The development of a mobile monitoring system to investigate the spatial variation of air pollution

Photos by Dave Gibb, NIWA

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The development of a mobile monitoring system to investigate the spatial variation of air pollution

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Executive Summary

NIWA has designed and built a mobile monitoring system with the aim of collecting data which will ultimately allow the assessment of how PM_{10} concentrations vary across urban airsheds. There are three phases to this project:

1) System design, build and trial

2) Identify system issues. Enhance and improve system

3) Airshed monitoring, data analysis and assessment of spatial variation of pollution

The mobile monitoring system took a year to design build and trial. This report details the outcomes of phases one and two of the project. The three main objectives of this report are to:

- Describe the system developed by NIWA for assessing spatial variability of airborne particulate matter concentrations

- Demonstrate the utility and application of data collected by the system

- Make recommendations for improvements to the system

The mobile monitoring system is comprised of three principal components: an aethalometer (measuring elemental black carbon), a GRIMM particulate monitor (measuring PM_1, $PM_{2.5}$ and PM_{10}) and an AirMar ultrasonic weather station and GPS unit. The components are linked into a data logging system and integrated into a single platform which is mounted onto a vehicle.

This report presents the results of the monitoring trials that were undertaken in Alexandra, Auckland and Christchurch in winter 2007. The trials were conducted with the specific and simple aims of assessing the utility of the system, assessing the quality of data being collected and identifying potential improvements to the system. The results presented should be treated as illustrative examples of what the system can achieve. The conclusions drawn here are subject to the limitations of the short record of trial data collected and can, at best, be treated as preliminary. More intensive and specifically designed mobile measurement campaigns would be required to provide conclusions upon which air quality management strategies could be based. Notwithstanding these limitations, key findings of the trials were that the mobile monitoring system can potentially be used to:

- Evaluate variability of PM concentrations both within and between airsheds (e.g. Dunedin vs Mosgiel, Nelson vs Tasman, and Christchurch vs Kaiapoi vs Rangiora)

- Identify potential locations for new monitoring sites within airsheds to ensure compliance with AQNES Regulation 15.

- Assess the representativeness of the data collected by existing monitoring sites
- Identify the source of PM and their geographical areas of impact
- Establish dynamic baseline data for exposure research that require information related to population movements.
- Validating the results of airshed dispersion models

A number of operational and equipment issues were identified with the monitoring system. These included:

- Differences between the GRIMM and AQNES compliant PM_{10} measurement methods
- Impact of driving speed on the sampling of PM_{10}
- Data acquisition, equipment communication, power supply and elevation data

Solutions have been formulated to address each of these issues. Plans and a timetable are in place to upgrade the mobile monitoring system so it is able to undertake an extensive monitoring programme in the winter of 2008.

It is anticipated that when phases two and three of the project have been completed the data collected will be of a quality such that they can be used to robustly assess air quality within airsheds and to aid the development of air quality management policies.

1. Introduction

1.1 Regulation, sources and monitoring of particulate matter in New Zealand

The Air Quality National Environmental Standard (AQNES) defines the concentration of particulate matter (PM_{10}) that shall not be exceeded within any airshed more than once per year as 50 μgm^{-3} (24-hour average). Exceedances of the AQNES for PM_{10} have been observed at around 30 urban areas within New Zealand (MfE 2008). Home heating is generally believed to be the biggest source of PM_{10} emissions when exceedances occur. However, road traffic emissions are also a notable source of PM_{10} emissions in urban areas such as Auckland.

The AQNES also includes a requirement for Regional Councils to monitor PM_{10} in airsheds where the ambient standard for PM_{10} is likely to be exceeded. The regulations also specify that monitoring must be conducted at a location where PM_{10} concentrations are likely to be highest or exceeded the greatest number of times within the airshed. Due to the monitoring requirements defined within the AQNES, it is important to have an understanding of if, and how the concentrations of air pollution vary within a particular airshed. This knowledge will allow air pollution “hot spots” to be identified and monitors placed accordingly.

1.2 Spatial variation of particulate matter within airsheds

A search of the scientific literature, revealed two surveys of spatial patterns of particulate matter that have been undertaken in New Zealand’s urban areas.

The first involved the use of a handheld Dustrak portable laser photometer to record data related to PM_{10} concentrations at 20 sites in Rangiora and Kaiapoi, near Christchurch (Hamilton et al. 2004). In addition, a Kestrel handheld instrument was used to record data associated with wind speed, air temperature and humidity data (Hamilton et al. 2004). Due to the “stop and go” nature of the sampling, two hours were required to traverse the 20 sites at both towns.

From sampling over five nights, contour plots were constructed based on the 10 measurements taken in each town. The survey identified that highest concentrations were recorded in residential neighbourhoods, which was attributed to burning of solid fuel on domestic heating appliances in those areas.

The second published study of spatial variability in New Zealand used the same instruments and technique at ten sites in Invercargill (Conway et al. 2007). While highest concentrations were observed in the southern residential suburbs, a complex meteorological environment was reported. Therefore, the limited number of observations possible using this technique may have been inadequate to identify the spatial pattern at a sufficiently high enough resolution.

For both of these studies, numerical modelling of air pollution concentrations and meteorology was undertaken using The Air Pollution Model (TAPM), which provided useful information about the distribution of pollution under various topographical and meteorological scenarios. However, the model performance was compromised due to the coarse spatial resolution of the gridded emission data.

Airshed particulate modelling has been conducted for some New Zealand urban areas, including Christchurch (Zawar-Reza et al. 2005), Hastings (Gimson 2006) and Rotorua (Fisher et al. 2007). These models demonstrate the variable nature of particulate concentrations throughout airsheds in New Zealand, depending on factors including the spatial distribution of emissions, topography and meteorological characteristics. For urban areas where airshed modelling has not been conducted, other means of assessing spatial variation are available.

Alternative methods of assessing the spatial variability of ambient particulate concentrations include:

- Very dense networks (VDN). For small scale studies, the use of a large number of sensors deployed densely throughout the study area gives the best description of the spatial and temporal variability in ambient concentrations. The large costs associated with setting up and maintaining a large network for urban areas generally makes this approach impractical for air quality management.

- Remote sensing (RS). The use of satellite information to derive air quality information is a growing field with more data being made available from the last generation of environmental satellites put into orbit (AURA, MODIS). This information is very useful to assess horizontal variability on scales ~10km. However, satellite imagery is not always available for the required period of time and it is dependent on a cloud-free atmosphere that is not always the case.

- Mobile measurements (MM). Advances in miniaturisation have made it possible for air quality instrumentation to be deployed on mobile platforms and be operated whilst on the move. Although relatively labour intensive, this method maximises the utility of single instruments and provides information about the spatial variability of pollutant concentrations. While the temporal variability at greater than weekly timescales is difficult to capture with these kinds of measurements, there are several advantages of the method.

A VDN approach could potentially provide excellent data to support an assessment, however this option has a very high price and to date has proved to be cost prohibitive. At this stage remote sensing doesn’t offer information on a fine enough spatial scale and there are fundamental issues with assessing the concentrations of particulate matter using open path methods.

To date the assessment of how PM_{10} concentrations vary within New Zealand’s airsheds has been limited to airshed dispersion modelling and a number of not-so-dense monitoring networks.

Recent developments in air quality monitoring technology mean that it now possible to build a relatively low cost mobile monitoring system that provides good quality, real time data at high spatial resolution. Such a mobile measurement system could provide data to allow the assessment of the variation of contaminant concentrations across an airshed for the purposes of identifying hot spots for monitoring sites, validating airshed dispersion models, or for input to the development or improvement of air quality management strategies.

1.3 Project Objectives

NIWA has designed and built a mobile monitoring system with the aim of collecting data which will ultimately allow the assessment of how PM_{10} concentrations vary across urban airsheds. There are three phases to this project:

1) System design, build and trial

2) Identify system issues. Enhance and improve system

3) Airshed monitoring, data analysis and assessment of spatial variation of pollution

The mobile monitoring system took a year to design build and trial. This report details the outcomes of phases one and two of the project. The three main objectives of this report are to:

- Describe the system developed by NIWA for assessing spatial variability of airborne particulate matter concentrations in New Zealand urban areas

- Demonstrate the utility and application of data collected by the system

- Make recommendations for improvements to the system

This report aims to demonstrate that the mobile monitoring system is capable of capturing robust and useful data. This report does not aim to provide a detailed assessment of how PM_{10} concentrations vary across any particular airshed.

In addition to collecting PM_{10} data the project was designed to help address two other issues: particulate matter smaller than PM_{10} and to differentiate sources of particulate.

Because home heating is the predominant sources of particulate air pollution within many of NZ’s airsheds, the majority of the particulate pollution experienced in winter is significantly smaller than 10 μm. While currently there are no New Zealand guidelines or standards for particle size fractions smaller than 10 microns, research has been consistently pointing at smaller particles $PM_{2.5}$ and PM_1 as directly linked to the health effects associated with suspended particles (WHO, 2005). For this reason the mobile monitoring system has been developed to monitor $PM_{2.5}$ and PM_1 alongside the AQNES metric of PM_{10}.

The sources of particulate pollution are of interest to air quality managers as this information can help formulate effective management policies. The system is capable of collecting black carbon data which is used as an indicator of whether the source of particulate is fossil fuel (e.g. coal or diesel) or biomass (e.g. wood).

2. Methodology

2.1 Instrumentation

Instruments were located both inside the vehicle and in a rooftop enclosure (Figure 1). A purpose-built conduit was used to bring cables and sample tubes through the vehicle rear passenger window, to and from the rooftop enclosure.

