated that Auckland's regional background air (beyond the city's periphery) is very clean but indicated the potential for localised but significant hot-spots of poor air quality in the CBD. The PENAP study sought to investigate this potential in a more systematic and detailed manner.

2.2 Overview of methods

A major, high quality monitoring campaign was conducted during winter/spring 2013 consisting of three components: fixed-location spatial monitoring for 6 weeks, intensive mobile (pedestrian) monitoring for two hours per day over 11 days and noise investigations.

A network of samplers was deployed on street furniture at 62 sites across the CBD for 6 weeks measuring levels of nitrogen dioxide (NO_2). **Nitrogen dioxide** (NO_2) is a traffic-related pollutant which is particularly sensitive to diesel emissions. It is a pollutant in its own right - linked with exacerbations and development of asthma – but also sensitises asthmatics to the effect of inhaled particles.

Although this spatial monitoring was able to cover multiple streets, it was limited in considering only one pollutant, in providing time-averaged data over weeks rather than at peak times of day when most people are exposed, and did not cover the whole length of each street.

To address these issues, and help understand and explain the variation in NO_2, intensive measurements using portable samplers were made by study participants acting as pedestrians along designated CBD street pavements during 11 morning peak and 11 mid-day periods. A portable device to measure NO_2 is not yet available – instead ultrafine particles (UFP) and carbon monoxide (CO) were measured. All three of these pollutants are emitted primarily by road vehicles and this combination is therefore suitable for the study objectives.

Ultrafine particles are a subset of PM_{10}, the measure of airborne particles monitored by Auckland Council and regulated under the National Environmental Standards. PM_{10} is a measure of the mass of airborne particles smaller than 10 μm per cubic centimetre of air. Fresh vehicle tailpipe emissions are overwhelmingly ultrafine (smaller than 0.1 μm). They also penetrate most deeply into the lungs, and there is growing international evidence that these are the particles that are most strongly associated with a wide range of adverse health impacts. **Carbon monoxide** (CO) is an acute neurotoxin at high concentrations. Its predominant source in urban streets is tailpipe emissions from petrol vehicles. Technological advances over the past three decades have led to major reductions in CO emissions. The impact has been observed by long-term CO monitoring by Auckland Council which show that concentrations in Auckland streets pose no direct health hazard. However, it remains useful to use CO as a proxy for petrol vehicle emissions in general.

Further details of the methods are provided in the Appendix.

Figure 2-1: A PENAP study participant undertaking mobile monitoring on Queen Street. She holds an ultrafine particle counter, has a carbon monoxide sensor on her belt and a noise dosimeter pinned to her abdomen.

Long-term monitoring undertaken by Auckland Council reveals predictable **seasonal variation** in all air pollutants with concentrations of traffic pollutants peaking during mid-winter and reducing in mid-summer. This is largely due to variations in the meteorological conditions that drive dispersion. To enable fair comparison within the study, and to compare the data with guidelines based on annual averages, the nitrogen dioxide data were adjusted for this seasonal effect using data from AC's long-term Queen Street monitoring site.

No long-term monitoring data of ultrafine particles previously existed in Auckland. Thus, the typical diurnal, weekly and seasonal patterns in this pollutant are currently unknown. This means that we are unable, at present, to estimate with confidence whether the particle levels reported here are typical, or abnormally high or low for Auckland. However, **the PENAP project did establish New Zealand's first long-term ultrafine particle monitoring** at the AC Queen Street site, commencing in November 2013. Within a year, it should be possible to establish the long-term variation in particle levels and further put the PENAP study results into context.

Because mobile monitoring was conducted intensively over short periods, the results need to be considered within the context of the meteorological conditions at the time. During the study, the mobile measurements were conducted in three phases, between which conditions changed from predominantly westerly winds in Phases 1 and 2 to north-easterly winds in Phase 3.

2.3 Results

2.3.1 Differences in air quality across the CBD

Our data cannot be directly compared to the National Environmental Standards for Air Quality which refer to 24-hour averages of PM_{10}, 1-hour averages of NO_2, and 8-hour averages of CO, none of which were measured. However, the Ministry for the Environment have adopted a guideline value of 40 $\mu g\ m^{-3}$ of NO_2 as an annual mean, based on the World Health Organisation guidelines. An annual mean value cannot be measured during a campaign of a few weeks, however, the passive monitoring data can be extrapolated to **estimate** an annual mean. This estimate must only be considered as indicative. The passive monitoring technique used in this study is a screening technology only and has insufficient accuracy for use in assessing compliance with standards and guidelines, plus the seasonal adjustment method introduces a small amount of additional uncertainty.

To establish the credibility of the technique, two samplers were placed on opposite sides of the street alongside the AC station yielding estimated annual mean concentrations of 40 $\mu g\ m^{-3}$ (west) and 39 $\mu g\ m^{-3}$ (east). Despite employing different and not directly comparable measurement technologies, these values are consistent with data from the AC monitor, which reported an annual mean NO_2 concentration of 38 $\mu g\ m^{-3}$ in 2012.

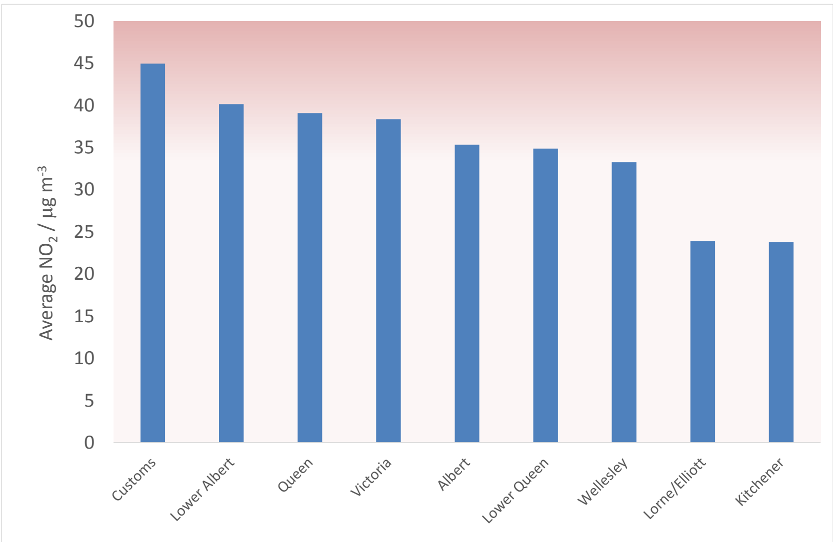

Figure 2-2 Estimates of seasonally-adjusted campaign-average nitrogen dioxide concentrations aggregated by street.

Figure 2-2 shows the average NO_2 concentrations observed grouped by street. The lowest concentrations were observed on Kitchener Street and on the shared streets – Lorne Street and Elliott Street (24 $\mu g\ m^{-3}$). The average concentrations were found to be approximately a third lower on these streets compared to all other streets (average of 38 $\mu g\ m^{-3}$). Amongst the other streets, average concentrations were lowest on Wellesley Street (33 $\mu g\ m^{-3}$) and highest (45 $\mu g\ m^{-3}$, i.e. 35 % higher) on Customs Street.

Figure 2-3 shows results from individual sites. From this figure it can be seen that substantial variations in observed concentrations can occur within any given street. The highest campaign-average concentration at a **single site** was 59 $\mu g\ m^{-3}$, whilst the lowest was 21 $\mu g\ m^{-3}$. This means that concentrations varied almost three-fold across the Study Area, which is less than 1 km across.

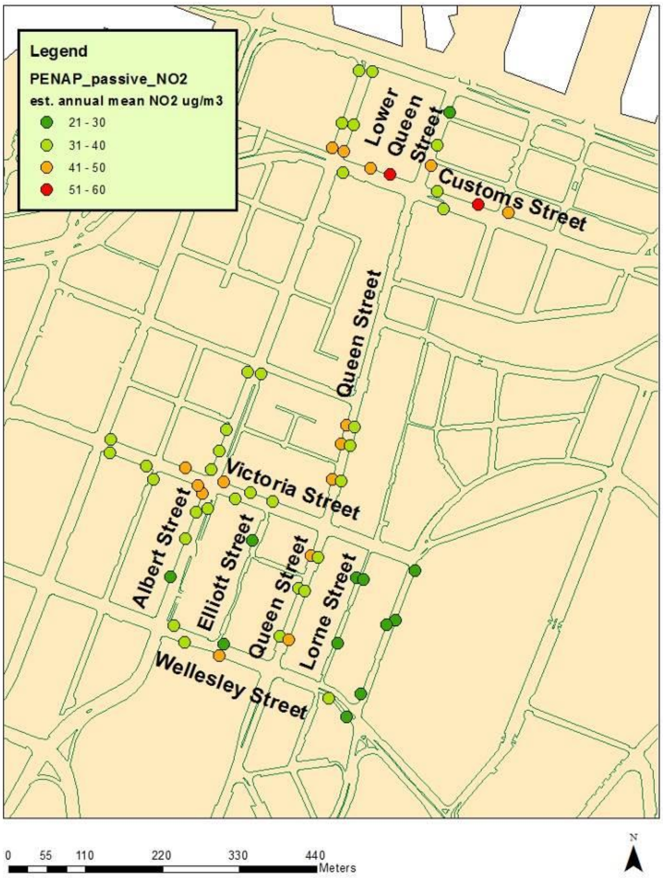

Figure 2-3 Variation in campaign-average nitrogen dioxide concentrations by passive monitoring.

Given the caveats discussed above, we estimated that the MfE/WHO Guideline value (40 $\mu g\ m^{-3}$) may have been exceeded in Customs Street (45 $\mu g\ m^{-3}$), and that NO_2 values were close to the Guideline value in Lower Albert Street, Queen Street and Victoria Street. Across the 62 sites, more than half yielded estimated concentrations within 10 % of the Guideline.

Taken as a whole, our results indicate that although NO_2 concentrations reported by the AC Queen Street monitor are broadly representative of the trafficked streets within the CBD, they may slightly under-represent the most polluted streets and more localised hot-spots in the CBD. However, the Queen Street site also substantially over-represents NO_2 concentrations in the less trafficked locations in the CBD, such as Elliott Street, or non-canyon or less-sheltered locations, such as Kitchener Street.

Findings from the mobile monitoring are broadly consistent with the fixed-point NO_2 data (Figure 2-4). Here data from Phase 1 and 2 should be considered separately due to differences in meteorological conditions. In each Phase the highest ultrafine particle concentrations were recorded on Victoria Street or on a “circuit” that included Victoria Street, along with Lorne Street, Wellesley Street and Elliott Street. The lowest concentrations were observed on Wellesley Street with Albert Street and Queen Street coming in between.

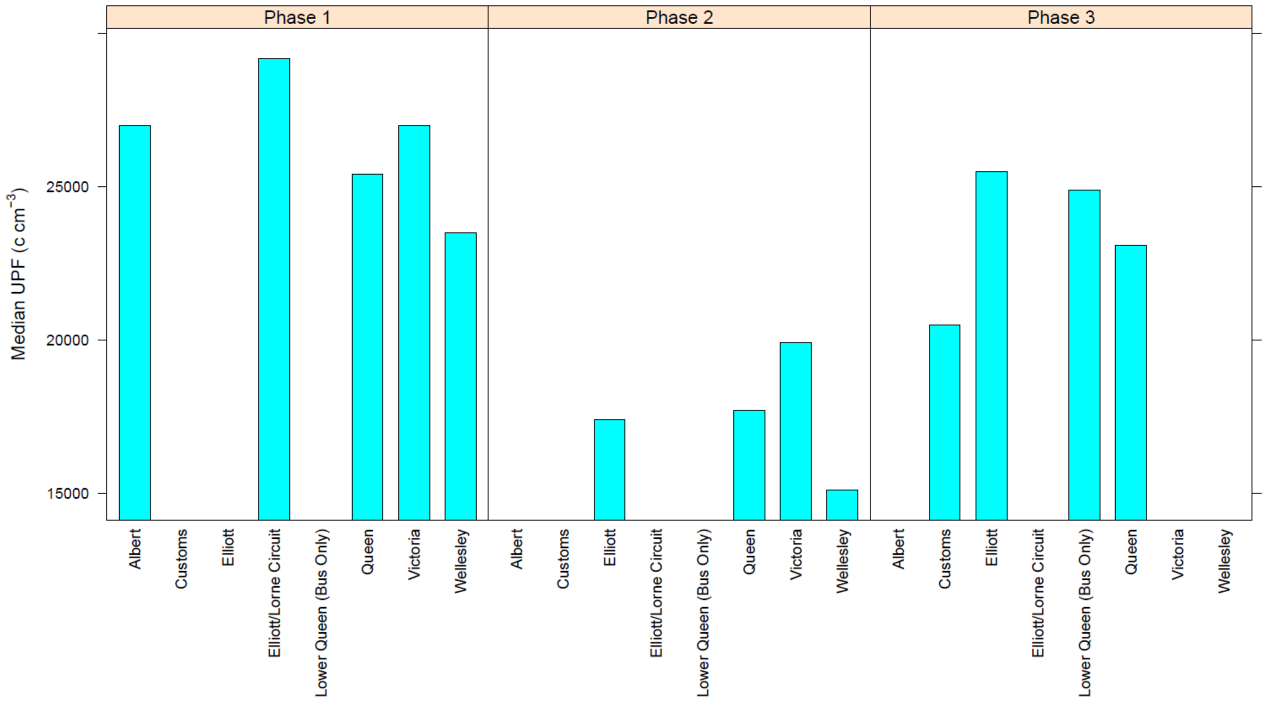

Figure 2-4: Median particle number concentrations observed by mobile monitoring for the three phases of the campaign (note y-axis does not start at zero). Not all streets were sampled during each phase.