2.1.1 Aethalometer

A Magee Scientific (Berkeley, California) AE22 aethalometer was housed in the vehicle with a sample tube passing through the window conduit into the rooftop enclosure. The aethalometer measures the optical absorption of particles on a filter through which an air stream is drawn. The optical absorption provides an index of mass concentration of ‘Black’ or Elemental Carbon (BC) particles that in urban environments are generally associated with coal or diesel combustion. The aethalometer used in this study uses two wavelengths: 880 nm (near-IR) to quantify BC and 370 nm (UV) that provides a qualitative measure of aromatic organic compounds. The dual wavelength measurement may be used for identification of different sources; for example, vehicle emissions vs. wood smoke from home heating or biomass combustion. Near real time measurements are possible with a time resolution from five second to one hour.

Figure 1: Mobile monitoring vehicle and (inset) rooftop enclosure. Rooftop instrumentation and air intakes are shown.

2.1.2 GRIMM particulate sampler

A GRIMM Model 107 Dust Monitor (Grimm Aerosol Technik GmbH & Co. KG, Germany) was housed in the rooftop enclosure, with power and data cabling via the window conduit. The GRIMM monitor is a low-volume sampler that uses a light scattering technique to continuously measure particle number concentration and size distribution in an air stream. Particulate mass concentrations ($\mu g\ m^{-3}$) are calculated internally by the instrument, making some assumptions about particle density and optical properties. Because particle density information is generally unavailable, it is recommended to calibrate the GRIMM by comparing results with those obtained by another measurement technique (Maletto et al. 2003).

Considering that the main objective of this system is to look at relative concentrations, a full calibration is unnecessary. However, during all the monitoring campaigns, the system was put at the same location as a regulatory monitoring station in the area of interest to assess the range of the difference, if any, between the GRIMM PM_{10} measurements and the official monitors.

The GRIMM is well suited to this mobile application due to the fast response time with near-continuous (six second time resolution), simultaneous measurements of PM_{10}, $PM_{2.5}$ and PM_1 mass values. Because the instrument provides this information on particle size distributions, concentrations of fine particles are identified, which are of particular interest because of the associated health effects.

2.1.3 AirMar PB100 Ultrasonic weather station

A PB100 (AIRMAR Technology Corporation, MILFORD, New Hampshire) ultrasonic weather station was mounted on the system’s rooftop enclosure (Figure 1). The PB100 includes a global positioning system (GPS) that allows the mobile system to record the exact location of measurements as they are logged. The weather station also provides measurements of wind speed and wind direction (both absolute and relative to the vehicle movement), air temperature, relative humidity and barometric pressure.

2.1.4 Data acquisition and accessory equipment

Instruments were interfaced with a Starlog data logger (Unidata Pty Ltd, O’Connor, Western Australia) that stored all data once every two seconds. This interval is shorter than the update interval of all the instruments and it was used to coordinate the signals from the GRIMM (every six seconds), the Aethalometer (every 5 seconds) and the GPS (every 10 seconds). A laptop PC interrogated the data logger in real time and provided an on-screen display of instantaneous data as they were recorded by the logger. The laptop was powered from the vehicle's battery via a dedicated 12 Vdc-240 Vac inverter. The data logger also had a dedicated power supply via a 12 Vdc 7 Ah sealed lead-acid battery.

A Sony HDD video camera was mounted on the vehicle dashboard and was operated throughout the monitoring, to provide a record of vehicles and other particulate sources encountered during each run.

An amber flashing light was operated on the rooftop enclosure for safety purposes. In an effort to provide representative data from the instruments, speed during the monitoring was kept below 40 km/hr wherever possible. However, this was potentially irritating or hazardous to other vehicles when speed limits exceeded 50 km/hr. The flashing amber light was therefore a worthwhile safety device to warn other drivers that the vehicle was involved in an activity other than regular transport.

2.2 System configuration and operation

Inside the vehicle, the Aethalometer enclosure, including the data logger and the main power inverter, was positioned on the rear seat, directly behind the driver. The laptop PC, continuously displaying data in real time, was also positioned on the back seat for diagnostic purposes by the operator. Four 12 Vdc batteries were placed in the rear of the vehicle and were used to power instruments.

The system was operated by two people. One person was driving while the second assessed the performance of the instruments, assisted with navigation and notified the driver when it was necessary to stop for maintenance.

2.3 Locations of experimental trials – winter 2007

During winter 2007, trials of the system were conducted in Alexandra, Auckland and Christchurch (Figure 2). Table 1 shows the dates and when the trials were performed and the number of measurements runs.

Table 1:. Measurement dates of the winter 2007 trials.

	Measurement dates	**Number of runs**
Alexandra	08 June to 03 July	8
Auckland	26 July to 09 August	4
Christchurch	23 to 30 August	3

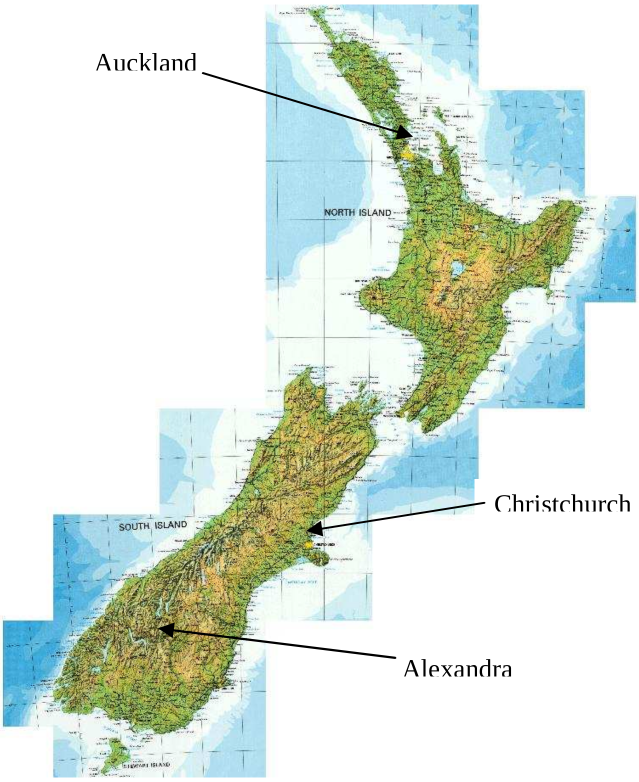

Figure 2: New Zealand map showing locations of trials

2.3.1 Measurement routes

To obtain the most information from the monitoring runs conducted in all three cities, different routes were selected for each urban area with two main objectives: spatial variability and hot spot identification.

One of the main advantages of mobile measurements is the ability to assess spatial variability of ambient concentrations. However, as it takes time to complete a route, the concentrations may change between the start and end of a measurement run. On the other hand, it is desirable to encompass a large area so that spatial variability may be identified by the instruments and potential hot spots are identified throughout the entire airshed. Therefore, it was important to either choose relatively small routes or to monitor at times of the day when the PM_{10} concentrations are relatively stable over the time it takes to complete a monitoring circuit. Either of both of these strategies will help minimise the effects of the temporal variation of ambient concentrations.

As a compromise between these two conflicting requirements, the routes were kept shorter than one hour in time and were travelled twice for each measurement run (i.e. once the first run was finish, an identical run was performed immediately after).

For the tests performed in Alexandra, Auckland and Christchurch, several routes were selected to satisfy different objectives. Details and maps showing the specific routes are contained in the Appendix: Monitoring route maps. Sections 2.3.2 and 2.3.3 offer general descriptions of the routes used.

2.3.2 Short circuit

Once a relevant area of the city was identified by local knowledge, a short (less than 10km) circuit was developed that included the identified area. This circuit was intended to be completed in less than 30 minutes so that two “laps” may be completed in one hour, to obtain values comparable with the time resolution of the air quality monitoring stations in the area.

Considering the size of the urban area in Alexandra, the short circuit was defined as a grid-like pattern covering all main roads in the city, and the north and south exits of the city. For Auckland and Christchurch, the short circuit was selected to cover part of the central part of the cities. In Christchurch this circuit included most of the CBD and a short stop (5 - 10 min) next to the Environment Canterbury air quality monitoring station in Coles Place. In Auckland, the short circuit covered the areas between Eden Terrace, Mt Roskill and Royal Oak, including passing by the air quality monitoring stations of Khyber Pass and Kingsland operated for the Auckland Regional Council (ARC).

2.3.3 Long circuit

Only in Christchurch and Auckland are the urban areas sufficiently large to warrant longer circuits, to capture a larger scale spatial variability. However, for these routes to be useful, they should be sufficiently long to capture the spatial variability but short enough so that ambient concentrations do not change considerably over time at each location. It was considered that a route of one to two hours would be useful.

In Auckland, the long route followed the Northwestern Motorway (SH16) from Grafton to Lincoln Road, turning then south towards Henderson and then east to Royal Oak, to finish again in Grafton (see Appendix for details). This route passed near ARC’s air quality monitoring stations at Lincoln Rd, Glen Eden and Khyber Pass Rd.

In Christchurch, the long circuit started at Riccarton and followed a quasi-circular route passing through the areas of Cashmere, Woolston, New Brighton, Burwood, Papanui and back to Riccarton via Ilam. During this trip, a short stop (~5 min) was made next to the Environment Canterbury air quality monitoring station at Woolston.

3. Results and discussion

This section presents the results of the monitoring trails that were undertaken in Alexandra, Auckland and Christchurch. The trials were undertaken with the specific and simple aims of assessing the utility of the system, assessing the quality of data being collected and identifying potential improvements to the system. The data collected in phase one of the project and the results presented in this section of the report are not intended to be used for the purposes of assessing air quality within those specific airshed nor to aid the development of any air quality management policies. The results presented below should be treated as illustrative examples of what the system can achieve. It is anticipated that when phases two and three of the project have been complete the data collected will be of a quality that they can be used to assess air quality within airsheds and to aid the development of air quality management policies.

3.1 Spatial Variation of PM_{10} concentrations in three urban areas

It is important to note that the findings presented in the following sections are only intended to provide illustrative examples of the way the data collected by the mobile system can potentially be used. The conclusions drawn here are subject to the limitations of the short record of trial data collected and at best can be treated as preliminary. A much more intensive and specifically designed mobile measurement campaign would be required to provide conclusions upon which air quality management strategies could be based.

3.1.1 Alexandra

PM_{10} concentrations measured on the 8 runs performed in Alexandra were averaged for the area around the town and are plotted in Figure 3. Results show that, during the measurement period, concentrations did vary significantly across the township. Unsurprisingly, the lowest concentrations were measured outside the town limits, particularly on the eastern exit. On the other hand, higher concentrations were measured in the south western part of the centre of Alexandra where Otago Regional Council's monitoring site is located. This monitoring station recorded relatively high levels with an average of 50 $\mu g\ m^{-3}$ for the campaign and concentrations reaching to more than 80 $\mu g\ m^{-3}$ during three days (27th and 28th of June and 3rd of July).

Two other hot spots were identified by high concentrations of $PM_{10.}$ One is in the north-eastern part of the town and the other to the north-west exit of Alexandra. More details about these hot spots are given later in this report.

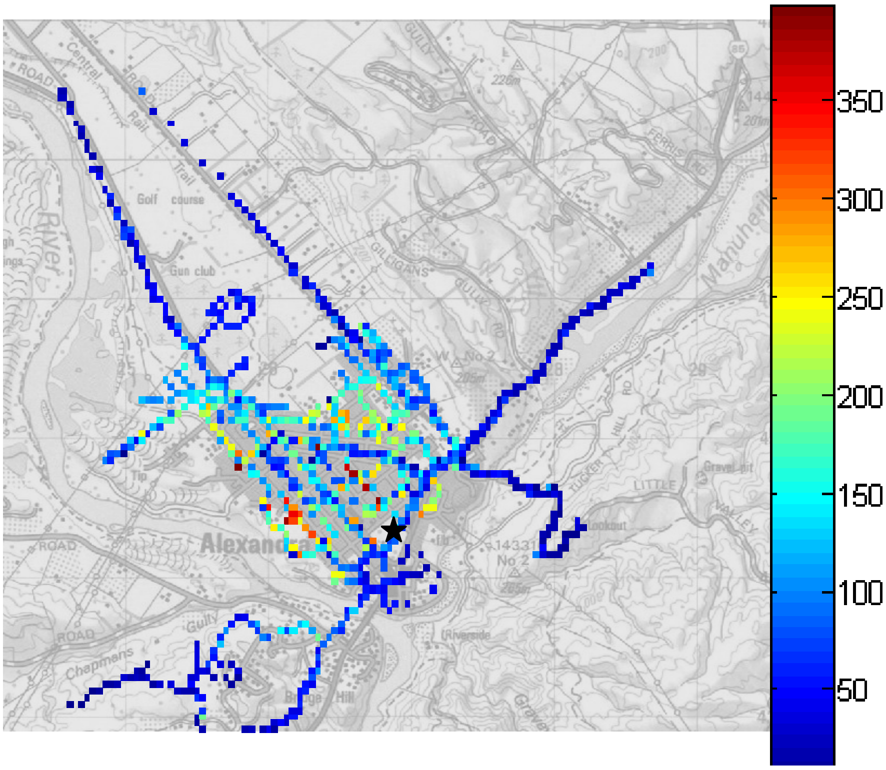

Figure 3: PM_{10} concentrations (μg m^{-3}) averaged for all the runs (8) undertaken in Alexandra. The black star indicates the location of ORC's air quality monitoring station.

3.1.2 Christchurch

PM_{10} concentrations measured in Christchurch were averaged over the 3 runs performed and are plotted in Figure 4. Results show that concentrations did vary significantly across the City. Generally the lowest concentrations were monitored when driving near the Heathcote-Avon estuary, New Brighton and along the semi-rural area of Queen Elizabeth Drive in the northern area of the city.

Relatively high PM_{10} concentrations were consistently observed in Addington, Spreydon, Cashmere, Woolston and the eastern CBD area of Fitzgerald Avenue.

It is important to note that the concentrations measured during this monitoring campaign were taken during late evening and night and may not represent the horizontal variability of the concentrations at other times of the day. The monitoring was undertaken late in August and during nights with relatively low concentrations of PM_{10} compared to the peak nights recorded earlier in the winter. In fact, the 24 hour average PM_{10} concentration measured by the monitoring network in Christchurch was 25 μg m^{-3} on the 23rd of August and around 20 μg m^{-3} on the 29th and 30th of August, compared to the maximum of 120 μg m^{-3} observed on the 23rd of July. Given these limitations, it is unlikely that the data collected are indicative of peak concentration hours on high pollution nights.

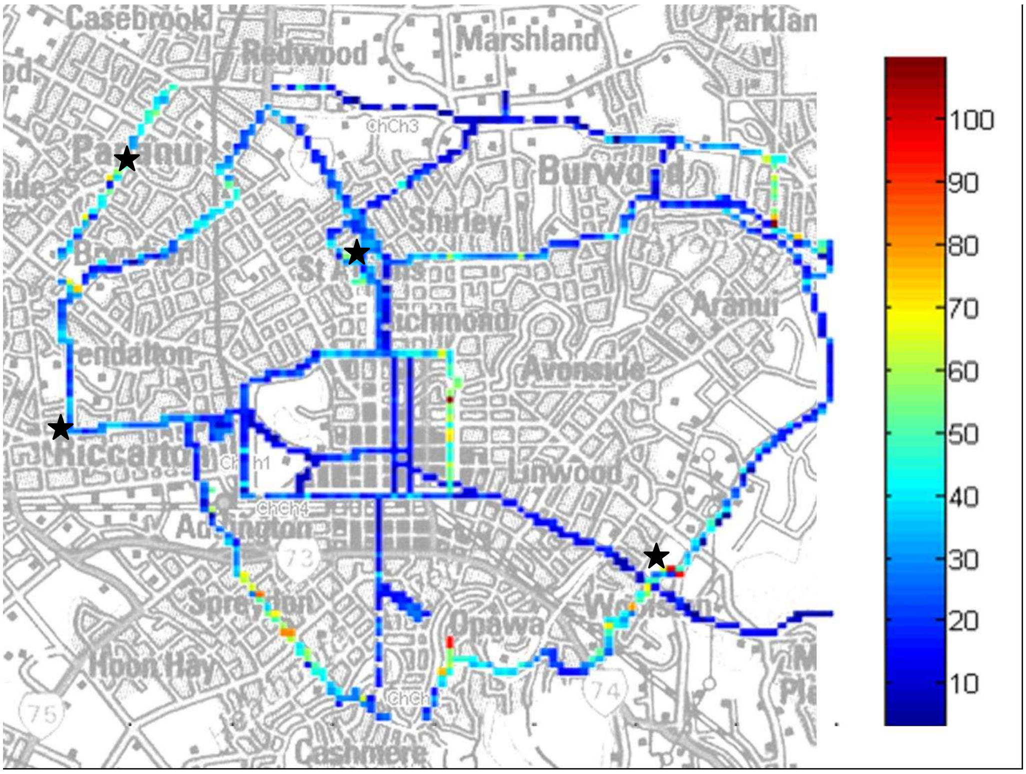

Figure 4: PM_{10} concentrations (µg m^{-3}) averaged for all the runs (3) undertaken at Christchurch. Black stars indicate the location of three Environment Canterbury and one MfE monitoring sites.

Notwithstanding these limitations, the mobile monitoring data suggests that <u>for the nights that were monitored,</u> the Woolston site was well located to pick up high concentrations of PM_{10} while the monitoring site at Coles Place was located in an area of relatively low concentrations. Some high concentration areas were identified in locations that are not currently covered by air quality monitoring stations. In summary, the limited data that has been collected (3 nights) suggests that at least one of the monitoring sites run by ECan was ideally located to pick up elevated concentrations of PM_{10}.

3.1.3 Auckland

PM_{10} concentrations measured on the 4 runs performed in Auckland were averaged for the area shown in Figure 5. The routes marked corresponded to the “short circuit” (right side loop) and “long circuit” (loop covering the whole area).

Results show that, during the measurement period, concentrations were generally lower than those measured in Alexandra and Christchurch. This was probably due to the combined impacts of frontal systems that passed through Auckland during the measuring campaign and a lower rate of use of domestic solid fuel burners. The weather patterns experienced during the campaign have relatively strong winds in connection with rain events, improving the dispersion capabilities of the airshed and thus lowering the ambient concentrations. Furthermore, the downtown monitoring site of Khyber Pass Road reported an average of 34 μg m^{-3} for the campaign, which is about 70% of the highest 24 hour average reported by the same site.

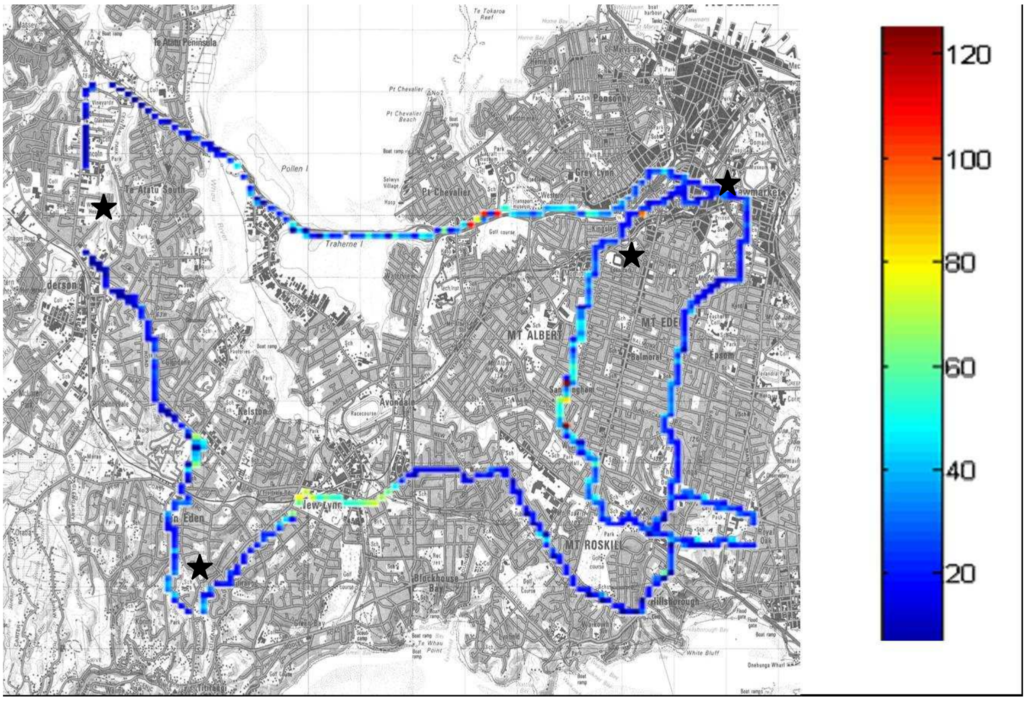

Figure 5: PM_{10} concentrations (μg m^{-3}) averaged for all the runs (4) undertaken in central Auckland. The black stars indicates the location of ARCs air quality monitoring stations.