No international standard or guideline yet exists for ultrafine particles due to the relative lack of available data and associated health studies, although this study contributed to filling that gap. However, a comprehensive meta-analysis of 71 studies of ultrafine particle concentrations measured around the world was presented by Morawska et al. (2008). They found median particle number concentrations of 8,830 cm^{-3} at “urban sites” and 39,130 cm^{-3} at “street canyon sites”. A recent review by Kumar et al. (2014) estimated an average concentration across 37 urban roadside sites[1] of 35,000 cm^{-3}. Nearly all of the cities yielding data for these reviews are larger than

1.0

[1] Excluding anomalously high values from Delhi, Shanghai and Hsinchu.

Auckland and consequently the concentrations measured in this study (ranging from 20,000 to 36,000 cm^{-3} for individual streets) appear consistent with international findings.

2.3.2 Traffic levels and intersections

The range of variation in concentrations between trafficked street canyons was similar for UFP and NO_2, i.e. the most polluted streets had UFP and NO_2 concentrations up to ~35 % higher than the least. Each location covered by the mobile surveys was allocated to one of 9 classes. This allocation is presented in map form in Figure 2-5. CO and particle data was aggregated across the whole campaign and each class ranked. The results are summarised in Table 2-1.

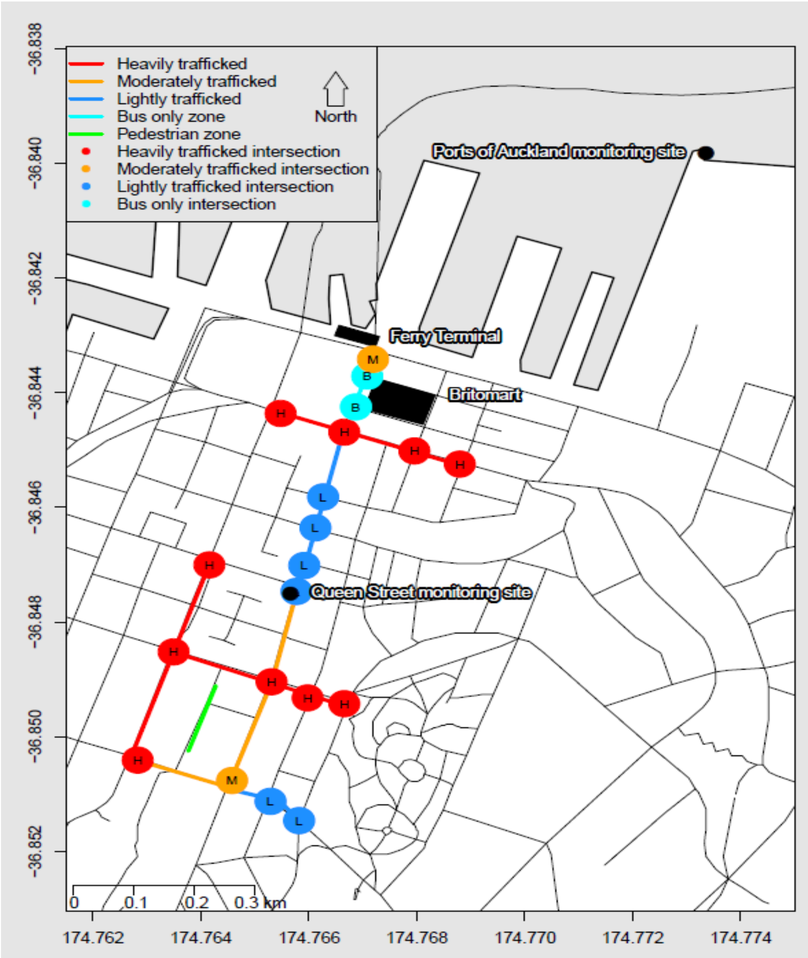

Figure 2-5: Surveyed streets and intersections allocated to 9 traffic classes for the purpose of analysis.

Together these results indicate that ultrafine particle concentrations around intersections were generally slightly higher than within mid-block street sections. This is consistent with the elevated concentrations of NO_2 observed around the Albert Street/Victoria Street intersection (Figure 2-3) where the uphill acceleration of vehicles travelling westwards on Victoria Street may also be a factor.

Table 2-1: Ranking of campaign-mean concentrations observed on road and intersections (1 = highest concentrations, 9 = lowest).

Class	Rank (ultrafine particles)	Rank (CO)
Intersection – heavily trafficked	1	1
Road – heavily trafficked	2	3
Intersection – bus only	3	7
Road – bus only	4	8
Intersection – moderately trafficked	5	4
Road – moderately trafficked	6	2
Road – lightly trafficked	7	5
Intersection – lightly trafficked	8	6
Pedestrian zone	9	9

The results for the intersections are also visualised in Figure 2-6.

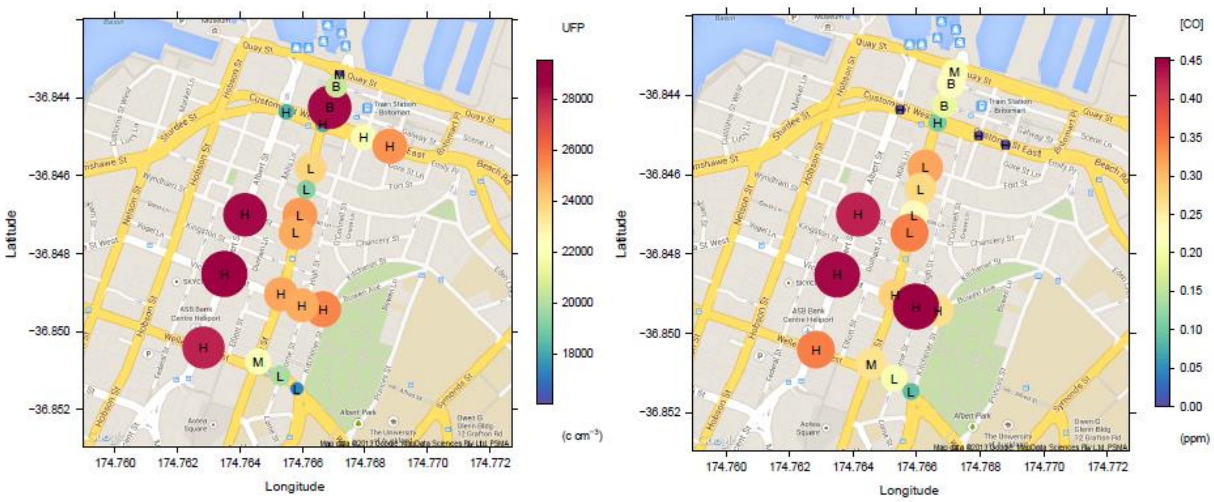

Figure 2-6: Median concentrations for 22 individual intersections (left: ultrafine particles, right carbon monoxide).

2.3.3 Shared spaces

The relatively low concentrations observed on Lorne Street and Elliott Street are almost certainly due to low levels of traffic, despite both intersecting busier streets. However, results for Elliott Street differed between pollutants, with the mobile monitoring results providing some counter-intuitive results. Here, observed concentrations of NO_2 were substantially lower than in the more trafficked streets, but concentrations of ultrafine particles were of a similar magnitude. In Phase 3 (Figure 2-4) Elliott Street provided the highest concentrations out of the four streets surveyed (Elliott, Queen, Lower Queen and Customs).

The NO_2 results represent an integrated value over 6 weeks (24-hrs-a-day). The ultrafine particle data were recorded over a one-hour period during the morning or mid-day on a limited number of days. Consequently, the particle data are much more representative of the particular weather conditions during the surveys rather than the average conditions over the whole of the campaign in the case of the NO_2 data. In particular, Phase 3 was characterised by moderate NE winds, during which Elliott Street is both downwind of busy streets and partially sheltered from the wind by the north side of Victoria Street, which may lead to elevated particle concentrations. Other possible explanations may be additional sources of particles on Elliott Street (e.g. smoking) or other atmospheric processes affecting each pollutant differently. Clues may lie within the PENAP database which should be investigated further.

2.3.4 The effect of street canyons

The sampler deployment included 10 pairs with samplers on opposite (east and west) sides of the same north-south oriented street (Albert, Queen, Lorne and Kitchener). On average NO_2 concentrations on the west side were 2 $\mu g\ m^{-3}$ higher than on the east side. However, the effect was particularly marked at the pairs on Queen Street either side of Victoria Street where concentrations on the west side were ~10 $\mu g\ m^{-3}$ higher than on the east side. These findings are consistent with the well-documented phenomenon of street canyon vortices in which concentrations of traffic pollutants can be increased on the side of a street which is sheltered from the prevailing winds. With south-westerly winds prevailing overall in Auckland it is highly plausible that the wind may form vortices in deep canyons, such as Queen Street, drawing pollutants preferentially towards the western side.

Kitchener Street has moderate levels of traffic. However, we observed concentrations that were close to those observed on Lorne Street and Elliott Street, and showed no difference on either side of the street. This is probably due to Kitchener Street being open to Albert Park on one side, facilitating the more effective dispersion of pollutants.

2.3.5 Customs Street and the Britomart area

Figure 2-2 shows that the highest NO_2 concentrations were observed on Customs Street where 7 samplers were placed. Figure 2-3 also shows two samplers on Customs Street reported particularly high concentrations (>50 $\mu g\ m^{-3}$).

Due to resource limitations, intensive monitoring in the Customs Street and Britomart areas was only conducted during Phase 3. For this Phase monitoring on Victoria and Wellesley Streets was discontinued and replaced with monitoring on Lower Queen Street and Customs Street. Phase 3 had somewhat atypical weather conditions characterised by north-easterly winds coming off the Harbour. Consequently, we conclude that the variation in concentrations between streets observed during Phase 3 are not typical of the long-term (and hence do not exactly match the NO_2 observations) because south-westerly winds, rather than north-easterly winds, are more common in Auckland overall.

During this Phase the lowest particle concentrations were recorded on the high-traffic Customs Street and the highest (24 % higher) on Elliott Street. The results presented in Figure 2-4 are consistent with a shift in the pattern of air pollution dispersion caused by changes in wind direction. In north-easterly winds, the Britomart area is more exposed to clean oceanic air which, together with higher wind speeds, may explain the reduced concentrations in Customs Street. However, the Phase 3 results show higher concentrations in Lower Queen Street than in Customs Street, despite the former being more exposed to north-easterly winds, and Customs Street having substantially higher volumes of traffic. We can hypothesise at this point that this is due to abnormally high emissions on Lower Queen Street which acts as a moderately busy bus terminus. This may be confirmed through extended analysis of the PENAP database.

No sampling was conducted along Quay Street. However, three of the NO_2 samplers were placed on Lower Queen Street or Lower Albert Street very close to Quay Street. These samplers measured low concentrations relative to Customs Street. Although the evidence does not yet exist, we speculate that this may be due to the open nature of Quay Street with more efficient dispersion, especially in northerly winds. Whether this may be compromised in north-easterly and easterly winds by emissions from the port cannot be discerned from the PENAP database, but is plausible and could be the subject of future study.

2.4 Air Quality – conclusions

The PENAP study has greatly expanded on the data previously collected by Auckland Council. Although currently represented by a single monitor on Queen Street, air quality in the CBD varies substantially from street to street in a mosaic of relatively clean and polluted spots. Levels of traffic-related air pollutants on CBD streets with moderate to heavy traffic can be double the levels found in adjacent low-traffic shared spaces, indicating the substantial improvements in air quality that can be gained through traffic management. The highest levels of air pollution were observed along and around Customs Street, despite it being less than 200 m from the open space and good dispersion of the waterfront. This study suggests that levels of nitrogen dioxide on many of our busier CBD streets may exceed the WHO Ambient Air Quality Guideline, despite Auckland having the rare natural advantage of almost zero levels at the city’s edge and a relatively windy climate. Although this study has generated substantial new data, the interplay between traffic, buildings and meteorology are complex and if this work is to inform consideration of how a liveable city can be designed and maintained, further investigation is recommended.

The study's specific conclusions are as follows.

1. Air quality measured during the study cannot be directly compared to standards or guidelines. However, based on data captured in this study we estimate that annual mean concentrations of the traffic-related pollutant nitrogen dioxide (NO_2) are close to, or slightly exceed the Ambient Air Quality Guideline in several streets in Auckland's CBD. However, concentrations of carbon monoxide (CO) are far below any relevant standards or guidelines.
2. There are no standards or guidelines against which to compare the levels of ultrafine particles observed in this study. However, the concentrations recorded are consistent with those found in other international cities.
3. There were significant differences in air quality observed between streets in the CBD, even adjacent streets. Amongst trafficked street canyons, the most polluted streets had ~35 % higher concentrations than the least polluted.
4. Results broadly indicate that more heavily trafficked streets have worse air quality.
5. Air quality was generally found to be worse at intersections than in mid-block sections.
6. Air quality was relatively poor at the southern end of Lower Queen Street considering that cars are not permitted to use it.
7. Further analysis is required to establish the degree to which the variations in air quality between streets can be further attributed to differences in vehicle fleet mixes (cars/vans/buses/trucks), or idling and accelerating behaviour.
8. Concentrations of NO_2 were substantially lower in the Shared Spaces of Elliott Street, Lorne Street, and in semi-exposed Kitchener Street compared to street canyons with more traffic. Concentrations in Customs Street were double those in Elliott Street. However, there was less difference observed for ultrafine particles. This may be due to NO_2 being measured continuously (24-hrs-a-day) but ultrafine particles being measured during morning peak and mid-day periods only. It may also relate to buildings at either end of Elliott Street sheltering it from the dispersive effect of the wind. This means that any potential gain in air quality from reducing or removing traffic may be dependent upon how "porous" the surrounding built environment is to dispersive air flow. This deserves further investigation.
9. Analysis to date indicates that Auckland Council's long-term air quality monitoring site in Queen Street is broadly representative of the CBD as a whole. However, it under-estimates concentrations in the most polluted parts of the CBD but also does not represent the substantially lower concentrations in low-trafficked or better ventilated parts of the CBD.
10. Shifts in wind direction appeared to have substantial differential impacts on air quality across the CBD. During parts of the study, concentrations of particles were higher in Elliott Street than in Customs Street. It is hypothesised that this was due to the occurrence of north-easterly winds during Customs Street sampling (as opposed to the more common

south-westerly winds) leading to improved ventilation of the Britomart area. This is partially supported by relatively low concentrations of NO_2 being observed at three sites close to Quay Street. This has implications for the use of a single monitoring site (e.g. Queen Street) to represent hourly and daily variation in air quality in the CBD due to potential meteorologically-driven biases on this timescale.

3.0 Noise in the Queen Street valley

3.1 Overview of Methods

To implement a soundscape approach to the assessment of Auckland's inner city acoustic environment, a variety of measurements were undertaken representing both the physical quantities of sound (i.e., the things that acousticians measure) and the human response to sounds (i.e., those things measured by social scientists). Levels of exposure, and impact thereof, were assessed using dosimetry, sound-level meter and sound recordings, and a soundscape questionnaire developed in New Zealand. Together, these three data sources cover the dominant approaches to the assessment of acoustic environment: 1) the objective, source-centred environmental noise management approach (e.g. noise levels), 2) the psychoacoustical approach, which relates the physical aspects of sound to human perception, and 3) the subjective, listener-centred, soundscape approach.

Dosimeters were worn by study participants whilst conducting mobile air quality surveys (section 2). A dosimeter is a small portable device which measures sound (or noise) level in decibels, which, in humans, is proportional to loudness. Sound was recorded in multiple localities along five central city streets and thoroughfares during the spring months of 2013. Sound recordings afford a more in-depth analysis of the acoustic environment, specifically the amount of acoustical energy contained at each frequency. A soundscape questionnaire, developed by PENAP Co-Principle Investigator Dr. David Welch, was distributed at three locations, each selected to reflect a range of pedestrian numbers and traffic volumes (viz Queen St, Elliott St, and Albert St). Data were also collected in Albert Park as part of a previous study (Tan, 2013). The soundscape questionnaire included questions that covered both a person's response to the soundscape (i.e., emotional responses), features of the soundscape (e.g., clarity or loudness), and two demographic questions (gender and age). Approximately 200 individuals completed the survey, distributed approximately equally across the three locations and during both the morning and midday periods. .

3.2 Results

3.2.1 Sound Levels in the inner city

The bar chart in Figure 3-1 displays sound levels (in dBA L_{eq}) recorded by dosimeters along the six routes and two different times of day (8:30AM and 12:30 PM). Figure 3-2 presents the peak data in units of dBA L_{peak}. Each bar represents the averages of four circuits obtained in an hour and, as values are outputted by the devices every minute, is thus calculated from 60 values. Differences in the sound levels between the six routes or between the two times in a particular route are tested statistically and reported as 'significantly different' (or not).

For the six routes and the two time periods, a number of statistically significant differences were found, as listed below.

Average sound levels:

- Morning sound levels in Elliott and Victoria Streets are significantly lower than the other four locales. At midday, they are significantly lower than at Customs and Queens Street.
- Customs Street was associated with higher sound levels than the other five areas during the morning. The same pattern held for midday levels. The only exception was that Customs Street had significantly lower sound levels than Queen Street during midday.
- During the morning, both Wellesley and Queen Streets had significantly lower sound levels than Albert Street.
- During midday, Queen Street had significantly higher sound levels than all of other measurement localities.
- For the Elliott, Queen, and Victoria Streets, the sound levels were significantly lower during the mornings, while for the Albert, Customs, and Wellesley Streets, they were significantly lower at midday.

Peak sound levels:

- Peak levels recorded during the morning were significantly lower at Elliott Street than the other five localities.
- Custom Street had significantly higher peak levels than the other five localities during the morning.
- Midday peak levels were significantly greater for Wellesley and Custom Streets, but were not statically different from each other.
- Peak levels were significantly lower in the morning for the Albert and Elliott Streets, and significantly higher in the morning for Customs Street.
- There were no significant differences between morning and midday peaks for Queen, Victoria, and Wellesley Streets.

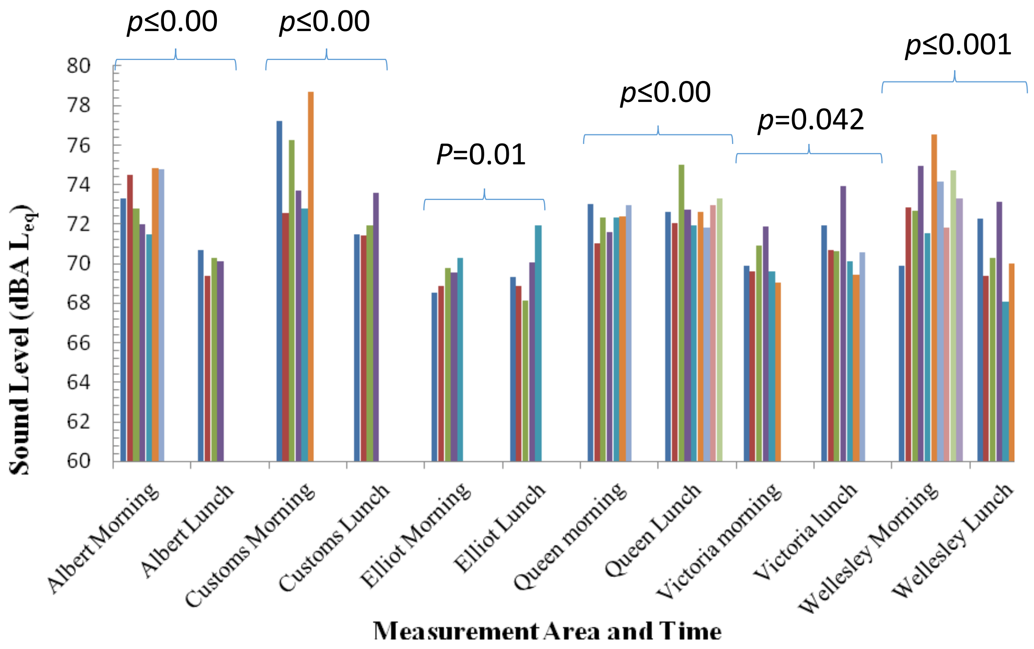

Figure 3-1: Average sound levels for six areas and two measurement times (morning and midday). Each coloured bar is the average for one day's measurements. For any one area, the statistically derived value of *p* indicates a significant difference between morning- and midday-averaged measurements if it is below 0.05. As a rule of thumb, the lower the value of p, the greater the difference between morning and midday sound levels. The symbol '≤' denotes less than or equal to.

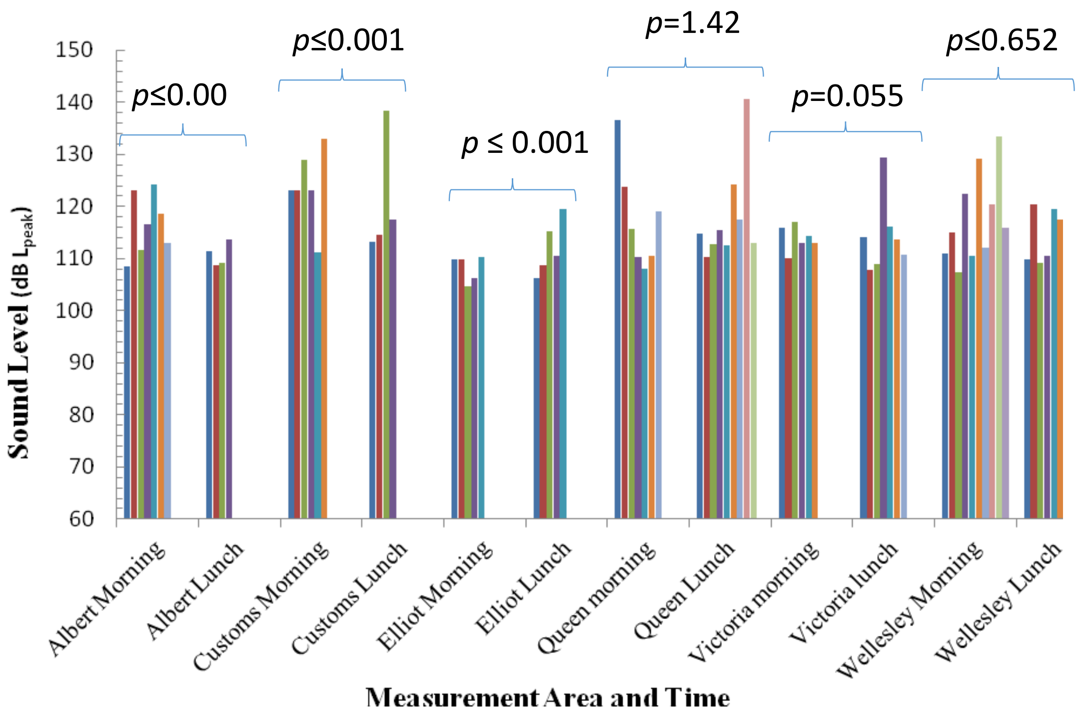

Figure 3-2: As for Figure 3-1 but for peak levels (dB L_{peak})

3.2.2 Human response to the acoustical environment - subjective soundscape assessment

The first section of the self-report soundscape survey addressed the perceived contribution of 'nature', 'people' and 'machine' sounds to the total sound environment. Figure 3-3 presents average responses calculated from three different locales (Queen Street, Elliott Street, Albert Street) at two different times (morning and midday), as well as data from Albert Park. Albert Park was included as a 'green-space' reference to which the street data could be meaningfully compared.