Nevertheless, variation in PM_{10} concentrations across the city was observed and a number of relatively high concentration areas were captured by the measurements. Relatively high concentrations of PM_{10} were monitored in Kelston, New Lynn and Dominion Road, between Mount Albert and Wesley. Another feature worth mentioning is the pattern measured along the Northwestern Motorway with high concentrations closer to the CBD that decrease after Te Atatu.

Similar cautions must be applied to the Auckland data to those noted for the Christchurch data. To reiterate, given these limitations, it is unclear whether the data collected are indicative of those that would be measured during peak concentration hours on high pollution periods. However, the mobile monitoring data collected suggest that for the nights that were monitored, the location of ARCs monitors did not coincide with the four identified hot spots.

It is worth noting that the variability in concentrations in that part of the city is possibly related to the small scale topography of the area that makes several small valleys that may behave independently from each other in terms of the atmospheric dispersion.

3.2 Further analysis of data collected in Alexandra

A more detailed analysis of the measurements taken in Alexandra is presented here to demonstrate the information that it is possible to extract from a mobile measurement campaign such as this.

Alexandra was chosen for the initial demonstration mainly because of its small size, high particulate concentrations during winter and relatively well defined emission sources. Alexandra's small size allowed mapping of particulate matter concentrations over most of its area. Furthermore, the low number of traffic sources means that the emission field is relatively stable in time.

Unless explicitly indicated, in this section all the analysis will be based on the composite dataset from the eight runs performed in Alexandra.

As is noted in Section 3.1, the findings presented in the following sections are only intended to provide illustrative examples of the way the data collected by the mobile system could potentially be used. The conclusions drawn here are subject to the limitations of the short record of trial data collected and at best can be treated as preliminary. A much more intensive and specifically designed mobile measurement campaign would be required to provide conclusions upon which air quality management strategies could be based.

3.2.1 Different size fractions of particulate matter

PM_{10} is of key importance as it is the only fraction of particulate matter that is regulated by the AQNES. However, as indicated before, recent research consistently points towards smaller fractions of particulate matter as better indicators of the health impacts of airborne particles.

Figure 6 shows the concentration fields of PM_{10}, $PM_{2.5}$, PM_1 and black carbon (BC) as an average of all the runs performed in Alexandra.

The fields in Figure 6 show similar patterns of high and low concentrations for all the measures. High concentrations in the south west of the city and low concentrations in the outskirts of Alexandra are apparent for PM_{10}, $PM_{2.5}$, PM_1 and BC. Also, it is interesting to notice that even while one should expect $PM_1<PM_{2.5}<PM_{10}$, the values are not too different when plotted in a similar colour scale.

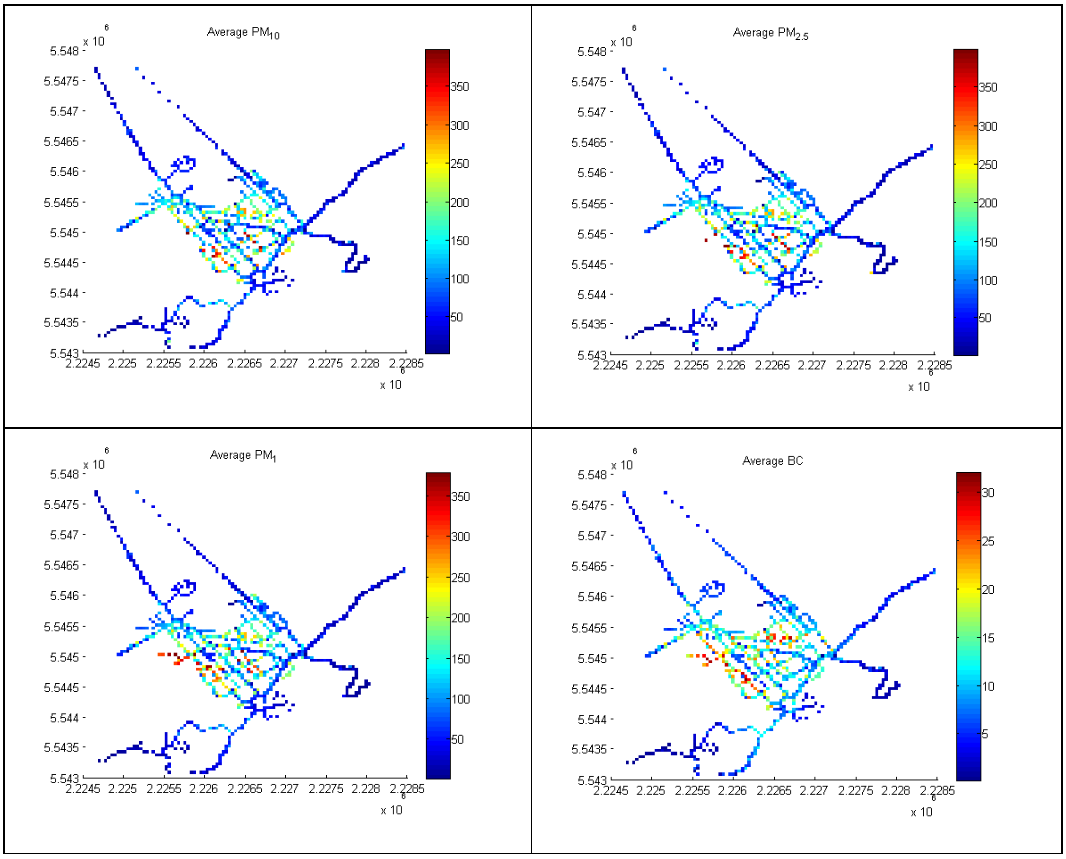

Figure 6 PM_{10}, $PM_{2.5}$, PM_1 and BC concentrations (µg m^{-3}) averaged for all the runs undertaken in Alexandra. Note that the map coordinates are NZMG. The colour scale represents the measured concentrations.

Of particular interest are the ratios between PM_1 and PM_{10} and between BC and PM_1. The PM_1:PM_{10} ratio (Figure 7) provides information about the relative abundance of the coarse and fine fraction of PM. The coarse fraction usually corresponds to wind-blown dust, re-suspended road dust or any other mechanically derived or suspended source of particulate. Depending on the local abundance of a dry soil source, the potential for the associated dust to be resuspended by the action of traffic, and the emission of tyre and brake wear products the coarse fraction could be a major component of PM_{10} with its size typically between 5µm and 10µm. On the other hand, combustion sources are normally associated to the fine fraction of PM because its particulate emissions are mostly below 1µm in size (Seinfeld and Pandis, 1998). Therefore, small PM_1:PM_{10} ratios are associated to a large impact of dust, while large ratios are usually indicative of combustion related aerosols.

As shown in Figure 7, the PM_1:PM_{10} ratio is very high throughout the Alexandra area. This indicates that the major source of PM_{10} is combustion and that in fact most of ambient aerosol mass is contained in particles smaller than 1µm. On the other hand, only small areas in the west and south-east of the town have PM_1:PM_{10} ratios lower than 0.6 which is an indicator of areas where mechanically derived dust is a major component of particulate matter.

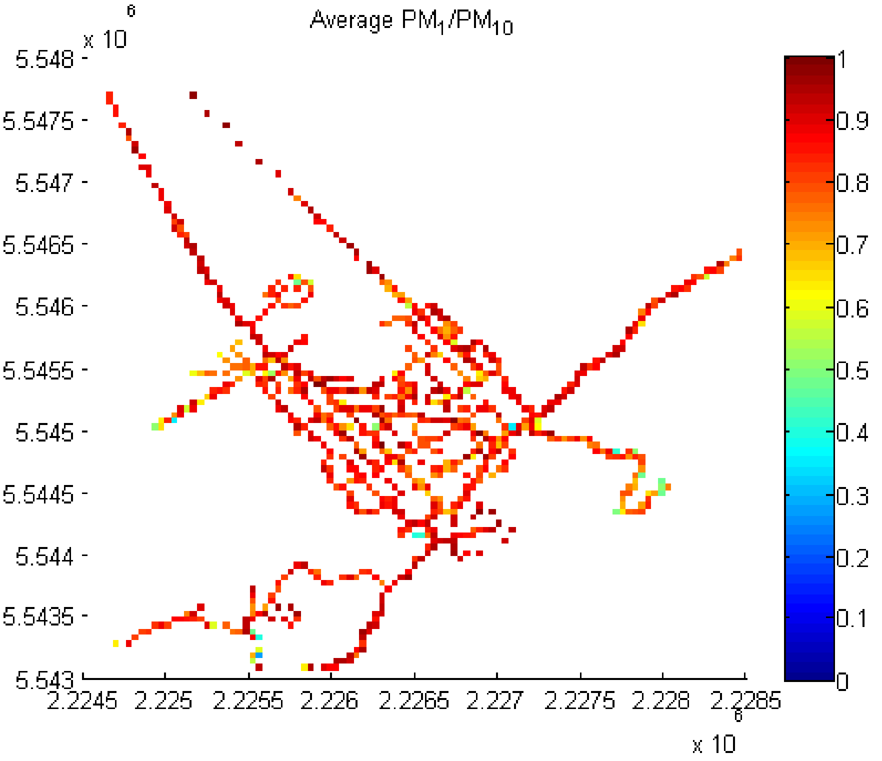

Figure 7. PM_1:PM_{10} ratio averaged for all the runs undertaken in Alexandra. Note that the map coordinates are NZMG. The colour scale represents the measured concentrations.