Of the three city streets assessed in the morning, machine sounds in Elliott Street were judged to contribute significantly less to the sound environment than either Queen (*p*=0.025) or Albert Streets (*p*≤0.001), a trend repeated in the midday data (p≤0.001). Additionally, for the morning data only, nature sounds contributed significantly greater to Elliott Street's sound environments than it did to Albert Street (*p*=0.003). Notably, all three areas record differences in 'people sounds', with Queen Street and Elliott Street recording increases between morning and midday, while Albert Street experienced a decrease. Additionally, nature sounds were significantly more prominent in Elliott Street during the morning than during midday hours.

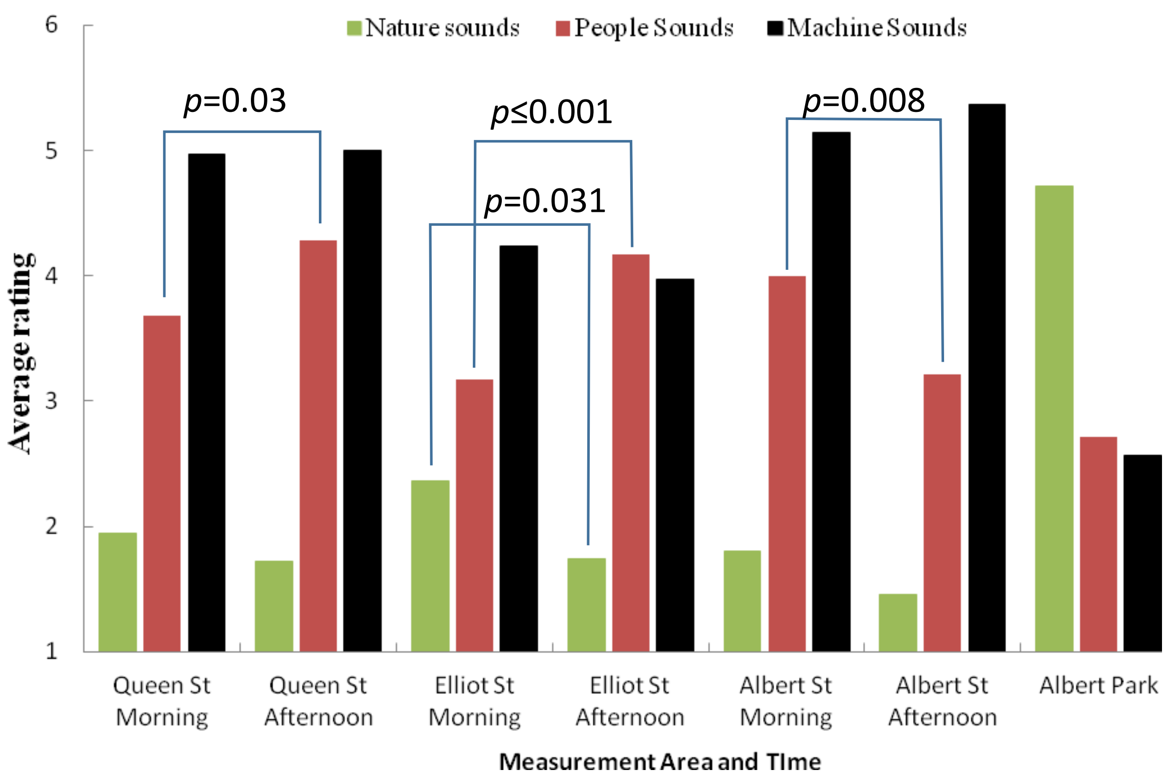

Figure 3-3**:** The average questionnaire outcomes for the level of contribution of the three types of sound to the total sound environment in each of the three city locations.

Figure 3-4 presents a radar plot of various human responses to their current acoustic environment, being one of three localities in either the morning or at midday. In relation to recordings made during the morning, statistical significance was noted for three soundscape features. Elliott Street was perceived as having a more harmonious soundscape (or 'Tone') than either Queen (p=.017) or Albert (p=.004) Streets, as well as being less stress-inducing (p=.016 and p=.018 respectively). Additionally, the soundscape in Elliott Street induced significantly greater feelings of health (or 'Wellbeing') than Albert Street (p=.038).

The midday data likewise returned statistical differences. First, the Albert Street soundscape was judged louder ($p \leq .001$), more complex (p=.008), duller (p=.018) and faster paced (p=.013) than that of Elliott Street. Second, the Elliott Street soundscape was judged less stress-inducing that Queen Street's (p=.023). When directly comparing morning and midday epochs within the same area, no significant differences between items in the soundscape questionnaire were uncovered. Though the Albert Park data was unable to be included in the statistical analyses, it is apparent from Figure 3-4 that when visually compared to the inner city street data, the soundscape was evaluated far more positively, keeping in mind that lower values on this plot indicate more positive judgments.

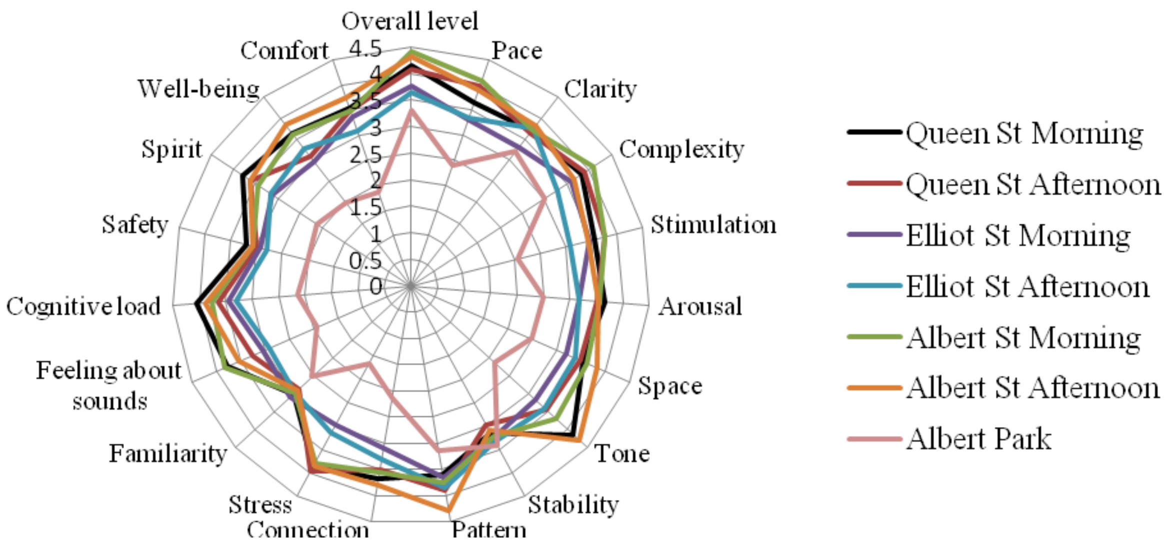

Figure 3-4: Radar plot showing the average questionnaire outcomes of the four locations. Note that lower averages indicate more favourable evaluation of soundscape characteristics than higher averages.

3.3 Noise – conclusions

Scrutiny of the data confirms that the robust data collection regimes implemented as part of the PENAP study have delivered high-quality information able to inform the PENAP project objectives. Objective measures of sound have accurately characterised the acoustic environment of Auckland's inner city precinct, while self-report surveys have provided a human characterisation of the same.

3.3.1 PENAP Objective 3

PENAP Objective 3 aims to characterise the nature of the noise in the Queen Street Valley (sound levels, frequency content, and intermittency) at different locations within the valley. The sound level data show values typical of most inner city acoustic environments, with average levels dependent on the type of street. The statistically significant lower levels found in Elliott Street, for example, would be expected given that this street is designated for 'shared' use (i.e., cars and pedestrians), and has relatively low traffic flows. Overall, however, the average sound levels (see Figure 3-1) often exceed 65 dBA L_{eq}, which would be classified by the OECD as a 'black acoustic area' if sustained across a 24 hour period. Furthermore, pedestrians are, on occasion, also exposed to excessively intense short duration sounds, above 120 dB L_{peak} in some cases. While exposure is not continuous and unlikely to result in noise-induced hearing loss, it will be nonetheless unpleasant. However, those choosing to block out the inner city acoustic environment using devices portable listening devices (such as MP3 players and IPod) may be putting themselves at risk for noise-induced hearing loss, as these device will be set to play audio files at volumes exceeding the ambient sound level.

3.3.2 PENAP Objective 4

The 4th PENAP objective *Assess people's perceptions of the urban soundscape and its contributors* was fulfilled using the soundscape questionnaire. The dominance of heavy transport, apparent when listening to the sound recordings, was also reflected in the human judgments of soundscape content. Inner city soundscapes were assessed to be dominated by machine noise and, to a much lesser extent, people noise. Elliott Street, with its shared environment, had the lowest machine noise of the inner city streets, and highest nature sound content. However, the inclusion of pre-existing Albert Park data served to highlight the difference made by enclaves of green space within urban environments. It was evident that inner city soundscapes were largely evaluated negatively, especially when compared to the ratings for Albert Park. Of the three inner city streets samples, Elliott Street's soundscape was perceived to be the least stress-inducing, and more harmonious/melodious. Figure 3-5 below indicates the reasons why study participants were using particular streets during the morning or at midday. Interestingly, though Queen Street is a popular place for shopping, proportionally it is not as popular for eating as Elliott Street, even though it contains numerous eateries. The quality of soundscape could be one explanation for this finding.

3.3.3 PENAP Objective 5

Increasing the liveability and vibrancy of Auckland City is the core objective of the Auckland Plan, which led to the articulation of the final PENAP Objective (number 5): *Assess people's perceptions of how the soundscape can be improved to make Queen Street a more vibrant street*. This objective is addressed indirectly by reflecting the PENAP data onto a multitude of international research indicating what urban dwellers consider to be an ideal soundscape. Preferred sounds are reliably reported (in order of preference) quiet, bird song, and water sounds. Equally reliably, traffic sounds are reported as the least preferred. The attainment of quiet in the urban living space is largely an engineering design consideration applicable to internal spaces only, for example, inner city apartments or shops. However, while it is not practical to provide outdoor quiet areas in the inner city beyond large scale green spaces such as Albert Park, there is still potential to reduce sound levels and other properties of sound (i.e., fluctuation, roughness, sharpness) that are known to induce annoyance. Fortunately, such efforts have been implemented in many European cities, and a large body of soundscape research is now emerging with the capacity to inform noise-reduction and sound-enhancing/unmasking strategy. Approaches are manifold, and include the modification of vehicles and associated transport networks, policy restricting the space-and-time of traffic flows, the construction of shared spaces and water features such as fountains, and more stringent noise conditions placed on recreational venues and construction sites. A promising ecological approach is the development of 'green buildings', which serve to absorb sound, insulate the buildings, and give homes to bird life through the planting of flora on both rooftops and outer walls.

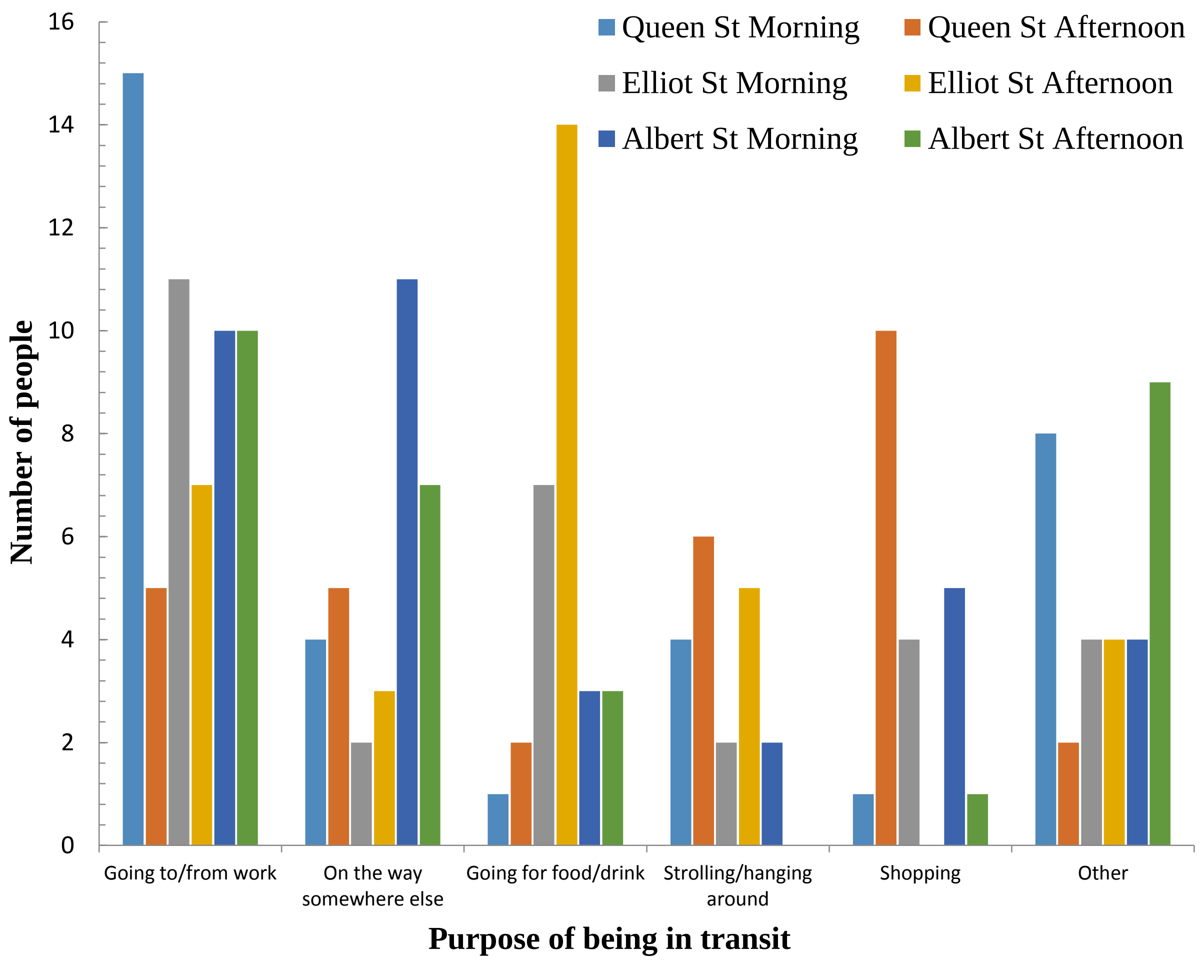

Figure 3-5: Current intent of respondents who completed the soundscape questionnaire.

4.0 Recommendations for further research

This project has described the general patterns of traffic-related air and noise pollution in Auckland's CBD. It has augmented the existing Auckland Council air quality monitoring station in Queen Street with a new capability to measure ultrafine particles from vehicle exhausts. It has also led to the creation of a large database which can support further research.

Whilst this report provides data on levels of air and noise pollution which give cause for concern, it also reveals the complexity of the interplay between traffic, buildings and street design and local meteorology. This makes it challenging to predict how air and noise pollution would change in response to changes to the city's form or management.

Project members plan to conduct further detailed analysis which will be submitted to peer-reviewed international scientific journals. In the near future the database will be opened to other researchers for further exploration.

In addition, further research is recommended to expand the knowledge base and understanding about the city's downtown environment.

1. Further analysis
    a. The PENAP study established New Zealand's first **ultrafine particles monitor at Queen Street** in November 2013. The data generated should be analysed and the results disseminated, at least every year. When combined with the PENAP database this will allow the significance of existing data from the Queen Street site for the wider CBD to become clearer.
    b. Near real-time and a simple analysis of historic ultrafine particle data from the Queen Street site should be made available on the **World Wide Web**.
    c. Deeper analysis of the high resolution mobile air quality and noise data (including sound recordings) should be undertaken to tease out the detailed **relationships with traffic movements**, such as volumes, bus routes and stop locations.
    d. The database should be re-analysed to consider the implications for **exposure of mobile pedestrians** who move from street to street.
    e. The database should be re-analysed to investigate the **correlations** between air quality and noise/soundscape.
2. Additional data
    a. Although the study relies on the sound assumption that road vehicle emissions are the dominant source of the three air pollutants measured (NO_2, CO and UFP), it is likely that **cooking** (restaurant, café), **smoking and shipping emissions** are also relevant sources at certain sites, or in certain wind directions. It is recommended that a future study is conducted which includes **source speciation** based on sample capture and laboratory analysis of chemical composition.

b. Additional long-term air quality observations should be made from an "**urban background**" or rooftop location in the CBD to complement those made by Auckland Council at Queen Street. The Queen Street site is dominated by local traffic emissions and is strongly influenced by street canyon vortices making it difficult to distinguish the impact of emissions from the rest of the CBD, from the Port and from the rest of Auckland. An urban background site will permit sources and influences from beyond the CBD to be clearly distinguished.

c. The worst air quality and highest noise levels were observed in **Customs Street**. However, due to resource limitations, this area was only surveyed intensively over two days. No measurements were made in Quay Street. The PENAP results hint that the waterfront area might be subject to enhanced dispersion, but also influence from ship emissions. With significant changes planned for Auckland's waterfront we recommend that this area is the subject of an extended PENAP study.

d. This study implies a substantial improvement in air and soundscape quality as a result of the conversion of **Elliott Street** into a shared space. However, the study also revealed that during part of our study Elliott Street had higher ultrafine particle levels than Customs Street. This shows that we should be wary of over-generalising a complex issue. A key question appears to be how much of the pollution in Elliott Street originated in that street, or was transported from other streets, in which case the air quality in any street is dependent upon how it is connected to, or sheltered from, other streets. This is a complex issue which deserves further investigation.

e. "**Intervention studies**" (which compare the situation before and after a change) represent a powerful "gold standard". Where significant changes to the CBD are planned (e.g. closure of a street, re-routing of traffic), even if only temporarily, we recommend that an observational study of air quality and noise is conducted to clearly demonstrate the impact of the change.

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Appendix A: Methods

Study area and monitoring sites

A Study Area was agreed amongst the collaborators on the basis of the following criteria:

Stakeholder interest in key road corridors: Queen Street (north of Aotea Square), Britomart, Customs Street, Victoria Street and Wellesley Street.

Including streets with both high and low total traffic volumes and heavy-duty-diesel (especially bus) volumes to allow for meaningful comparisons.

Concentrating on streets with tall (> 16 m) buildings on both sides[2] to improve fair comparison.

The Study Area chosen is indicated in Figure A-1.

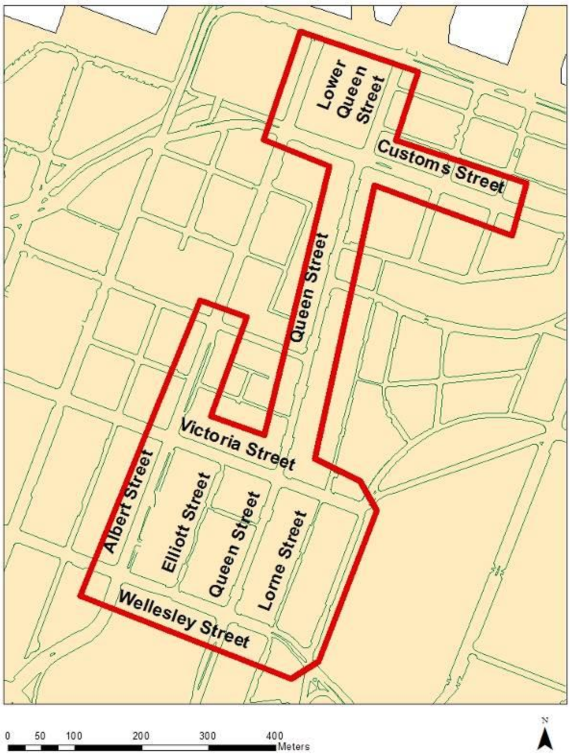

Figure A-1 PENAP Study Area

1.0

[2] It is well established that street canyons – where the ratio of the average building height to street width is greater than ~0.7 – increase the concentration of traffic-related air pollution due to reduced dispersion. With typical street widths of 20 – 28 m in Auckland CBD this applies to streets with buildings higher than ~16 m, or typically 5+ storeys.

Study components and timing

The PENAP study was an observational study, consisting broadly of three stages:

- Detailed design and study area selection (May – July 2013)
- Observations (Aug – Oct 2013)
- Analysis and reporting (Oct 2013 – Feb 2014)

The observational campaign consisted of several elements:

- Air quality
  - Passive monitoring (62 sites, 6 weeks continuously, 19th Aug – 1st Oct 2013)
  - Fixed continuous reference monitoring (2 sites)
  - Mobile monitoring (22 x 1 hour surveys, morning or mid-day, multiple streets, between 19th Aug and 19th Sep 2013)
- Noise
  - Sound recordings at various sites within the study area
  - Soundscape questionnaire surveys in CBD streets
  - Mobile noise monitoring (alongside air quality mobile monitoring)

Air Quality

Passive monitoring of nitrogen dioxide

Nitrogen dioxide (NO_2) is a traffic-related pollutant which is particularly sensitive to diesel emissions. NO_2 was measured using “diffusion tube” samplers deployed on 62 lampposts or other street furniture across the Study Area for three deployments of two weeks in duration. Analysis was carried out in a laboratory located at the University of Auckland, yielding a single number representing the average pollutant concentration over the deployment period. Diffusion tube sampling is a technique widely used internationally and extensively by Auckland Council (ARC, 2007) and the NZ Transport Agency (NZTA, 2012). Together these samplers provide an indication of the differences in pollution levels between sites/streets across the Study Area over the whole of the campaign period.

Long-term monitoring undertaken by Auckland Council has revealed that concentrations of NO_2 vary seasonally, with concentrations peaking during mid-winter and reducing in mid-summer. This is largely connected with variations in the meteorological conditions that drive dispersion. This study was conducted in the late-winter and early-spring period and, as such, we would expect a general downward trend in concentrations to have been evident during the campaign, and for concentrations to be slightly higher than the long-term (annual) average. To enable fair comparison within the study, and to compare with annual averages, the data were adjusted for this seasonal effect using data from AC's long-term Queen Street monitoring site.

Mobile monitoring of ultrafine particles and carbon monoxide

The central aim of the PENAP project was to characterise air quality (and noise) at the street level where large numbers of pedestrians experience it, and to investigate the role differences in traffic play. Although the nitrogen dioxide monitoring (see above) was able to cover multiple streets, it is limited in considering only one pollutant, in providing time-averaged data over two weeks rather than at peak times of day when most people are exposed, and does not cover the whole length of each street. To address these issues, an additional layer of temporally-specific spatial monitoring was included.

Recent technological advances have made it possible for high-quality, high-resolution air quality monitoring to be conducted by mobile pedestrians. An extended PENAP field team was recruited amongst researchers, students and AC staff to carry instrumentation during scheduled walks within pre-selected street blocks. Table A-1 and Figure A-2 indicate the blocks chosen. On selected days a study participant would be allocated to one of the study blocks. At pre-determined times (8:00, 8:15, 8:30 and 8:45, or 12:30, 12:45, 13:00 and 13:15) they would walk a clockwise loop around that block. The aim was to sample every weekday during peak traffic (8:00 – 9:00) and mid-day (12:30 – 13:30) on a sufficient number days to capture data for every block several times.

Each team member carried a GPS receiver, a noise dosimeter, and a carbon monoxide sensor (Langan T15n). **Carbon monoxide** (CO) is an acute neurotoxin at high concentrations. Its predominant source in urban streets is tailpipe emissions from petrol vehicles. However, technological advances over the past three decades have led to major reductions in CO emissions. The impact has been observed by long-term CO monitoring by Auckland Council which show that CO concentrations in Auckland streets pose no direct health hazard. However, in this study we use CO as a proxy for petrol vehicle emissions in general.

In most cases a portable particle counter (TSI P-Trak) was also carried. This device reports **particle number concentrations** (PNC), i.e. the number of airborne particles per cubic centimetre of air. PNC is crucially different to PM_{10}, the measure of airborne particles monitored by Auckland Council and regulated under the National Environmental Standards. PM_{10} is a measure of the mass (rather than the number) of particles smaller than 10 μm per cubic centimetre of air. Fresh vehicle tailpipe emissions are overwhelmingly ultrafine (smaller than 0.1 μm). Because of their small size, they possess relatively little mass and do not contribute much to PM_{10}. However, numerically they dominate urban air. They also penetrate most deeply into the lungs, and there is growing international evidence that these ultrafine particles are most strongly associated with a wide range of adverse health impacts. Thus, in this study, and following substantial international precedent, we report particle number concentration in order to represent ultrafine particles (UFP).