Nevertheless, one must bear in mind that the results presented here are only for the period where measurements were taken (evenings and night) and may not represent the distribution of fine particles at other times of the day. Furthermore, as addressed in Section 4, there is an unknown impact of the driving speed on the performance of the sampling inlet leading to a potential underestimation of the coarse fraction when moving relatively fast.

3.2.2 Black carbon – an indicator of source type

Information about other particulate measures, particularly black carbon (BC), can provide clues about the types of emission sources present in the area. As BC is emitted at different intensities from different sources, a map of the relative abundance of BC in the particulate matter would help map different combustion sources in the area.

Even though it is possible to find black carbon in the coarse fraction of PM, it is not normally associated with coarse dust and it is used therefore as a tracer of combustion sources. Only in areas where coal is handled in open spaces it is possible to find black carbon particles of sizes large than 1μm. Therefore, the BC:PM_{10} ratio (Figure 8) could provide clues about the distribution and type of combustion sources in the area.

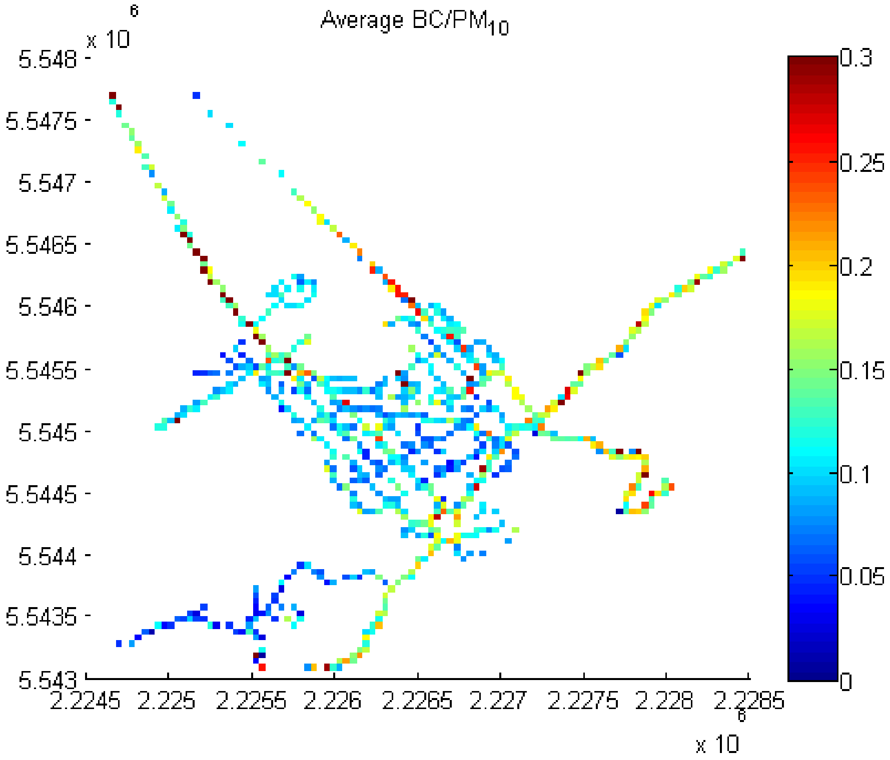

Figure 8. BC:PM_{10} ratio averaged for all the runs undertaken in Alexandra. Note that the map coordinates are meters NZMG. The colour scale corresponds to the ratio.

Not all combustion sources produce the same amount of black carbon. Diesel combustion has been shown to produce about 10 times more BC per unit of fuel burnt than petrol engines (Imhof et al, 2005). Wood combustion aerosols tend to be less black and absorb less light than fossil fuel combustion (Olivares et al, 2008). Therefore, areas with high values of BC:PM_{10} ratio would indicate areas where fossil fuels are dominant while areas with smaller ratios may be associated with wood burning activities.

Figure 8 shows that there are relatively large areas in Alexandra where the BC:PM_{10} ratio is relatively low, indicating areas where wood burning may be the relevant source of carbonaceous materials. On the other hand, high values of BC:PM_{10} ratios were observed along the mayor roads indicating probably that diesel traffic also has an impact on the observed BC concentrations. Of particular interest is the north-west exits of the town where there are areas of high BC:PM_{10} ratios that do not extend far from the town. This is different from what is observed in the north-east to south-west link where high ratios are observed throughout. One explanation may be that those roads are more used by diesel vehicles. However, because the measurements were performed during late evenings and nights, there was very little traffic and therefore, it seems likely that the combustion of coal in that area is responsible for those high BC:PM_{10} ratios.

Returning our attention to the hot spots identified in the PM_{10} field (see section 3.1.1). Figure 8 shows that the two high concentration areas identified have relatively high BC:PM_{10} ratios, indicating that either traffic or coal burning are likely to be significant sources of particulate in those areas.

Nevertheless, the same warning indicated for the PM_1:PM_{10} ratio is valid here that the results presented here may not represent the distribution of small particles at other times of the day.

3.2.3 Ultraviolet and Infrared measurements of Black Carbon

The mobile monitoring instruments measures BC at two different wavelengths, Ultraviolet (UV) and Infrared (IR). However the current data acquisition set up makes the comparison between the UV-BC and the IR-BC signals difficult, particularly putting them on the same map. However, a preliminary analysis of this data was performed for **one** of the runs in Alexandra (03 July 2007) when the 24 hour PM_{10} concentration was highest as reported by the monitoring site in the town.

The difference between UV-BC and IR-BC (Δ-C) has been used as an indicator of aromatic compounds within the black carbon (Allen et al, 2004). Because wood burning smoke contains a larger fraction of aromatic compounds than other combustion sources, it is possible to use Δ-C as a qualitative tracer for wood burning.

Figure 9 shows the horizontal distribution Δ-C (left hand plot) and black carbon (right hand plot) in Alexandra. Note that even though the colour scale is the same for both plots, only the BC plot presents quantitative information. The Δ-C plot should be read only as relative concentrations.

The main feature observed in Figure 9 is that the areas of high black carbon concentrations are also associated with high Δ-C values indicating that wood burning is probably a major contributor to the observed black carbon concentrations. However, the relatively high BC concentrations observed to the north of the central part of the town correspond to an area of relatively low Δ-C values and therefore where sources other than wood burning contribute to the carbonaceous aerosols. This is consistent with the BC:PM_1 plot presented earlier that indicates that the north part of the town may be impacted by particulate matter discharged from the burning of coal as well as wood.

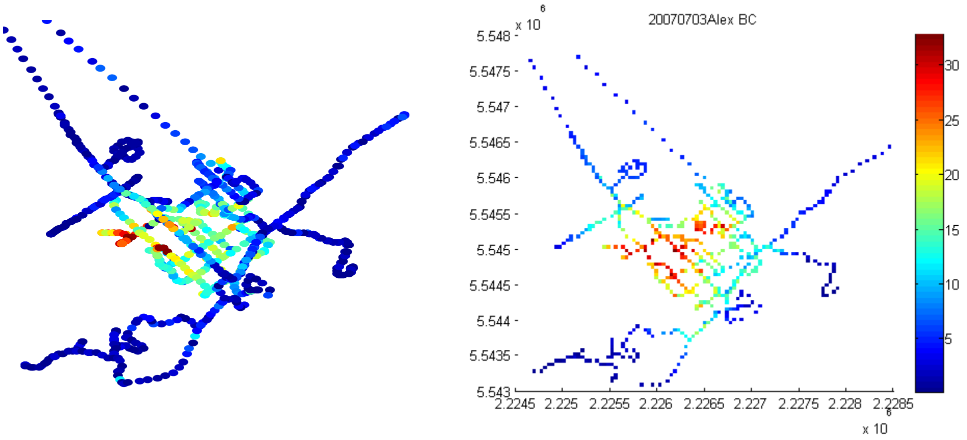

Figure 9: Δ-C and black carbon horizontal distribution in Alexandra for the measurements taken on July 3rd 2007

3.2.4 Measurements taken at the Otago Regional Council monitoring site

One of the key issues when deploying non-regulatory approved measurement methods, such as those employed in this mobile monitoring system, is their performance when compared to standard technologies.

As indicated before, the GRIMM PM monitor uses light scattering to determine particulate matter concentrations. A similar, but not identical, monitor from GRIMM recently gained regulatory approval in the EU. The main differences between the EU approved system and that used in this system is the sampling conditioning and calibration protocol. The approved system includes sample heating and drying while the GRIMM used in this study does not include sample conditioning. Furthermore, the USEPA has not granted regulatory approval to any of the GRIMM monitors. The Otago Regional Council operates a Beta Attenuation Monitor (BAM) at a permanent site in Alexandra. The BAM instrument is an approved method for monitoring PM_{10} under NZ's AQNES.

As it was indicated before, no calibration of the GRIMM was performed before the study was undertaken because the main objective was to investigate the relative concentrations in different areas of the city. Nevertheless, it is very useful to have an idea of the level of agreement between the PM concentrations measured by the GRIMM and the regulatory method BAM (Beta Attenuation Monitor). To undertake this comparison, the mobile system was placed alongside with the ORC monitoring station at Alexandra for 120 hours in late June and early July. Figure 10 shows a comparison of the measurements of both instruments during this period.