Table A-1 Study Area street blocks

Street block	Main features
Lower Queen Street	Bus station (incl. idling)
Customs Street (Albert Str – Gore Str)	High traffic; buses (incl. idling)
Queen Street (Customs Str – Wellesley Str	Moderate traffic; some buses
Albert Str (Wyndham St – Wellesley St)	Moderate traffic; buses
Victoria Str (Kitchener Str – Albert Str)	Moderate traffic; buses; gradient
Wellesley Str (Kitchener Str – Albert Str)	Moderate traffic; buses; gradient
Elliott Street	Shared Space – low traffic
Lorne Street	Shared Space – low traffic

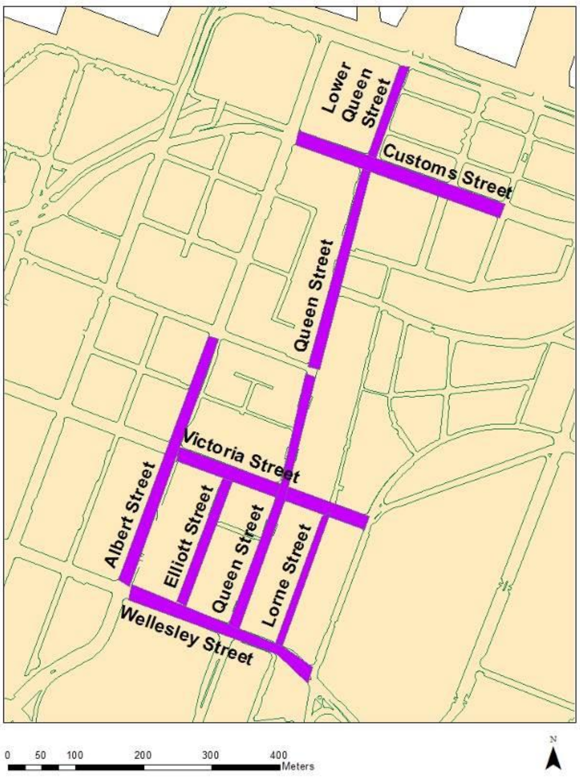

Figure A-2 Street blocks selected for mobile monitoring

A large database was accumulated with a good spread of coverage between streets with differing traffic characteristics. Surveys were completed on 11 mornings and 11 mid-day periods between 19th August and 19th September, comprising 129 person-hours and providing nearly 100,000 air quality measurements. The air quality instruments proved to be highly reliable yielding good quality data. Inter-comparison experiments were conducted to characterise performance and ensure that data from different units could be directly compared.

Limitations on instrument and personnel availability, as well as adverse weather, required that the study be split into three phases. In Phase 1 (12 surveys in August), surveys focussed on the central area. In Phase 2 (8 surveys in early September), surveys on Albert Street were discontinued, but additional data on Elliott Street were captured. Phase 3 (2 surveys in mid-September) focussed on Customs Street and Lower Queen Street and discontinued surveys on Victoria Street and Wellesley Street.

No long-term monitoring data of ultrafine particles **previously** existed in Auckland. Thus, the typical diurnal, weekly and seasonal patterns in this pollutant are currently unknown. This means that we are unable, at present, to estimate with any confidence, whether the particle levels reported here are typical, or abnormally high or low for Auckland. However, **the PENAP project did establish New Zealand's first long-term ultrafine particle monitoring** at the AQ Queen Street site, commencing in November 2013. Within 6 months, it should be possible to establish the long-term variation in particle levels and further put the PENAP study results into context.

Comparing particle concentrations between streets is somewhat complex. Street-level concentrations of traffic pollutants are strongly influenced by meteorological conditions. Resource limitations prevented us from sampling every street of interest simultaneously. Direct comparison of data captured on different days is suitable as long as meteorological conditions are the same. In the case of our study, meteorological conditions varied between the three phases. This is illustrated by the wind roses shown in Figure A-3. These figures show that a wide range of wind speeds and directions occurred during Phase 1 with westerly winds prevailing. Phase 2 occurred during periods of stronger winds with a westerly component and also north-westerly and south-westerly conditions being common. Phase 3 was characterised by strong north-easterly winds. Only one street was sampled consistently during every survey – Queen Street. Figure A-4 shows the average concentrations recorded on the Queen Street surveys for each of the three phases, showing that concentrations were not consistent, but were higher in Phase 1, lower in Phase 2 and in between during Phase 3. This is broadly consistent with the differences in weather (especially wind speed and direction) between the three phases. For this reason, the three phases are analysed separately.

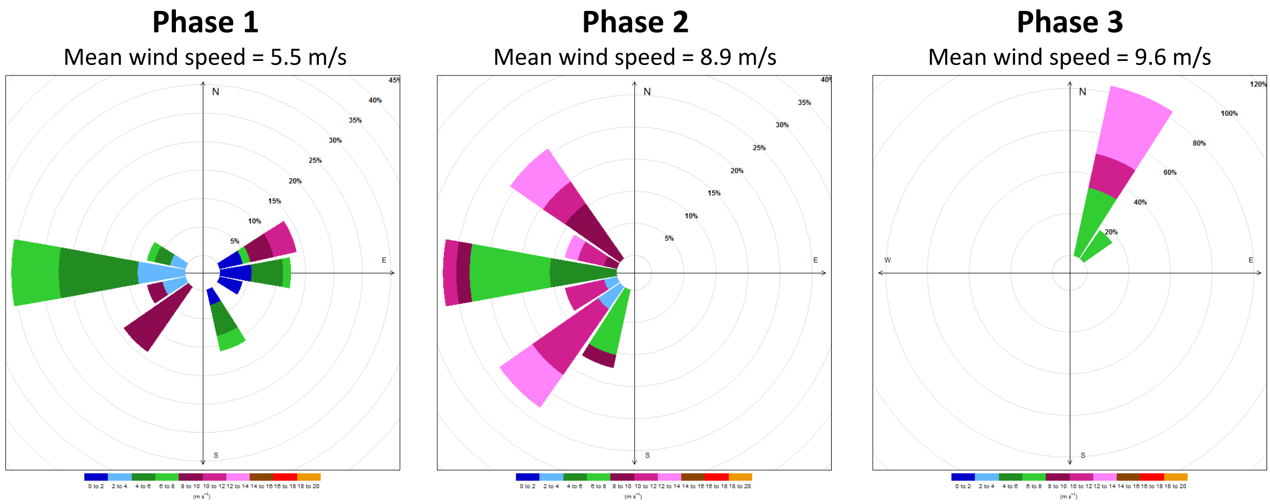

Figure A-4: Wind roses for the three phases of the campaign. The size of each sector represents its frequency during the campaign and the colours represent wind speed. For example, phase 3 shows winds from the NE only of moderate speed. All data was measured on the Sky Tower.

Noise

Sound was recorded in multiple localities along five central city streets and thoroughfares during the spring months of 2013, including measures of sound level (in decibels) and also recordings of key sound sources, such as road transport. Additionally, soundscape survey data were collected at selected sites in late spring. This section provides a description of data acquisition equipment and methods.

Dosimetry

A dosimeter is a small portable device, capable of being attached to an item of clothing such as a collar (see Figure A-6), which measures an individual's exposure to sound. As part of the mobile monitoring component of the PENAP study, personal sound exposure over the six walking routes (See Figure A-2) was assessed using a commercially-available dosimeter (CEL-350 dBadge, Casella) providing sound level measurements every minute along with the ultrafine particle concentration data and GPS information. Primarily, dosimeters measure sound (or *noise*) level in decibels, which, in humans, is proportional to loudness. In the PENAP study, the dosimeters reported sound level using two different types of decibel measures: dB LA_{eq} and dB L_{peak}. The dB LA_{eq} measure represents the average level of sound within a certain time period, for example, the average sound level across a three-hour rock concert. The dB L_{peak} measure, on the other hand, measures the highest sound level in a given time period, for example, explosives being detonated as part of the rock concert's finale. As a technical aside, each measure utilise what is known as the 'A-filter', which adjusts the sound level measurement depending on the frequency of the sound. This is in response to the fact that the sensitivity of the human ear is frequency-specific; the human ear is much more sensitive to sounds of some frequencies compared with others. Prior to collecting sound level measurements, each dosimeter was professionally calibrated, ensuring that the measurements were certified to be both accurate and reliable.

At the beginning of each measurement run during the mobile monitoring campaign, a dosimeter was attached to the shoulder of the PENAP study participant, and then the device was locked to prevent tampering or accidental setting changes. Measurements begun at either 8:30 AM (morning) or 12:30 PM (midday) sharp, and lasted approximately one hour. The study participant travelled the prescribed route in a specified time (15 minutes), while also carrying their P-TRAK device and PPS monitor. For each data run, the team member completed four circuits, resulting in one hour of measurements. The dosimeter calculated the standardised (re: International Organization for Standardization) sound level parameters (i.e., dB LA_{eq} and L_{peak}) and recorded them electronically. These values were then downloaded onto a personal computer at a later time, graphed and subjected to statistical analyses.

Figure A-6: Dosimeter attached to shirt (left), and sound level meter (right).

Sound Recordings

Sound recordings were made using a professionally-calibrated sound level meter (Solo SLM, 01dB-Metravib). In contrast to a dosimeter, which provides discrete sound level statistics every minute, a sound level meter records continuously (here 44,100 times per second). Because an actual, albeit digital, representation of the sound is obtained, it can be played back, listened too, and salient events identified (e.g., a truck starts its engine or a bus drives past). These recordings also afford a more in-depth analysis of the acoustic environment, specifically the amount of acoustical energy contained at each frequency. Consider a sound level meter recording of a pianist playing a cherished piece; like the human hearing system, analysis of the sound recording can reveal which piano key (i.e., frequency information) is being struck at which instant in time (i.e., temporal information), and with what force (i.e., sound level information). A contextual example would be poorly-adjusted brakes on a heavy vehicle, which would reveal itself as relatively intense energy at higher frequencies – perceived by individuals as a high-pitched squeal. A graph representing time on the horizontal axis, frequency (or pitch) on the vertical axis, and the colour representing sound level, is known as a spectrogram. Such graphs give an immediate and intuitive illustration of the acoustical environment.

During recordings, the sound level meter was positioned on a tripod at least 1.5 metres away from any reflective surface that might impact recording quality. For each location, the duration of measurement typically lasted between 3-5 minutes, a duration deemed to be sufficient to obtain a recording that is representative of the acoustic environment. All recordings were made in conditions during which the wind speed was less than the recommended maximum specified by the sound level meter manufacturer, and field notes were made by the operator as salient sound events occurred (e.g., a truck comes to a halt, or a bus accelerates away from a traffic light). These sound recordings also allow the properties of sound associated with the psychology of hearing such as loudness, sharpness, roughness, and fluctuation strength to be calculated using industry standard acoustics software (dBSonic). For brevity, these 'psychoacoustical' measures are defined using examples in Table A-2. It was thus possible to ascertain the impact of specific events (e.g., two cars exchanging horn blasts) by relating the field notes to the coinciding psychoacoustical measures.

Table A-2: Properties of sound associated with the psychology of hearing.

Parameter	Description
Fluctuation Strength	Rhythm, rain on the roof
Loudness	Relates to sound level or intensity. Increasing the volume on a personal stereo produces an increase in sound level, and such an increase is typically perceived as louder.
Roughness	Used to represent subjective sound quality. For example, the sound quality on a mobile phone is a lot rougher when reception is very poor than when reception is excellent.
Sharpness	Refers to the density of sound, with denser sounds described as less sharp. How sharp a sound is perceived depends upon its frequency (pitch), where high-pitched sounds are perceived as sharper than low-pitched sounds. A classic example of a sharp sound is the drawing of fingers down a chalkboard, while slow breaking waves at a beach are at the other end of the continuum.

Human Factors

A soundscape questionnaire, developed by PENAP Co-Principle Investigator Dr. David Welch, was distributed at three locations, each selected to reflect a range of pedestrian numbers and traffic volumes (viz Queen St, Elliott St, and Albert St). Data were also collected in Albert Park as part of a previous study (Reference to Mei's thesis). The soundscape questionnaire (provided in the Appendix) included questions that covered both a person's response to the soundscape (i.e., emotional responses), features of the soundscape (e.g., clarity or loudness), and two demographic questions (gender and age). Approximately 200 individuals completed the survey, distributed approximately equally across the three locations and during both the morning and midday periods.