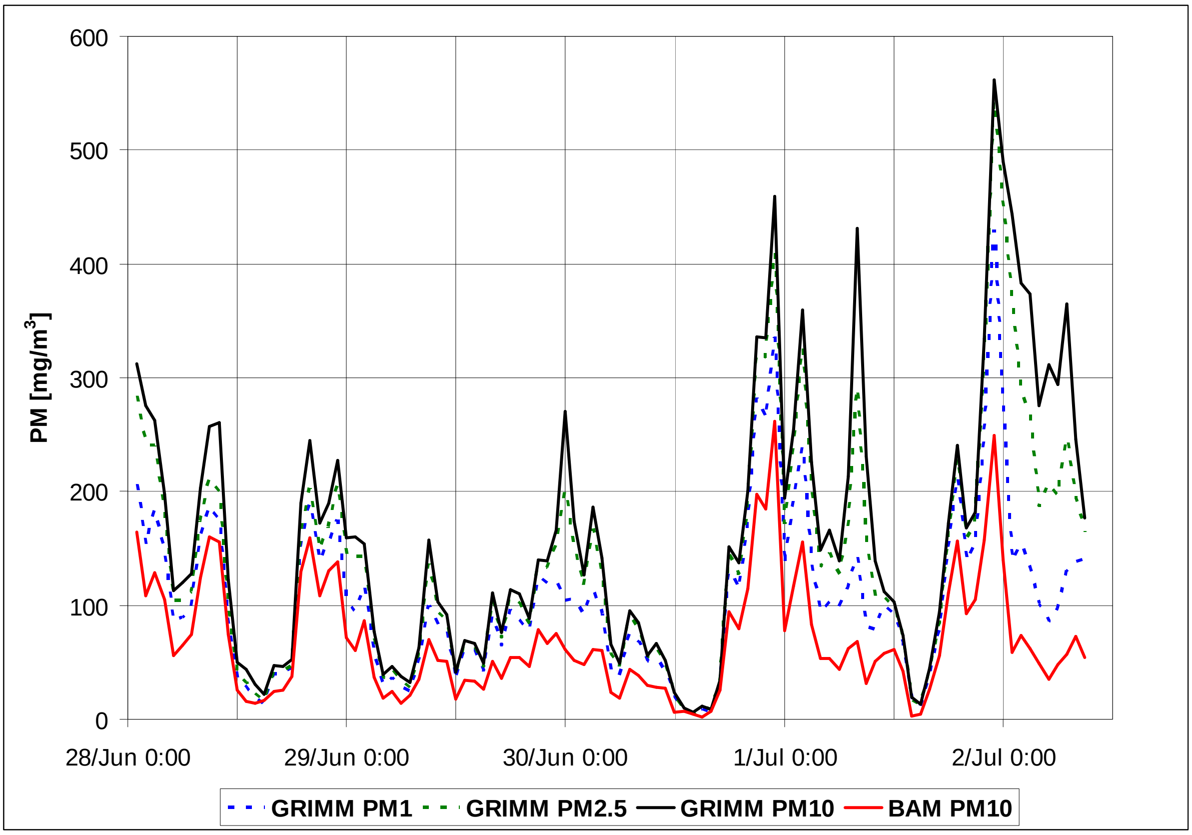

Figure 10: Time series of the PM_{10} concentration measured by ORC's BAM at Alexandra and the co-located mobile platform.

Figure 10 shows that there is an excellent correlation between the measurements taken by the GRIMM and BAM, however the mobile system seems to give PM_{10} concentrations up to twice as high as those measured by the BAM. The PM_1 signal from the GRIMM matches the BAM PM_{10} concentrations more closely that the GRIMM PM_{10} data. The correlation between the GRIMM's PM_1 and the BAM's PM_{10} is more than 0.9. This result suggests that the GRIMM may be sizing the particles differently than the BAM.

As described above, the GRIMM is an optical instrument that bases its particulate measurements in the light scattering properties of individual particles. Therefore, its definition of PM_{10} is slightly different to that used in regulatory standards. The GRIMM identifies the *optical size* of a particle. For example, at a particle classified by the GRIMM as having 10µm in diameter means that it has scattering properties equivalent to a 10µm spherical latex particle. On the other hand, the BAM has a PM_{10} inlet attached and therefore the size in this case is the *aerodynamic size*. This difference means that the size fractions identified by the GRIMM are not necessarily the same as those defined *aerodynamically*. These two sizes are normally very similar but there are situations where they differ.

Unpublished data from a study in a subway in Stockholm-Sweden (C. Johansson[1] pers. comm..) indicated that an optical particle spectrometer, similar to the GRIMM, was unable to properly size iron particles (from the wear of train wheels) because of the high reflectance of those particles that makes them appear larger than they actually are. Black particles are also optically active, absorbing within the visual spectrum. Therefore, it is possible that the GRIMM under-estimates the size of a black particle relative to its aerodynamic size because its scattering is reduced by absorption. However, without a detailed particle size distribution and a performance check of the inlet of the BAM, it is not possible to identify the source of the differences between the two instruments.

The difference in PM_{10} measurements made by the BAM and GRIMM are significant and it would be beneficial to able to explain with certainty why these differences occur. This issue will be investigated further if an opportunity to undertake co-located mobile system and AQNES compliant measurements at additional sites is available for future campaigns. However, because the analysis of data presented in this report relies on the relative differences of the measurements made by the mobile system, the absolute differences between BAM and GRIMM PM_{10} measurements is not considered critical to the results and conclusions presented in this report.

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[1] Christer Johansson is an Associate Professor at the Department of Applied Environmental Sciences - Stockholm University and also a environmental officer at the Stockholm Environmental Agency. (christer.johansson@itm.su.se)

4. Assessment of the operational features of the mobile monitoring system

4.1 Issues encountered

4.1.1 Air pollution episodes

One of the key questions that this system intends to inform is “what is the horizontal distribution of air pollution during high concentration episodes?” and there are a few issues that need to be considered when designing a monitoring campaign with that as an objective.

Particularly relevant for answering the “geographical distribution” question is the number of routes taken and the meteorological characteristics of the days/nights when measurement takes place.

As indicated before, this report intends to show the kind of information that is available from a mobile monitoring system and because of that the focus is on the capabilities of the system as the relatively small number of days/runs performed in the cities does not allow for wide generalisation of the results.

For more comprehensive campaigns, care must be exercised when choosing the dates and time of the measurements that should reflect the objective of the particular monitoring campaign.

4.1.2 AQNES compliant monitoring

As shown before (see Figure 10), the absolute concentrations measured by this mobile system differ from approved methods (BAM) and the reason behind that disagreement is not clear.

However, it is important to note that this monitoring system is not intended as AQNES compliant and that the main value of the information relies on the relative concentrations measured by the system in different locations. Therefore, while it would be beneficial to have the mobile monitoring system co-located with an AQNES compliant monitor, it is not necessary in terms of identifying variations in the PM_X and BC concentration field in urban areas.

4.1.3 Impact of driving speed

Absolute wind speed (U_{abs}) is the sum of vector components of both vehicle speed and ambient wind speed. Ratios of PM_1:PM_{10} appear to be affected by the magnitude of U_{abs}, with lower ratios (i.e. relatively more coarse particles) being observed at lower U_{abs} (Figure 11). This suggests that driving speed may influence the particle size ratios and total mass of particulate observed by the system.

The relationship observed between PM_1:PM_{10} ratio and absolute wind speed points towards a shortcoming of the particle sampling system. Because of the variability of the ambient concentrations of aerosols, if the aerosol is being sampled correctly we should expect the PM_1:PM_{10} ratio to be uniformly distributed and not shown any kind of pattern when compared to absolute wind speed. Figure 11 shows that the PM_1:PM_{10} ratio appears to be shifted towards high values for high absolute wind speeds and to be uniformly distributed for low absolute wind speeds. This behaviour points towards the inlet being unable to sample all the particles at high wind speeds. The fact that the PM_1:PM_{10} ratio is higher at high absolute wind speed indicates that when the inlet is experiencing strong wind, larger particles tend not to be sampled whereas smaller particles are still being sampled. This relationship was also evident at Christchurch and Auckland (Figure 12).

This observation can be explained by the fact that at higher wind speeds larger particles (with greater mass) have greater inertia. This means at high U_{abs} rather than being sucked down into the sample line the large particles pass undeviated over it. The smaller particles (with smaller mass) have lower inertia and even at high U_{abs} they are drawn into the sample line.

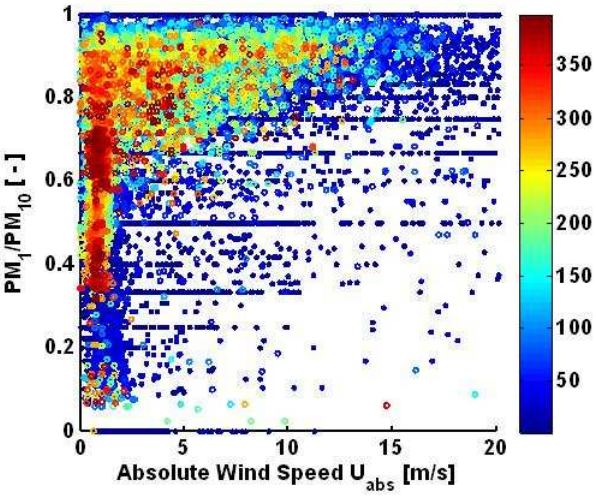

Figure 11: Ratio of PM_1:PM_{10} vs. absolute windspeed (U_{abs}) for data collected at Alexandra. The colour scale and the size of the circles indicate the PM_{10} concentrations.

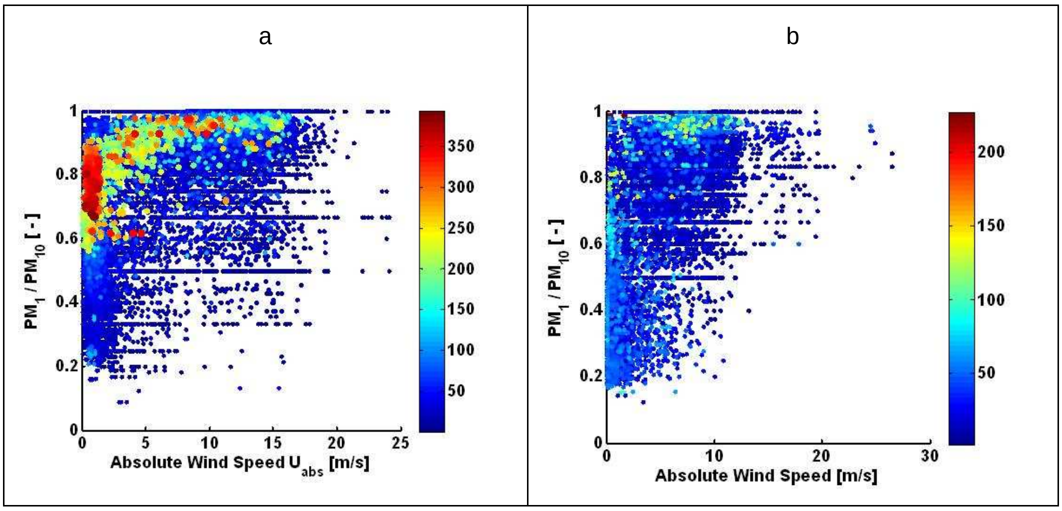

Figure 12: Ratio of PM_1:PM_{10} vs. absolute windspeed (U_{abs}) for all the data collected at Christchurch (a) and Auckland (b).

However, it is also possible that different particulate size fractions do occur in places where traffic itself is travelling at different speeds. For example, lower wind speeds may be associated with times when the mobile platform was stopped at traffic lights and may possibly be capturing a higher mass of resuspended road dust or vehicle exhaust from vehicles travelling through green lights on the perpendicular roadway. With the current information it is not possible to isolate one or the other explanation and therefore further investigation of this issue is necessary.

To attempt to overcome the apparent loss of PM_{10} at high U_{abs} the intakes of the mobile monitoring system will be redesigned to facilitate sampling more iso-kinetically than the current system allows.

4.1.4 Data Acquisition (DAQ) system

The concentrations measured by a mobile system are very sensitive to the immediate surroundings of the platform. Strong tailwind can blow the sampling car emissions towards the inlet, exceptional events such as heavy polluting vehicles encountered in the road or big localized plumes can also affect the representativeness of the measurements. Therefore, a system to manually flag events in the data record would be valuable and add information to the analysis of the results.

As indicated before, the present data logger configuration can only accept analogue signals from the instruments and can’t control any of the instruments’ operation parameters. As the operating conditions of a mobile platform change very fast, it is necessary for the system to be able to react to such changes and therefore there is a need for the DAQ system to be able to fully communicate with the instruments.

Currently if any changes need to be made to the instrumentation, the vehicle must be stopped and the changes made manually to the instrument.

Incorporating the DAQ system into the mobile monitoring equipment would allow these two issues to be resolved. In addition to this, a DAQ instrument control would offer the following advantages:

- Improving the time resolution of the recorded signals;
- Flexibility to log events associated with the data;
- Faster reaction times to changes in the instrument set ups as required by the monitoring situation;
- Have a single interface and alarm display for the operator to quickly identify potential problems with the system;
- Avoiding time that is otherwise required to retrieve and format data; and,
- Elimination of one component (ie. data logger) and associated power supply that have potential to fail;

4.1.5 Power supply

Multiple power supplies create a greater probability that power failure will occur to equipment. Separate power supplies were used in the present configuration for:

- Datalogger
- Aethalometer and AirMar
- Grimm
- Flashing light
- Laptop PC
- Video camera

At times power was lost to system components. For example, the 12 Vdc-240 Vac inverter failed on one of the Christchurch routes and laptop power was lost while a repair was performed. It is also cumbersome, while engaged on other tasks, for the operator to monitor many battery voltages for multiple components and there is potential for failure to observe battery power supplies as they approach exhaustion.

As a safety measure, it would also be useful to have a switching system, such that each component can be easily toggled to avoid unnecessary wear of delicate electronic systems during the set up phase.

There are numerous advantages to be achieved by integrating the individual power supplies to a centralised system.

4.1.6 GPS elevation data

To reliably and accurately obtain elevation data, a GPS upgrade is required. Regular GPS receivers rely solely on satellite information to obtain the vertical position but for this method to work accurately it is necessary to have a satellite as low in the horizon as possible. This is not normally the case in urban environments where buildings hide the horizon from the GPS receiver and the instrument is forced to operate with only overhead satellites. More specialized units include a barometric altimeter that can accurately measure the vertical position even with no satellite lock. Such an instrument would be especially valuable for investigation of small scale topographical influences on PM distribution.

4.1.7 Instrument interfacing

Using the existing data logging system requires interfacing via analogue outputs from instruments. This is far from ideal because both the Grimm and the Aethalometer have a very large range that when translated into a 0 to 10 V analogue signal suffer from bit-resolution problems on top of those within the instrumentation.

4.1.8 Cabling

It would be useful to upgrade the cable entry conduit so that the system may be mounted on any vehicle. The current cable entry system is designed as a custom fit to the rear window of a Ford Territory vehicle.

4.1.9 Rooftop enclosure

The current rooftop enclosure is a “chilly-bin” that was used for prototype development. A purpose-built enclosure would be appropriately robust and could be designed to facilitate easier access to instrumentation.

4.1.10 Video footage

It was considered that the video camera information is superfluous to the system. Inclusion of the video camera adds another component that requires operation and monitoring by the observer. However, it is questionable whether the video footage is useful. To capture highest pollution concentrations, monitoring is invariably undertaken at night, with a consequence that video footage is often of poor quality due to inadequate lighting. It is also very time-consuming to download and save the video files to DVD for storage. The sheer volume of footage also makes it unlikely that it will ever be utilised and an event logging system might be a more useful approach.

4.1.11 GRIMM upgrade

Data from the Grimm would be more useful and robust if the full 32 channel particle size distribution was recorded instead of the three channels recorded. This problem can only be overcome with a customised software upgrade from the manufacturers of the GRIMM instrument. This possibility is being investigated.

It is also understood that the most recently manufactured Grimm samplers have nafion driers that overcome water vapour interference, so that data are comparable with those from the reliable TEOM FDMS (pers. comm. Delbert Eatough[2]).

4.2 Potential upgrade solutions

With a finite budget available for system improvements, it is considered that the following upgrades would offer the greatest value:

4.2.1 Adapt sample tube inlet

Consideration was made of possible solutions to overcome the problem of apparent coarse fraction PM loss due to vehicle speed:

(a) Maximum absolute wind speed could be determined, above which unacceptable loss of coarse PM occurs. Vehicle speed might then be regulated so that absolute wind speed never exceeds this threshold. It is unlikely that this offers a practical solution, because driving slower than 40 km/hr will cause aggravation to other road users. Moreover, when high ambient wind speed (u) is encountered, the threshold absolute wind speed might be achieved

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[2] Personal Communication with Delbert Eatough, Department of Chemistry and Biochemistry Brigham Young University, Provo, Utah

only at a very low vehicle speed (or in the case of $u > 40$ km/hr, the vehicle would need to be stationary or reversing to achieve the threshold U_{abs}!)

(b) A full isokinetic sampling train (similar to that used for aircraft-borne measurements) could be developed so that a very high flow is drawn through the inlet and the Grimm and Aethalometer sample tubes are sub-sampled from the main tube. This is the best possible solution and would allow the system to operate at any vehicle and wind speed. However, this solution is also the most expensive and complex to implement and it would put a higher burden on the power source because of the large airflow requirements of the main inlet.

(c) Rather than using a vertical sample tube inlet, a 90° bend could be used to construct a “hockey-stick” shaped inlet, with the entry positioned facing the same direction as the vehicle.

It is idealistic to expect solution c) to completely overcome the loss of coarse fraction PM, however, it is an inexpensive option that is worth trialling as a pragmatic approach to mitigating the effect of U_{abs}. Using the hockey stick inlet in combination with ensuring that the vehicle stays below or as close as practical to U_{abs} should help mitigate the loss of the coarse fraction of PM.

Another potential solution which is likely to resolve the apparent loss of the coarse fraction of PM is to adapt the sampling regime from continuous sampling at speed to stop-start sampling. The mobile monitoring system is flexible enough to allow either continuous or stop-start campaigns. The selection of the type of monitoring regime used can be determined by the individual characteristics of the airshed and Council requirements of the specific measuring campaign being performed.

4.2.2 PC with LabVIEW DAQ system

LabVIEW (National Instruments: Austin, Texas) is a PC-based graphical development environment, designed for engineers and scientists to interface with real-world signals, analyse data and share results through intuitive displays and reports. LabVIEW includes a data acquisition component with built-in signal processing and analysis functions. This off-the-shelf software offers an ideal platform for the mobile monitoring DAQ system.

4.2.3 Serial bus and vehicle cabling conduit

To facilitate the acquisition of digital data, a bus system is recommended for serial interfacing of instruments. Also, a generically adaptable conduit system is proposed so that cabling and sample tubes may be fitted to any vehicle with a rear window.

4.2.4 GPS upgrade

It is recommended to acquire a 3D GPS so that accurate and reliable elevation data are available for topographical analysis. The Garmin CSX60 has been suggested initially.

4.2.5 GRIMM calibration

Where and when practical, the GRIMM will be calibrated against a AQNES compliant method, to avoid source variation of particle density introducing systematic error to particulate concentration (μg m^{-3}) calculation. This would be required at least once for all airsheds where different source (and subsequent variation of particle density and optical properties) profiles are likely to occur.