Appendix B: Sound recording results

Acoustical characteristics of the sound source - Sound levels and frequency content

The provision of sound recordings and accompanying field notes afforded a more in depth examination of inner city sounds levels than data generated with the dosimeters. Plots such as those presented in Figure B-1 can be generated and compared to field notes, allowing the acoustic impacts of salient sound events to be assessed. This recording, used repeatedly in this report, was obtained from Albert Street at midday. It is three-and-a-half minutes in duration, and contains four salient events, notably a motorbike with a loud muffler and, on three occasions, accelerating buses. The impact of these events on the acoustic environment is evident, and, across multiple sound recordings, a recurring pattern of acoustic domination by transport-related sound was observed.

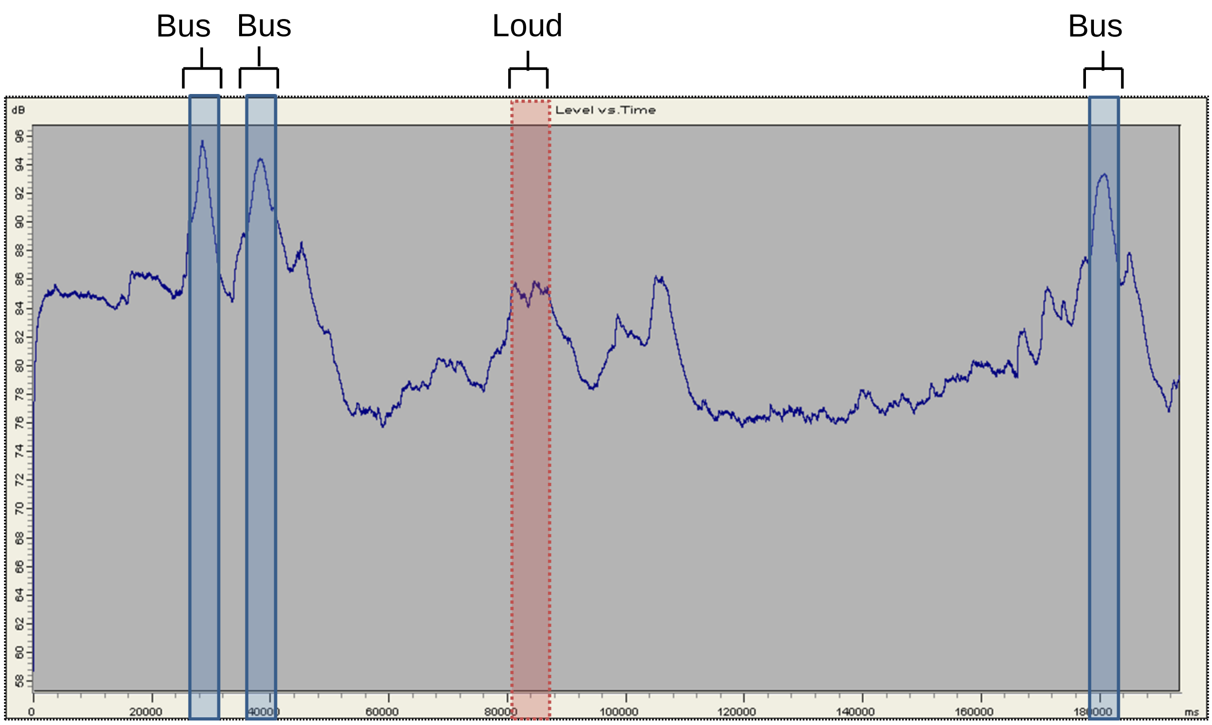

Figure B-1: Sound levels (in dBA) for a three-and-half minute recording obtained in Albert Street. Four Salient events are identified through the use of field notes, and are indicated at the top of the figure.

As Figure B-2 shows, spectrograms allow the level and frequency of the recorded sound to be scrutinised for the duration of the sound recording. Inner city traffic flows are variable, creating a highly variable soundscape both in level but, as importantly, in frequency. As part of the PENAP study, a large number of spectrograms were generated and then referenced to field notes in order to couple salient sound events in the environment to the characteristics of the spectrograms. Figure B-2 is one such spectrogram generated using a sound recording obtained in Albert Street during the midday (as per Figure B-1 above), and can be considered representative of a typical spectrogram derived from the recording of a typical inner city street. The imprint left by the documented sound events constitute striking contrasts, especially for the first two bus events, where high sound levels in the lower frequencies (around 200 Hz) would likely be considered unpleasant by individuals in possession of normal sensibilities. Taken together, it is apparent from the spectrograms that traffic noise, especially that produced by heavy vehicles, dominates the acoustic environment of the inner city streets included in the PENAP study.

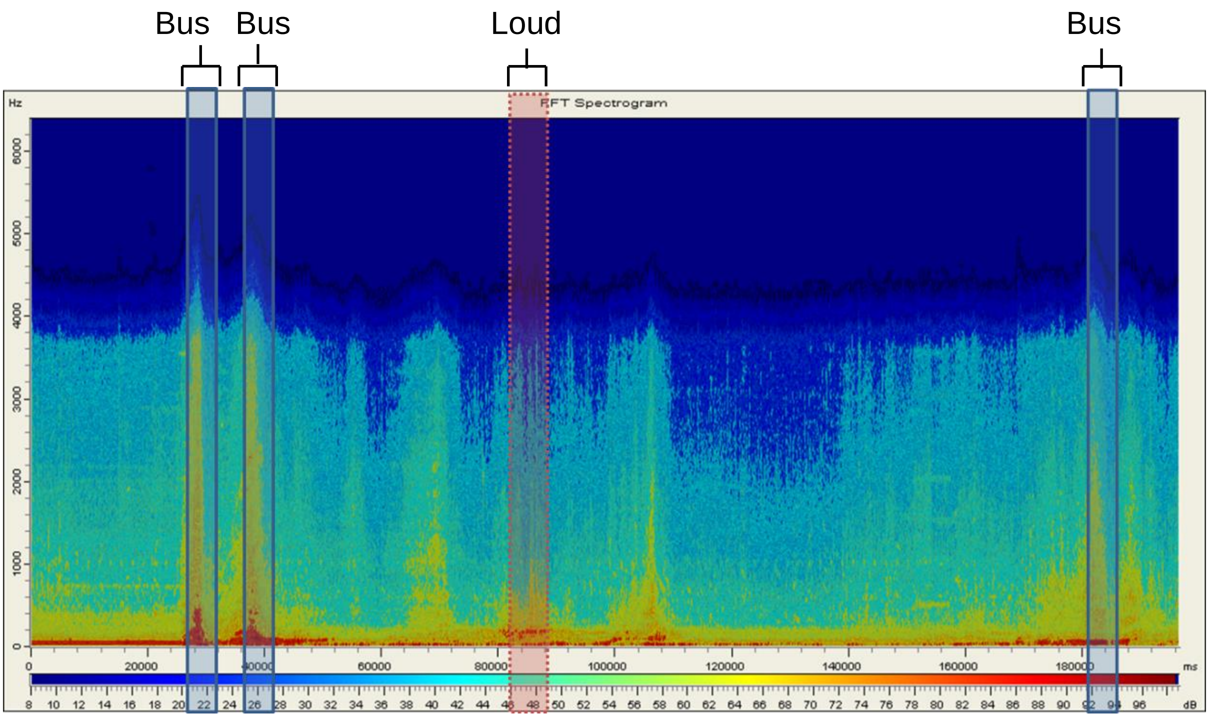

Figure B-2: Spectrogram, produced using industry standard software (dBSonic), of a sound recording made at midday on Albert Street. The horizontal axis represents time (in milliseconds), the vertical axis frequency (or 'pitch') (in Hertz), and pixel colour decibels (in dBA – refer scale at bottom of figure). Field notes identified four key sound events during the recording, which are identified at the top of the figure.

Psychoacoustical analysis of the soundscape

Data obtained from sound level meter recordings permit psychoacoustical analyses, deriving measures thought largely to influence human response to the immediate acoustic environment. Psychoacoustic measures extracted from sound recordings include sharpness, roughness, fluctuation, and loudness, all of which can be considered to constitute an objective psychoacoustical evaluation of the soundscape (see Table A-2). Typically, as scores on these measures increase, so too do negative evaluations from humans. Using the same recording presented in Figures B-1 and B-2 above, Figures B-3 (Loudness), B-4 (Sharpness), B-5 (Roughness) and B-6 (Fluctuation) demonstrate how changes in the acoustic environment impact psychoacoustical measures. Of interest are the differences between the three buses, with the final bus coinciding with a peak in level (Figure B-1), but in contrast to Buses 1 and 2, no corresponding peak in loudness (Figure B-3). This may be explained by differences between the buses (e.g., type, age, or condition of the bus) or driving characteristics. For example, a better maintained engine will have a different sound output to a poorly maintained engine, even though their sound levels may be equivalent. It can be demonstrated that a motorcycle engine, modified to produce 3 dBA lower sound levels, can actually be perceived as 25% louder, due to differences in frequency content. Bus 3 also has lower roughness and fluctuation strength, and would likely emit less annoying sounds than buses 1 and 2. The high fluctuation strength of the motorcycle with the loud muffler likewise indicates the presence of an annoying sound.

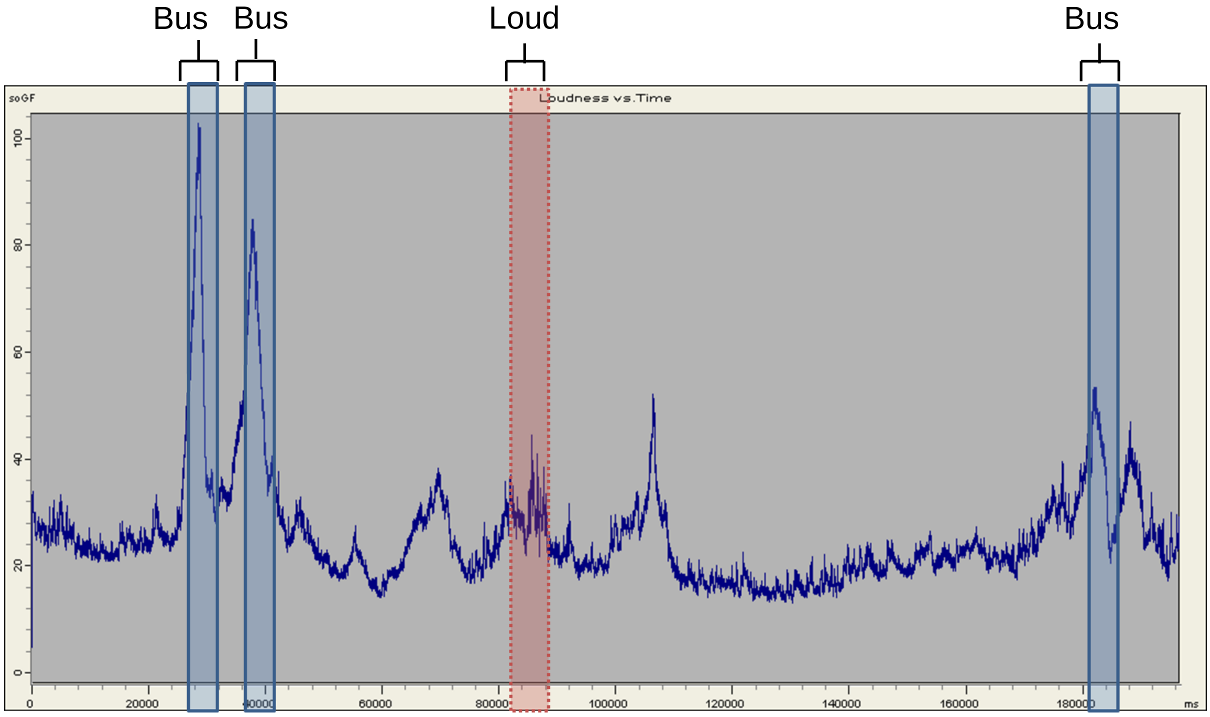

Figure B-3: As for Figure B-1, but psychoacoustical loudness is reported instead of level.