4.2.6 Grimm upgrade

Fitting the GRIMM with a nafion drier and an upgrade to facilitate a full particle count distribution is suggested. This is not the most urgent recommendation and it is unclear if a nafion dryer could be installed on the mobile sampling platform. This possibility will be investigated, but at this stage given the budget available for upgrades it likely that this upgrade will be deferred.

4.3 Upgrades that have been completed

According to the priority of the upgrades indicated earlier, some of the activities have already been implemented and will be available for future monitoring campaigns:

4.3.1 Inlet

The inlet of the system was upgraded increasing the sampling flow (from 6 litres per minute to 25 litres per minute). This was achieved by incorporating an auxiliary pump to draw a high flow of air through the inlet and a narrow sampling tube to increase the speed of the sampling air. After the initial sampling, the inlet also divides the flow iso-kinetically between the instruments allowing their pumps to operate at their design settings. Preliminary trials with this new inlet have given very promising results increasing the operating vehicle speed to more than 80 km/hr.

4.3.2 DAQ and signal conditioning system

The data acquisition (DAQ) system was changed and it is now based on a PC running NIWA-developed software to communicate with all the instruments simultaneously providing a single interface point for the operator. This system now takes digital signals (RS232) from the Aethalometer, the GRIMM, the AIRMAR and the GPS. Furthermore, this system is now able to easily incorporate new instrumentation according to the needs of particular campaigns.

4.3.3 3D GPS

The GPS used in the system now incorporates a barometric altimeter to provide reliable vertical positioning even in the absence of satellite signal.

4.3.4 Power

The power circuit was completely redesigned and redundant components were eliminated. All the instrumentation and auxiliary components are now operating from an independent power source from the vehicle. This is intended to reduce the power consumption and to make the whole system as independent as possible from the platform where it is being deployed.

5. Summary of project outcomes

NIWA has designed and built a mobile monitoring system with the aim of collecting data which will ultimately allow the assessment of how PM_{10} concentrations vary across urban airsheds. There are three phases to this project:

1) System design, build and trial
2) Identify system issues. Enhance and improve system
3) Airshed monitoring, data analysis and assessment of spatial variation of pollution

The mobile monitoring system took a year to design, build and trial. This report details the outcomes of phases one and two of the project. The three main objectives of this report were to:

- Describe the system developed by NIWA for assessing spatial variability of airborne particulate matter concentrations in New Zealand urban areas
- Demonstrate the utility and application of data collected by the system
- Make recommendations for improvements to the system

The mobile monitoring system is comprised of three principal components, an aethalometer (measuring elemental black carbon), a GRIMM particulate monitor (measuring PM_1, $PM_{2.5}$ and PM_{10}) and an AirMar ultrasonic weather station and GPS unit. The components are linked into a data logging system and integrated into a single platform which is mounted onto a vehicle.

The report presents the results of the monitoring trails that were undertaken in Alexandra, Auckland and Christchurch. The trials were embarked on with the specific and simple aims of assessing the utility of the system, assessing the quality of data being collected and identifying potential improvements to the system. The results presented should be treated as illustrative examples of what the system can achieve. Key findings of the trials were that the system can potentially be used to:

- Evaluate variability of PM concentrations both within and between airsheds (e.g. Dunedin vs Mosgiel, Nelson vs Tasman, and Christchurch vs Kaiapoi vs Rangiora).

- Identify potential locations for new monitoring sites within airsheds to ensure compliance with AQNES Regulation 15.

- Assess the representativeness of the data collected by existing monitoring sites

- Identify source types of PM and their geographical areas of impact

- Establish dynamic baseline data for exposure research that require information related to population movements.

- Validating the results of airshed dispersion models,

A number of operational and equipment issues were identified with the monitoring system. These included:

- Differences between the GRIMM and AQNES compliant PM_{10} measurement methods

- Impact of driving speed on the sampling of PM_{10}

- Data acquisition, equipment communication, power supply and elevation data

Ideas have been formulated to address each of these issues. Plans and a timetable are in place to upgrade the mobile monitoring system so it is able to undertake an extensive monitoring programme in the winter of 2008.

It is anticipated that when phases two and three of the project have been complete the data collected will be of a quality that it can be used to robustly assess air quality within airsheds and to aid the development of air quality management policies.

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Colin Grace (NIWA, Christchurch) and Lou Reddish (NIWA, Auckland) for investing their creative powers and technical expertise into the development and building of the mobile monitoring system.

Appendix: Monitoring routes maps

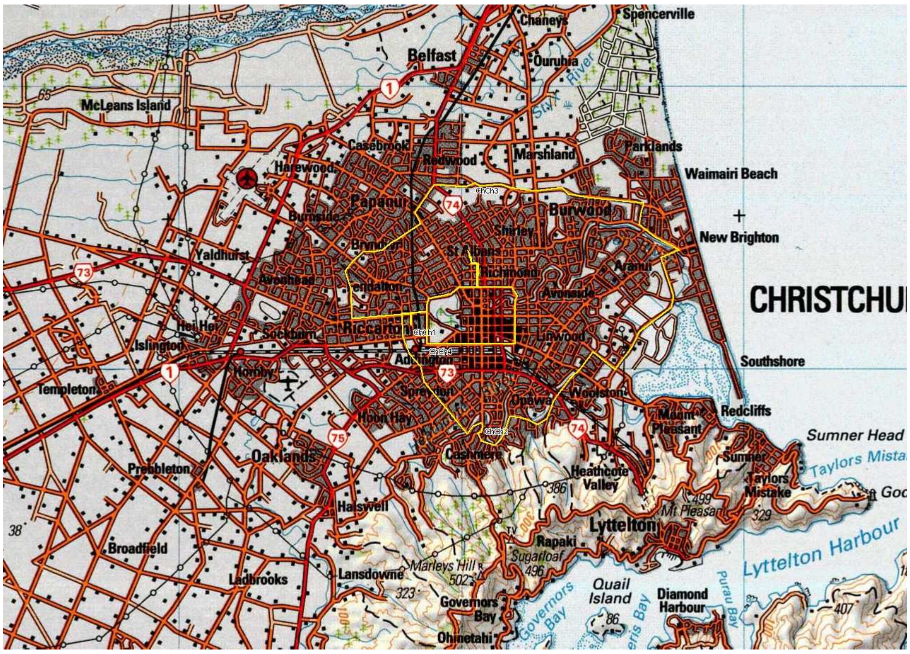

Figure 13. **Christchurch city indicative monitoring routes. The inner and outer loop are indicated by the yellow line.**

Figure 14. **Auckland area indicative monitoring routes. The small and large routes are indicated by the yellow line.**

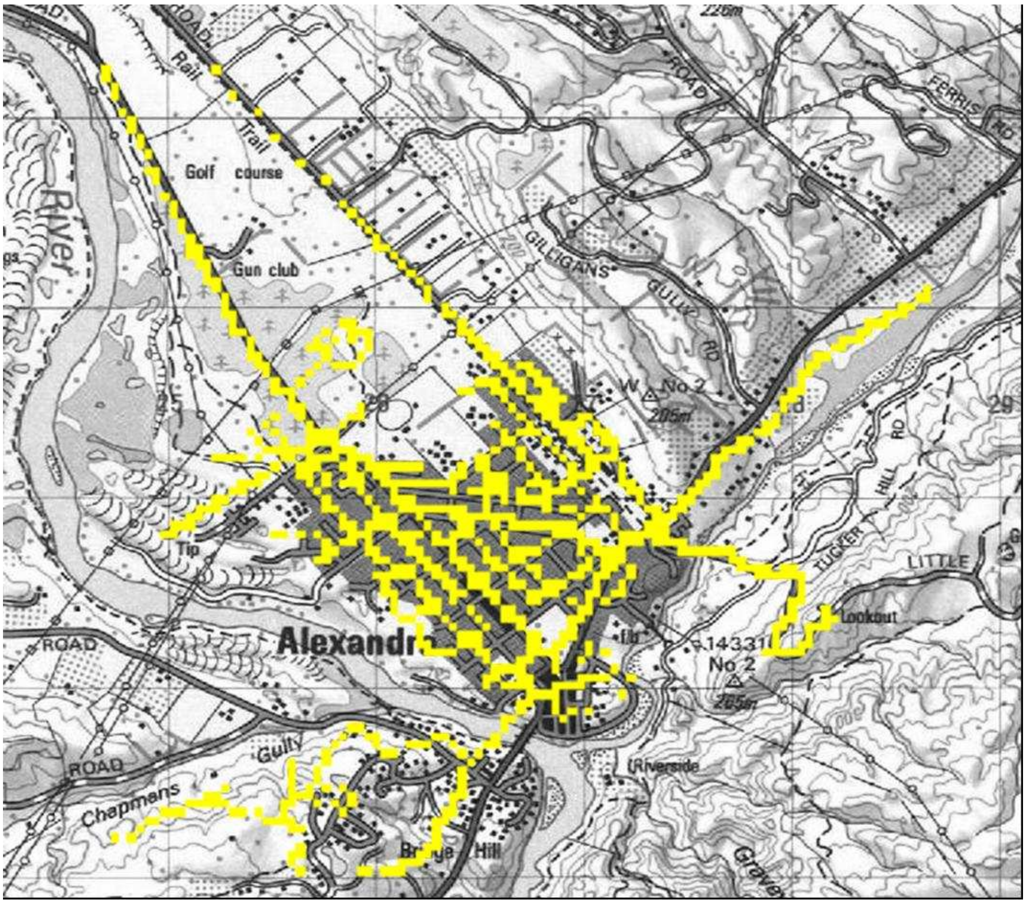

Figure 15. Alexandra indicative monitoring routes. The yellow lines indicate all the routes driven within the urban area of Alexandra.