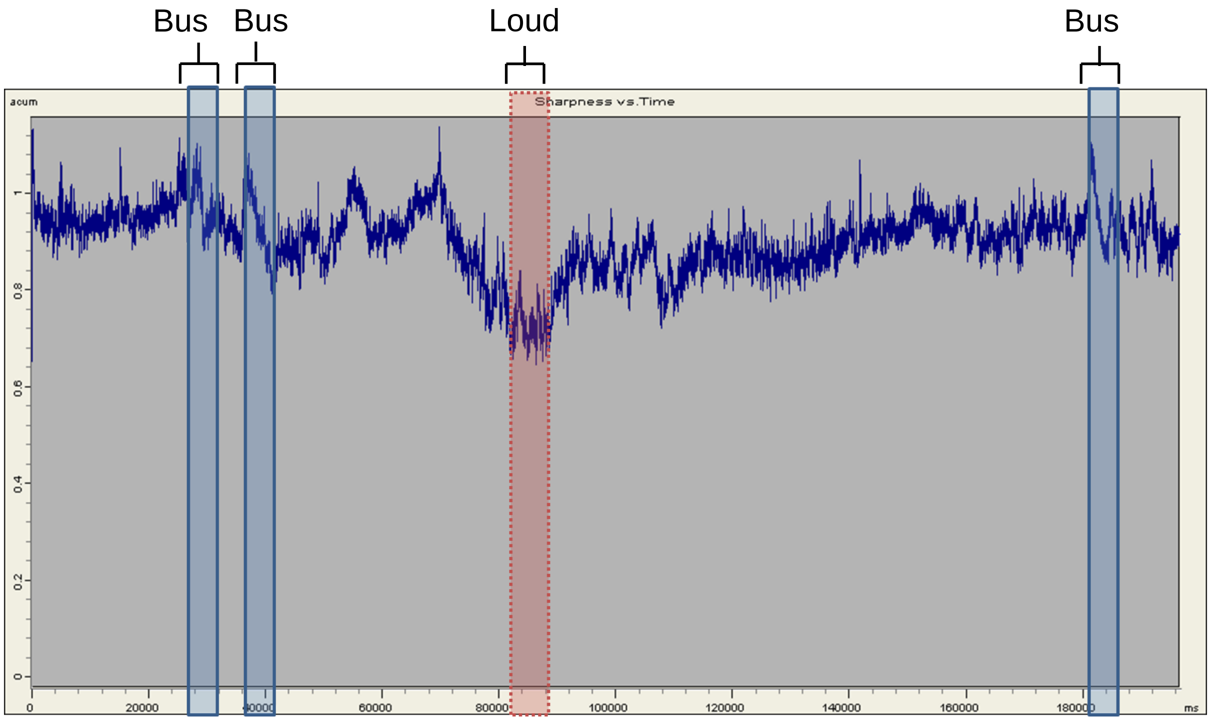

Figure B-4: As for Figure B-1, but psychoacoustical sharpness is reported instead of level.

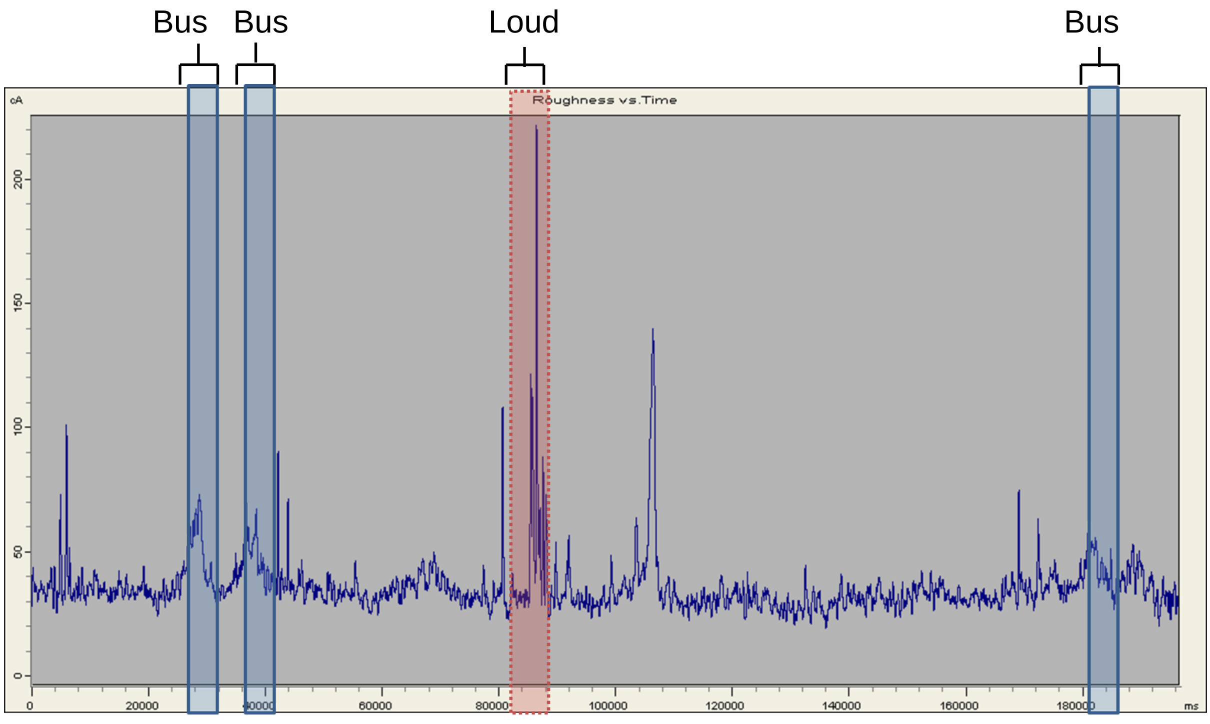

Figure B-5: As for Figure B-1, but psychoacoustical roughness is reported instead of level.

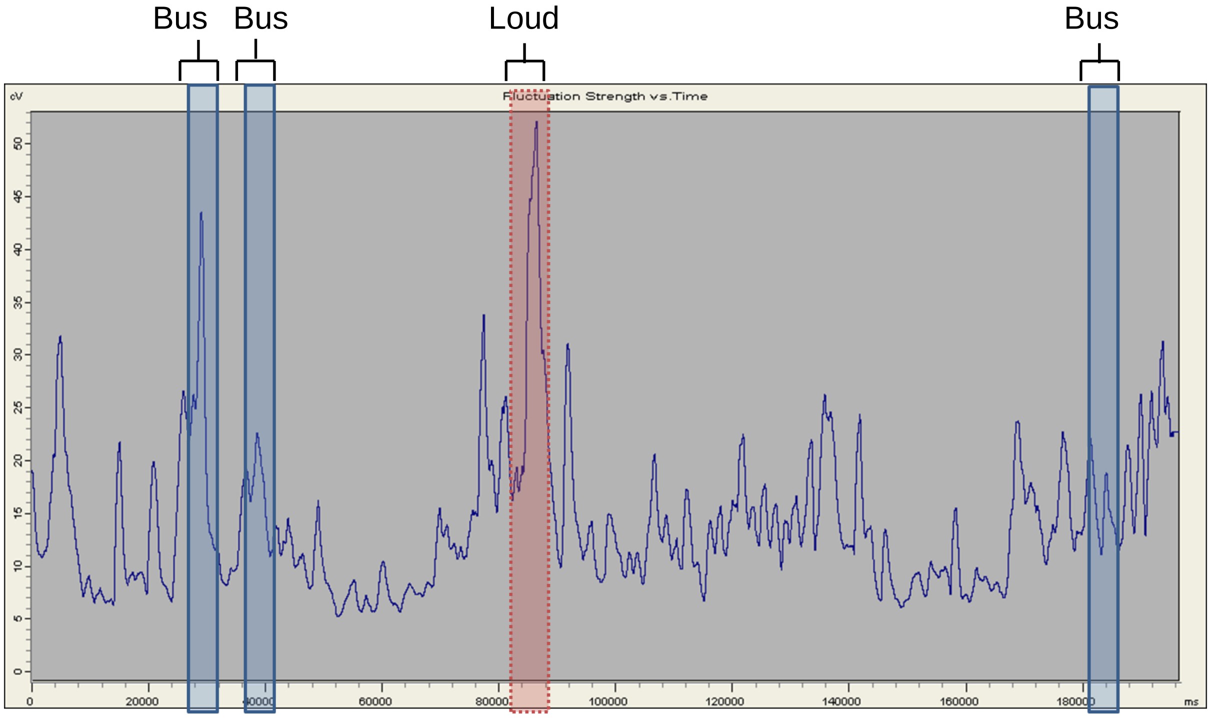

Figure B-6: As for Figure B-1, but psychoacoustical fluctuation is reported instead of level.

Appendix C: Soundscape Questionnaire

Soundscape Questionnaire

This questionnaire aims to assess the sound environment (soundscape).

Your Gender **(tick)** **Your Age (in years)**

Male ❑ Female ❑ ____________________

Please indicate how much the following types of sound contribute to the total sound environment.

	None						Entirely
Nature sounds		1	2	3	4	5	6
	None						**Entirely**
People sounds		1	2	3	4	5	6
	None						**Entirely**
Machine sounds		1	2	3	4	5	6

Please listen to the sounds around you and rate the sound environment and your response(s) towards it by circling a number (1-6) on the following scales. If the scale is irrelevant to you, tick the 'not applicable' box beside it.

Soundscape feature/ your response									Not applicable (tick)
	Very soft							**Very loud**	
Overall level		1	2	3	4	5	6		❑
	Leisurely							**Fast**	
Pace		1	2	3	4	5	6		❑
	Clear/ distinct							**Unclear/ blurred/ disorderly**	
Clarity		1	2	3	4	5	6		❑

	Simple sounds							**Complex sounds**	
Complexity		**1**	**2**	**3**	**4**	**5**	**6**		❑
	Soothing/ hypnotic							**Arousing**	
Stimulation		**1**	**2**	**3**	**4**	**5**	**6**		❑
	Vibrant/ exciting							**Overwhelming/ intense**	
Arousal		**1**	**2**	**3**	**4**	**5**	**6**		❑
	(Please tick the N/A box if it is not arousing in any way)								
	Spacious/ liberating/ vast							**Congested/ claustrophobic/ enclosed**	
Space		**1**	**2**	**3**	**4**	**5**	**6**		❑

PTO→

									Not applicable (tick)
	Harmonious/ melodious							**Discordant/ harsh**	
Tone		**1**	**2**	**3**	**4**	**5**	**6**		❑
	Dynamic/ changing/ up-and-down							**Monotonous/ in the same manner/ flat**	
Stability		**1**	**2**	**3**	**4**	**5**	**6**		❑
	Rhythmic/ predictable							**Irregular/ random**	
Pattern		**1**	**2**	**3**	**4**	**5**	**6**		❑
	A sense of belonging							**A sense of alienation**	

Your connection to the soundscape		**1**	**2**	**3**	**4**	**5**	**6**		❑
Relaxation/ stress	**Relaxation/ tranquillity/ peace**	**1**	**2**	**3**	**4**	**5**	**6**	**Stress/ anxiety annoyance/ anger**	❑
Familiarity	**Familiar/ usual**	**1**	**2**	**3**	**4**	**5**	**6**	**Novel/ unusual**	❑
Your feeling about these familiar sounds	**In comfort zone/ at ease**	**1**	**2**	**3**	**4**	**5**	**6**	**Mundane/ dull/ boring**	❑
(Please tick the N/A box if it is not familiar in any way)									
Cognitive load	**Refreshed/ rejuvenated**	**1**	**2**	**3**	**4**	**5**	**6**	**Distracted/ mentally overloaded**	❑
Your safety	**Safe/ a sense of control**	**1**	**2**	**3**	**4**	**5**	**6**	**Threatened/ fearful**	❑
Spirit	**Uplifted/ meditative/ transcendent**	**1**	**2**	**3**	**4**	**5**	**6**	**Oppressed/ depressed**	❑
Your well-being	**Healthy/ wholesome**	**1**	**2**	**3**	**4**	**5**	**6**	**Affliction/ infirmity**	❑

	Contented/ comfortable							Desire to escape/ uncomfortable	
Comfort		**1**	**2**	**3**	**4**	**5**	**6**		❑

Compared to most people, how sensitive are you to the following things? (please circle a number)

	Never							**Much more than most people**
Noise		**1**	**2**	**3**	**4**	**5**	**6**	
Smells and pollution		**1**	**2**	**3**	**4**	**5**	**6**	

In the current environment, how annoying do you find the following things

Noise		**1**	**2**	**3**	**4**	**5**	**6**	
Smells and pollution		**1**	**2**	**3**	**4**	**5**	**6**	

What was your main reason for being in the street today? (please circle)

Working or on the way to/from work	**On the way somewhere else**	**Going for food/drink**	**Strolling/hanging out**	**Shopping**	**Other**

Were there any aspects of the sound environment (soundscape) that were not covered in the questionnaire?

Other aspects: