Evaluation of road surface contaminant loadings in Waitakere City for the development of the Vehicle Fleet Emission Model - Water

Ministry of Transport
Te Manatū Waka

Evaluation of road surface contaminant loadings in Waitakere City for the development of the Vehicle Fleet Emission Model-Water

Prepared for

MINISTRY *of* TRANSPORT
TE MANATŪ WAKA

by

Paul Kennedy & Jennifer Gadd
Kingett Mitchell Limited

December 2002

Revised October 2003

Blank

TABLE OF CONTENTS

Appendix A: Summary of site characteristics and rainfall information.

Appendix B: Waitakere City road surface sample texture and metal concentrations

Appendix C: Waitakere City road surface material PAH concentrations

Abbreviations

ADT	Average daily traffic
Cu	Copper
g	gram
HD	Heavy duty
HDV	Heavy duty vehicles
IC-PMS	Inductively coupled plasma mass spectrometer
kg	kilogram
km	kilometre
L	litre
LoS	Level of Service
mm	millimetres
MoT	Ministry of Transport (New Zealand)
Pb	Lead
PAH	Polyaromatic hydrocarbons
PC	Passenger car
PGE	Platinum group elements
PM	Particulate matter
RAMM	Road asset maintenance and management
Rh	Rhodium
SIM	Selective ion mode
VFECS	Vehicle fleet emissions control strategy; MoT programme
VFEM	Vehicle Fleet Emissions Model
VPD	vehicles per day
WCC	Waitakere City Council
Zn	Zinc

Blank

1. INTRODUCTION

1.1 Background

Moncrieff et al. (2002) described the outputs from Stage 2 of the Ministry of Transports (MoT) programme on the effects of motor vehicle emissions on aquatic environments. The primary objective of Stage 2 was to produce an analytical framework and environmental management approach required to identify and deal with environmental management issues associated with road transport emissions to aquatic environments. Following the completion of Stage 2, Stage 3 was initiated, involving the development of an parallel version of the VFEM-W (Vehicle Fleet Emission Model – water) for assessing potential emissions from motor vehicles to road surfaces and hence the stormwater system. The Stage 3 project required the field collection of data on contaminant loadings on road surfaces to provide a preliminary examination of the outputs from the VFEM-W in relation to the amount of contaminants present on New Zealand roads. To assist in the identification of appropriate emission factors for the model (refer Kennedy et al. 2002) a separate study was undertaken and the results utilised in the model. The field verification included:

1. Identification of some 40 sites to be sampled within the road network in Waitakere City and 'replicated' dry sampling and analysis of road surface material collected at each site for key contaminants.
2. Correlation of the results obtained with VFEM-W output data.

This correlation is intended as a first initial examination in New Zealand of vehicle emission contribution to road surface (as determined using VFEM-W) and comparisons with the loads of key contaminants present on the road surface.

2. FIELD SAMPLING

2.1 Site Selection

The study described in this report is confined to five Stormwater Management Units (SMUs) within Waitakere City. The five SMUs represent the core area of Waitakere City being utilised for the integration of the VFEM-water and the WCC traffic/GIS systems. The SMUs are Lincoln (SMU 14), Central Park (32), Henderson Creek (9), Henderson Creek South (10) and Lower Opanuku (15). The study area includes the Henderson Centre, Lincoln Road industrial area, residential areas, parks and a small section of the North-Western Motorway. The key freshwater receiving environments are Opanuku Stream, Taikata Inlet and Henderson Creek. The estuarine receiving environment for these streams is Henderson Creek, which is an upper estuarine arm of the Waitemata Harbour.

Roads are complex systems in terms of vehicle-road interaction (refer Moncreiff & Kennedy 2002, Kennedy et al. 2002) because of the various factors that influence the way in which contaminants are emitted from the various vehicle emission sources. For example, tyres wear differently on straight and curved roads and on inclined roads and under braking and acceleration and brakes wear differently depending upon the speed and the stopping distance. To minimise the number of variables that would need to be considered, the road areas sampled in the study were limited to relatively linear sections of road (as noted further below). The sample sites were divided into two groups; linear sections and intersections. In order to minimise effects from other sources, the sites were selected on the basis that they were:

- Not near industrial premises or any other significant sources of dust/deposition such as construction.

- Not in close proximity to commercial areas.
- Not next to major intersections (either traffic lights or roundabouts).
- Not short cul-de-sacs where cars are regularly turning around.
- In close proximity to sites selected by URS Ltd for Waitakere City Council (WCC) as being high priority for stormwater treatment within Waitakere City.
- Generally straight.
- Generally level.

All sites were initially selected as a desktop exercise based on traffic counts (ADT, average daily traffic) and followed up with ground truthing of the sites to ensure their applicability.

Linear Road Sites

Linear road sites are identified as general sites that are straight and level with little interruption to normal driving conditions on the road. Sites were selected to cover the range of road types within the SMUs, which includes local roads, district arterial routes and regional arterial routes. Roads were broken down into categories by traffic counts. Traffic data was provided by Waitakere City Council, via their RAMM database). The categories were:

- < 99 vehicles per day (VPD)
- 100 - 499
- 500 - 999
- 1000- 4999
- 5000 - 9999
- 10,000 - 19,999
- 20,000 - 29,999
- > 30,000

Within each of these categories, three sites were selected. 20 sites were selected as presented in Table 1.1 and shown in Figure 1.1. Appendix A provides a summary of general site information. All roads were single lane with the exception of Lincoln Road, which had two lanes. Two lanes results in lane changing which should, increase tyre wear (Kennedy et al. 2002).

Intersection Sites

Intersection sites consist of sections of road within 25 m of intersections and round-abouts. Twelve intersection sites were selected to investigate the differences in contaminant loads adjacent to major intersections as compared to adjacent straight sections of roads. Sites sampled are identified in Table 1.2 and are shown in Figure 1.1.

There was insufficient information available in published literature on differences in driving behaviour and road surface contaminants to indicate whether there could be detectable differences in concentration or loads across the road surface. In order to investigate this, a decision was made to sample the intersection in two parts across the road width.

At the intersection, the lanes were identified as the entry and exit. The exit is the lane approaching the intersection (exiting the main road) and the entry is the lane leaving the intersection (entering the roadway). These were sampled as independent samples to investigate whether there were any identifiable differences between the two sections of the road.

Table 1.1 - Sampling sites located on straight sections of road.

Category	ADT	Road Name	Description	Date
< 99	65	Pomelo Rd	Off Amberley Ave	15/05/02
	70	Stephen Ave		01/08/02
	110	Coletta Ln	Off Vodanovich Rd	15/05/02
100 - 499	120	Borich Rd	Seymour to Solea Rd	01/08/02
	190	Longburn Rd	Off Pomaria Rd	16/05/02
	360	Kingdale Rd	Off Pomaria Rd	16/05/02
500 - 999	570	Sylvan Cres	Whole road	15/05/02
	891	Harrington Rd	Between Rathgar & Harry Ward	17/05/02
1000 - 4999	1320	Vodanovich Rd	Any part	30/07/02
	1500	Keeling Rd	Henderson Valley Rd to end	16/05/02
	2020	Seymour Rd	Manui Pl to Benita Pl	30/07/02
5000 – 9999	5151	Corban Ave	Henderson Vly to Bruce McLaren	17/05/02
	5472	Pomaria Rd	Kingdale Rd to Stephen Ave	30/07/02
	8587	Border Rd	Henderson Valley to Taranui Pl	17/05/02
	7500	Bruce McLaren Rd	Hindmarsh St to Farwood Dr	16/07/02
10,000 - 19,999	17282	West Coast Rd	Parrs Cross to Selak Pl	16/07/02
	17464	Lincoln Rd	Poinsettia Pl to Universal Dr	01/08/02
	19000	Henderson Valley	Hickory Ave to Corban Ave	16/07/02
>20,000	27800	Edmonton Rd	Central Park Dr to Alma St	04/12/02
	38178	Lincoln Rd	Universal Dr to Daytona Rd	03/12/02

Note: ADT – Average daily traffic.

Table 1.2 - Sampling sites located on intersection.

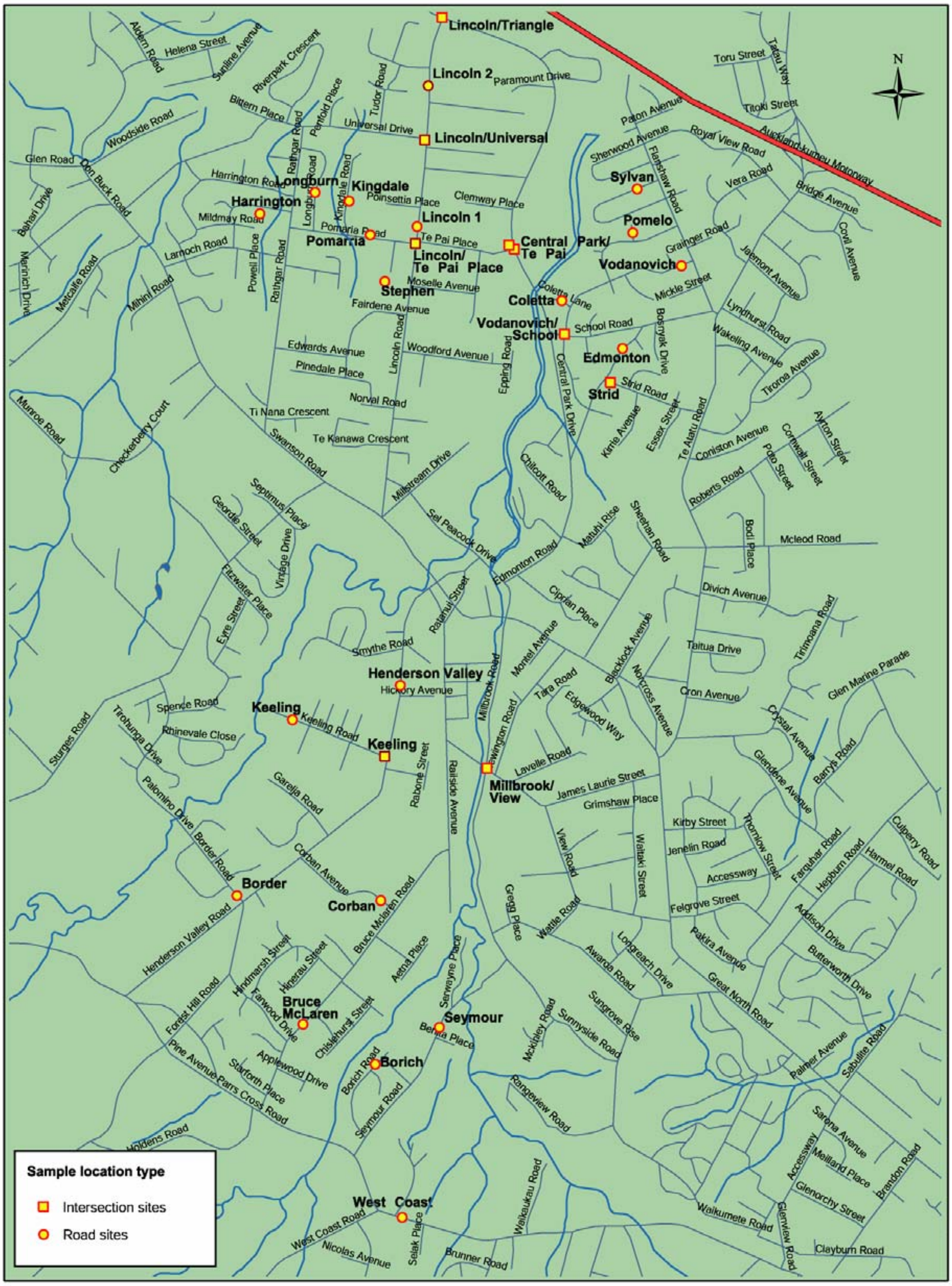
Category	ADT	Road Name	Description	Date
1000 - 4999	1513	Strid Rd	Intersection with Edmonton Rd	02/08/02
	2065	Vodanovich Rd	Intersection with School Rd	02/08/02
	2700	Keeling Rd	Intersection with Henderson Vly	02/12/02
5000 – 9999	5800	Te Pai Place	Intersection with Central Park Dr	03/12/02
	8000	Central Park Dr	Intersection with Te Pai Place	03/12/02
	9612	Millbrook Rd	Intersection with View Rd	02/12/02
>20,000	17089	Lincoln Rd	Intersection with Triangle Rd	05/12/02
	22558	Lincoln Rd	Intersection with Te Pai Place	04/12/02
	38178	Lincoln Rd	Intersection with Universal Drive	05/12/02

2.2 Sampling Procedure

2.2.1 Equipment

A PacVac 2000 Contractor model vacuum cleaner was used to collect dust samples from the road surface and gutter. The cleaner was fitted with a plastic hose, tube and foot. The foot is a stationary type foot with 6 mm long bristles. The cleaner uses disposable 2 ply paper bags capable of retaining particles to 0.3 µm. The vacuum cleaner was powered from a petrol generator fuelled by unleaded petrol.

Figure 1.1 - Location of sampling sites in Waitakere City.



2.2.2 Sampling Procedure

An area of road 1 m wide was marked out using string lines. Samples were collected by vacuuming this section of road from the left hand gutter to the right hand by passing the vacuum cleaner four times over each section (refer following section). The area was then measured and recorded. At each location three strips were sampled at 15 m intervals. At intersections, the intervals between strips were reduced where necessary to ensure that the section vacuumed remained within the area affected by the intersection.

2.2.3 Dust removal assessment

To assess the efficiency of the vacuum cleaner to remove surface material on the road, a defined area (1 m wide across the length of the road) was vacuumed using a single pass of the cleaner. The material was bagged as sample 1. This process was repeated a further 4 times and the samples labelled 2-5. Samples were collected in this fashion from 3 sites.

2.2.4 Sample Handling and Processing

The sample collected in the paper vacuum bag and the paper bag was placed into a clean, labelled zip-lock bag. The following information was recorded for each sample site:

- Street name.
- Date.
- Part of street (start street no - end street no.).
- Time of sampling
- Number of strip repetitions required to collect the sample.
- Weather conditions.
- Presence of any cars.
- Location of other sources of dust e.g., fires, industrial sources.
- Any other additional and relevant information.

2.2.5 Decontamination Procedure

On each night/day of sampling all work was undertaken working from the road with the least traffic to the most wherever possible. Between roads/samples the vacuum cleaner was cleaned by running the cleaner with a blank bag inside. The bag was run for at least 3 minutes to minimise carryover of dust. The foot of the cleaner was cleaned thoroughly by vacuum and inspected for debris or dust. The bag was replaced with a clean, unused bag for each site sample collection.

2.3 Timing of Sampling & Traffic Management

The timing of sample collection was limited by health and safety and traffic management considerations. Most low intensity roads were sampled during day-time. Roads with larger traffic counts were typically sampled at night when traffic numbers were low.

Traffic management during sampling was determined following consultation with Waitakere City Council roading department and Transit New Zealand. Traffic management was undertaken using a professional traffic management company. All work was undertaken according to the Transit publication “Working on roads”.

2.4 Laboratory Methods

2.4.1 Sample Handling

Following sample collection, individual sample bags from the same sampling location were combined and weighed. The whole sample was sieved through a 2 mm non-metal sieve, weighed and the sample fractions greater (gravel) and less than 2 mm (sand, silt and clay) were weighed. The <2 mm sample was then sieved through a <0.063 mm non-metal sieve to provide information on the weight of sample <2 mm, >0.063 mm and <0.063 mm. The material from this sieving provided material for chemical analysis of <0.063 mm material.

2.4.2 Physical characteristics

Information on the physical particle sizes present in each sample were obtained by weighing following sieving as noted above. All data on the % by mass of sample in each of the three mass fractions is summarised in Appendix B. Information on the material present in the gravel fraction was obtained by visually inspecting the material under a low power binocular microscope. The material present was physically separated into the key types of materials present which were: gravel, other inorganic material (e.g., shell fragments); glass, plastic, metal, plant material, organic matter. This information is not presented in this report.

2.4.3 Metal Analysis

Copper, lead and Zn analysis were undertaken on <0.063 mm and <2 mm fractions following nitric/hydrochloric acid digestion and ICP-MS (Perkin Elmer Elan 6000 Inductively Coupled Plasma Mass Spectrometer) according to US EPA method 200.2. A procedural blank was analysed with each batch of samples and there was one duplicate and one spiked sample per twenty samples. An in-house reference sample was also analysed with each batch of samples. Detection limits were 2, 0.4 and 4 mg/kg (dry weight) for Cu, lead and Zn respectively. All results are presented on a dry weight basis. All data is summarised in Appendix B.

2.4.4 Polyaromatic hydrocarbons

PAH concentrations were measured in the <2 mm fraction samples. The samples (15.0 g) were extracted into dichloromethane (20 mL) using ultrasonication. The extract was cleaned up using Florisil and analysed using Agilent 6890 or 5973 gas chromatography instruments fitted with mass spectrometer detectors (GC-MS) and autosamplers. The instruments were operated in Selective Ion Monitoring (SIM) mode to increase selectivity and sensitivity.

Anthracene-d10 was used as a surrogate (system monitoring compound), and naphthalene-d8, acenaphthene-d10, phenanthrene-d10, pyrene-d10, chrysene-d12, perylene-d12 and benzo[g,h,i]perylene-d12 were used as internal standards.

Detection limits varied depending upon sample composition and the individual PAH, from <0.4 mg/kg for naphthalene to <0.04 mg/kg for anthracene and benzo[k]floranthene. All PAH data is summarised in Appendix B.

3. ROAD SURFACE MATERIAL AND CONTAMINANTS

3.1 Material recovered

3.1.1 Material build-up

Pollutant build-up is an important factor in the estimation of the amount of pollutant removed by rainfall to stormwater. Build-up is the process by which material accumulates on the street surface during the dry period between storms. This process is a function of the supply of material and loss of material by wind, street cleaning practices and other physical processes. Equilibrium is reached on the road surface when the rate at which material and contaminants being deposited on the road surface is equalled by the rate at which they are removed from the road surface.

As pointed out by Vaze & Chiew (2002), there have been few studies of the material build-up processes since the work of Sartor & Boyd (1972) (and also Pitt 1987). Modelling of the removal process may assume that rainfall of over a certain intensity removes all of the pollutant present on the road surface. However, as noted in the recent paper by Vaze & Chiew (2002) this is extremely unlikely. Furthermore, Pitt & Voorhees (1993) discussed wash-off of particulates from road surfaces and concluded that after about 15 mm of rainfall about 90% of the available particulates would wash-off (about 3 g/m^2). This amount was only 22% of the total loading. Accumulation on the road surface therefore starts from a base of the material remaining after the previous rainfall event.

Physical removal processes are determined principally by wind, which can be natural or generated by on-road vehicle movement. Other processes may also influence contaminant build-up with temperature influencing the amount of volatile contaminants present on the road surface. Pitt (1987) (quoted in Heaney et al. (1999)) identified that surface roughness has a significant effect on contaminant loading and the permanent storage loading (the amount not removed by rainfall or wind events).

Ball et al. (1998) noted that both wind and rainfall events have the ability to “clean” a road surface and identified that rainfall events of more than 7 mm/hr and wind events with a velocity >21 km/hour were required to result in surface cleaning. Ball et al. (1998) also identified that a generic hyperbolic function should be used to estimate the pollutant loads on road surfaces. Their study indicated that at 4 days the load of material in the street gutter reached 82% of that at 8 days. At 5, 6 and 7 days the relative load was 88, 91 and 97% of that at 8 days.

Early work by other studies (e.g., Sartor & Boyd 1972 etc.,) identified that pollutant loads on road surfaces reached equilibrium over a period of time. Heaney et al. (1999) summarised the information obtained on days to maximum loadings identified in a range of studies. The authors found that the number of days to maximum loading on smooth and intermediate textured streets ranged from 5 to 70 with an average of >25 days. On rough surfaced roads the time ranged from 10->50 days with an average of >30 days. The sites identified included Nevada, California, Ontario and Washington. In some locations such as California, the intervening dry periods were 20-100 days.

Vaze & Chiew (2002) undertook their study in the central business area of Melbourne and sampled the car parking bays in the middle of Bouverie St. The study involved the collection of three 0.7 m^2 samples on dry days over a 36-day period. Their sampling showed that material build-up occurred rapidly after rain but then slowed as a result of redistribution. The material on the road surface was considered to comprise a free and fixed load. Vaze & Chiew (2002) measured what they termed free and fixed loads. The free material comprised that material able to be removed using vacuuming only and fixed load was that material vacuumed following light brushing. Generally the fixed load is a constant with the free load increasing steadily after rain (e.g., from 50% up to about 80% (interpreted from graphs in Vaze & Chiew 2002)) (Figure 3.1).

In summary, he published literature indicates that under most conditions build-up occurs relatively rapidly following significant rainfall. Under appropriate conditions build-up may continue but equilibrium or near equilibrium conditions are likely as the rate of accumulation tends to slow over time. Site build-up would be expected to be a relatively site specific process and that equilibrium/removal effects are likely to become increasingly more important in locations where there are very long dry periods. Overall, there is a balance between the rate of accumulation and the interval between significant rainfall events in selecting the appropriate number of dry days after rainfall events when sampling road surface materials should be carried out. In the current study, sampling was undertaken typically after 3 days of dry weather following a rain event Appendix Table A2 provides a summary of the number of days prior to sampling in this study that significant rain occurred. Based upon the work of Vaze & Chiew (2002) and the typical dry interval periods in Auckland, 3 - 4 days was considered a suitable period after rain when sampling should be undertaken.

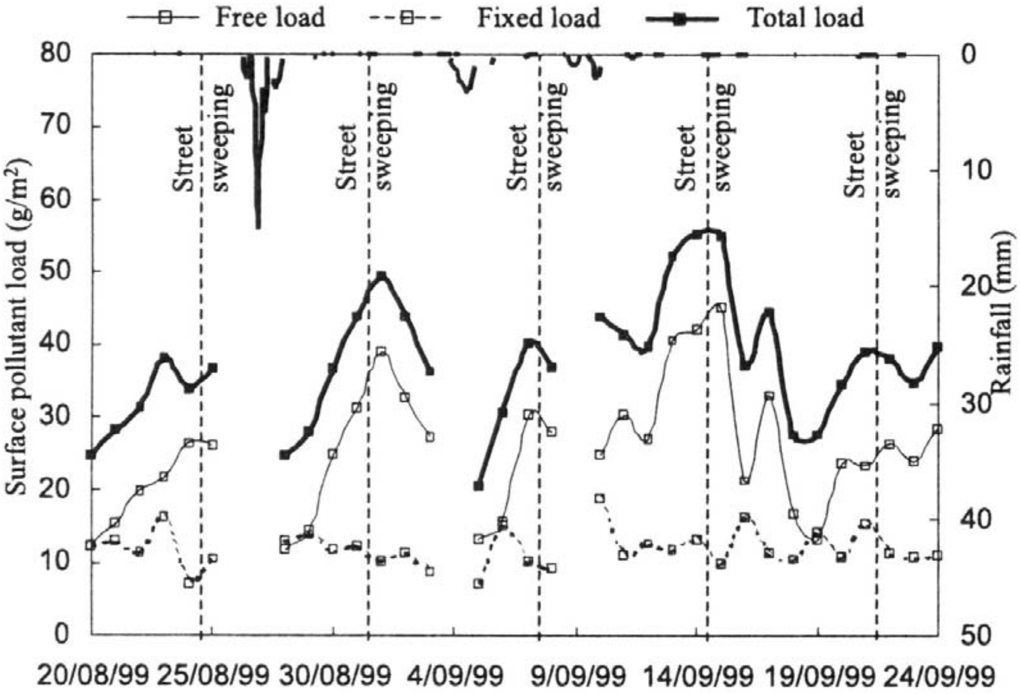


Figure 3.1 - Changes in road surface material load over time (From Vaze & Chiew 2002).

3.1.2 Method of collection

There are a variety of options for collecting material present on the surface of roads. Bris et al. (1999) examined the use of dry and wet removal sampling techniques. Overall, the authors found that wet vacuuming removed more particles than dry vacuuming. For the 200-2,000 µm particle size fraction, there was generally little difference between the wet and dry removal processes. The dry vacuuming removed 95% of the load when the surface load was greater than 5 g/m^2. For the particle fraction <50 µm they found that dry vacuuming removed 85% of the material at loadings of 5 g/m^2. The authors also found that the amount of fine particles removed increased with the use of brushing prior to vacuuming. However, they commented that the brushing introduced less discrimination in sampling.

As part of the confirmation of methodology for this study, a number of sites were vacuumed multiple times to determine whether vacuum collection was effective in collecting all of the material present on the road surface as described in Section 2.2.3. Figure 3.2 shows that the repetitive removal of material on the road surface showed that the fourth sweep of the vacuum cleaner removed 95 % of both the total material <63 and 2,000 µm of the 5th sweep.

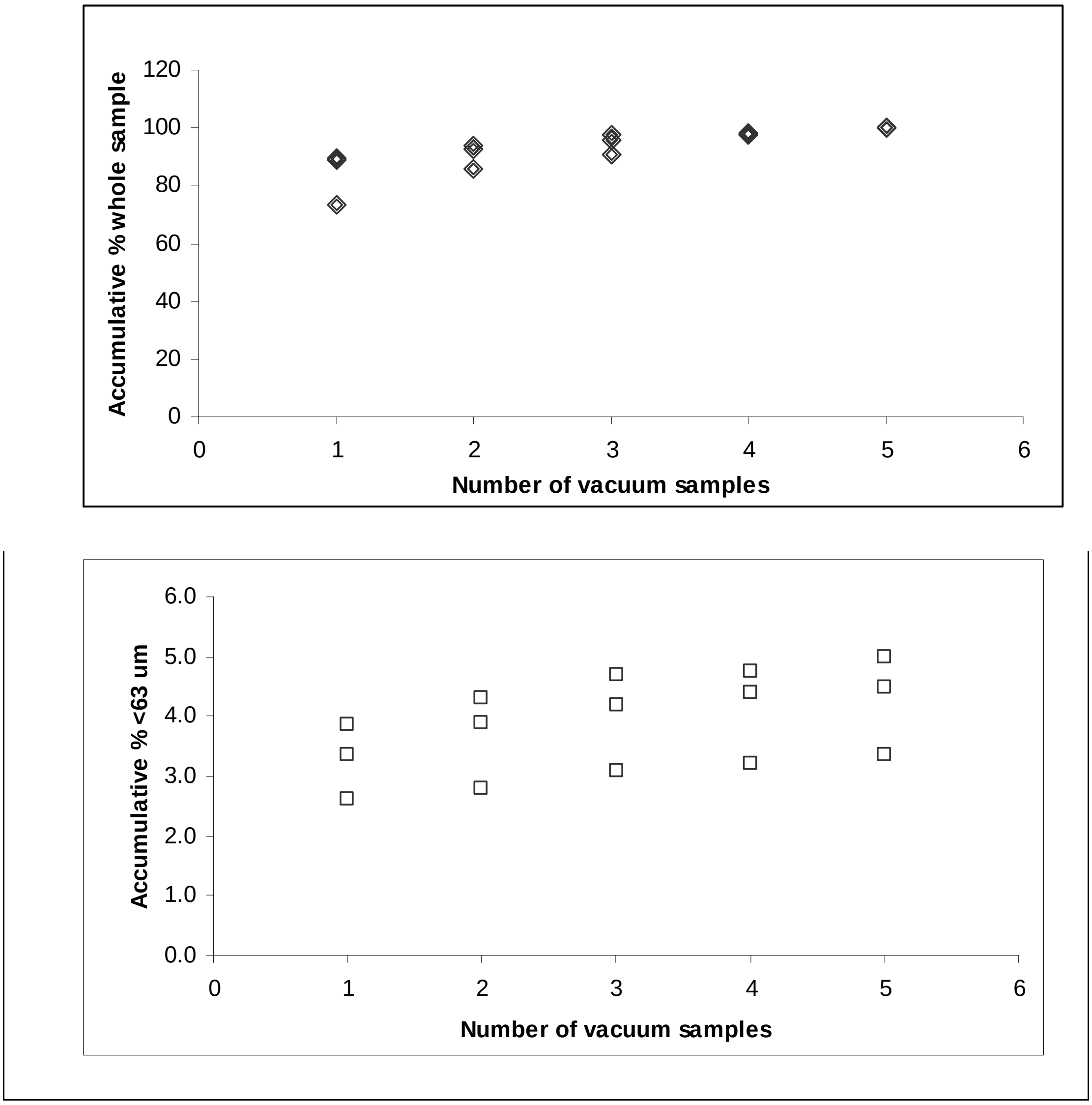


Figure 3.2 - Summary of road surface material vacuum removal efficiency.

3.1.3 Material load

Most of the first 22 sites examined had between 20 and 60 g/m^2 of material on the road surface (200-600 kg/ha) (Figure 3.3). This data compares well with the amount of material found by Vaze & Chiew (2002) in their recent Melbourne study (refer Figure 3.1) and Bris et al. (1999) in their Paris study. The former work found most samples in a range 10-40 g/m^2 and the latter 8.5-17 g/m^2. The current study vacuumed an average of 26.8 m^2 per site compared to about 2.1 m^2 by Vaze & Chiew (2002) and 0.64 m^2 by Bris et al. (1999).

Figure 3.3 presents data for straight road sites and intersection sites separately. Examination of the data in the figure indicates that although the loads at the intersection sites may be slightly lower than that present on the straight sections of road, the amounts were not significantly different (p=0.0583, two tailed t-test).

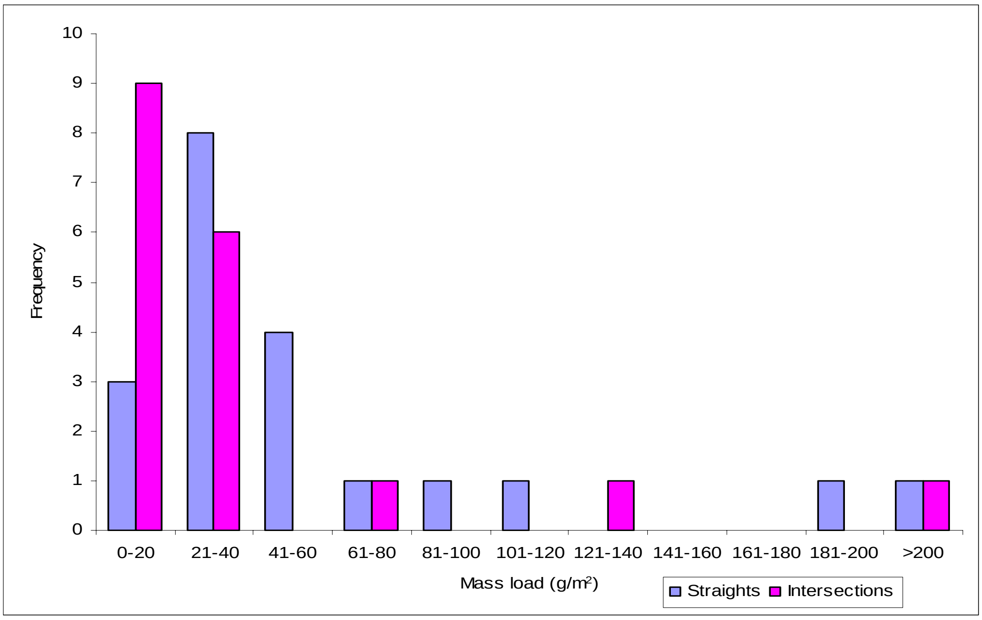


Figure 3.3 - Surface material loads on Waitakere City Roads.

3.2 Particle size

Examination of Figure 3.4 shows that all samples collected had <20% of their total mass in the <63 µm particle size fraction. Five of the samples collected had >40% of their total mass present in the >2 mm particle size fraction. These samples were Strid Rd entry and exit (leaves), Vodanovich Rd, Pomelo and Sylvan Roads (gravel). Median proportions of the three fractions in all of the samples collected were, 63 µm 7%, 63-2000 µm 64 % and >2,000 µm 29 %. The percentage of road surface material in the <63 µm fraction (silt and clay) is similar to the proportions of fine sediment measured on road surfaces in New Zealand and internationally (Table 3.1). The Waitakere City road surface samples have proportions of fine material at the upper end of this range.

Table 3.1 - Proportion of road surface material in fine sediments.

Proportion in Fine Fraction	Reference
5.9%, <0.43 µm	Sartor & Boyd 1972, Ellis & Revitt 1982
1 % <43 µm	Lau & Stenstrom 2001
6% <43 µm	Ball et al. 1998
2.0-3.6% in the <47 µm size range	ARC 1992
3.6% <74 µm	Malmquist 1978

3.3 Metals

Concentrations of Cu, lead and Zn were measured in the <63 µm and <2000 µm fractions of each sample collected. Table 3.2 provides a comparison with data from Waitakere City with some recent and older international data. Generally the median concentrations identified are similar to those seen in other large cities.

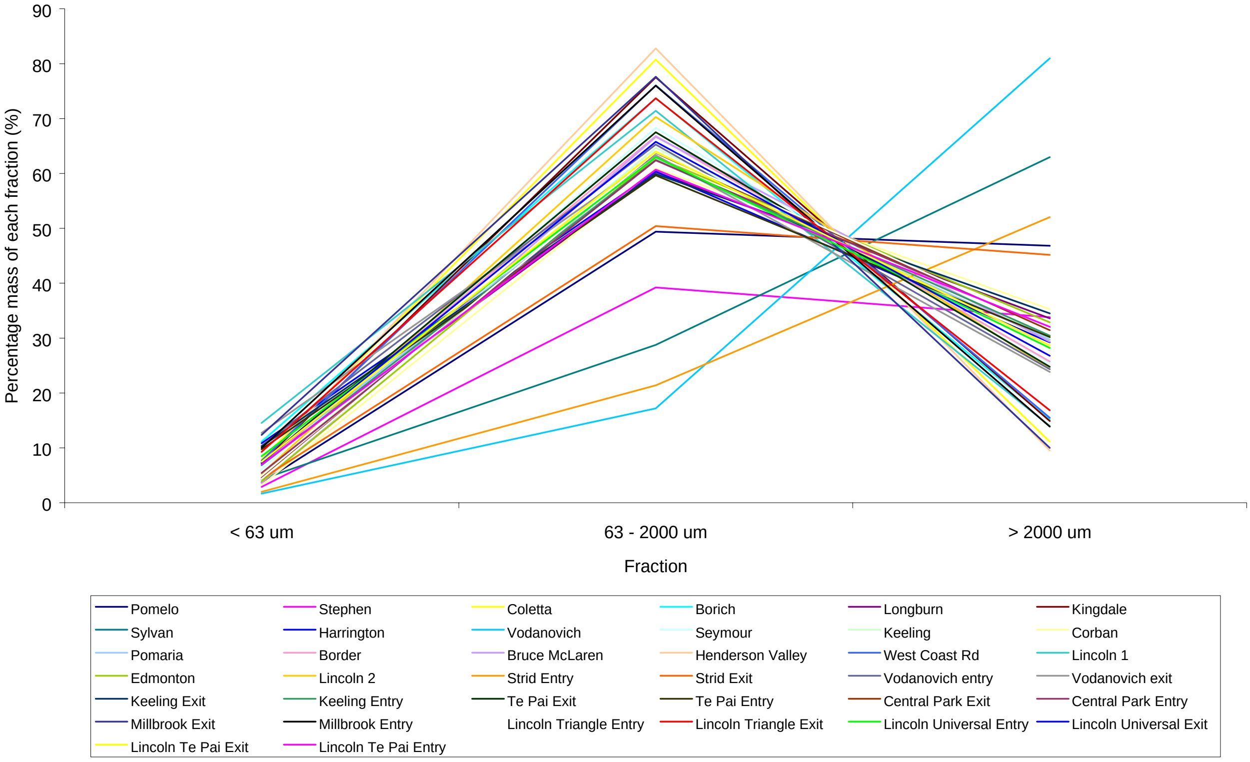


Figure 3.4 - Particle size proportions in Waitakere City street surface material.

Table 3.3 provides a summary of the concentration data obtained for the samples collected within Waitakere City and compares this with other data collected within New Zealand. For Cu and Zn, the Waitakere data in both fractions is similar to older data from Christchurch and Wellington. For lead, there has been a significant decrease in the concentration in street dusts since lead was removed from petrol in 1998. The concentrations measured in the <2000 µm and <63 µm fractions of road surface material in Waitakere City are on average less than 20 % of those measured in other locations sampled in Auckland and around New Zealand prior to lead being removed from petrol.

Table 3.2 - Selected international gutter dust metal concentrations (all data mg/kg dry weight unless noted).

Location	Copper	Lead	Zinc	Reference
Waitakere City	149 (48-1,600)	169 (28.2-695)	326 (130-983)	This study
Mascot, Sydney	97-280	230-1,600	440-850	Brockbank et al. (1999)
Gymnea, Sydney	51-330	520-1600	300-560	Brockbank et al. (1999)
Los Angeles	236 (221)*	144 (349)	367 (974)	Lau & Stenstrom (2001)
Hong Kong	173	181	1,450	Li et al. (2001)
Hong Kong	635	1,287	2,902	Yim & Nau (1987)**
London	191; 204	2,008; 4,053	1,176; 1,171	Fergusson & Ryan (1984)
New York	171; 540	2,213; 2,952	984; 2,638	Fergusson & Ryan (1984)
Halifax	119; 54	1,919; 674	620; 315	Fergusson & Ryan (1984)
Kingston	72; 59	909; 817	996, 533	Fergusson & Ryan (1984)

Notes: * - whole sample and (<0.047 mm). ** - Cited in Li et al. (2001).

Table 3.3 - Summary of trace element concentrations in Waitakere City road surface samples and NZ urban roadway gutter dusts in (all data mg/kg dry weight).

Element	Location	Fraction analysed	Median	Minimum	Maximum	N	Ref	Year of sampling
Copper	**Waitakere**	**<2 mm**	149	48	1,600	38	-	2002
	Wellington	<2 mm	184	32	1,572	94	1	1978
	Auckland	<2 mm	318	166	447	3	2	1992
	Christchurch	<0.963 mm	106	48	258	3	4	1984
	Waitakere	**<0.063 mm**	297	142	539	38	-	
	Auckland	<0.047 mm	428	139	432	3	2	1992
	Wellington	<0.036mm	488	264	649	3	1	1978
Lead	**Waitakere**	**<2mm**	169	28.2	695	38	-	2002
	Wellington	<2mm	1,108	296	6,399	23	1	1978
	Auckland	<2 mm	720	627	2,524	3	2	1992
	Christchurch	<0.963 mm	1,294	887	10,070	3	4	1984
	Waitakere	**<0.063 mm**	276	151	559	38	-	2002
	Karori	<0.036 mm	1,926	550	4,247	11	1	1978
	Taita	<0.036 mm	1,266	748	2,157	8	1	1978
	Remuera	<0.036 mm	1,708	285	3,982	8	3	1983-84
	Clendon Park	<0.036 mm	1,504	674	2,863	10	3	1983-84
	Auckland	<0.047 mm	796	663	3,050	3	3	1983-84
Zinc	**Waitakere**	**<2 mm**	326	130	983	38	-	2002
	Wellington	<2 mm	507	147	1658	23	1	1978
	Christchurch	<0.963 mm	429	365	850	3	4	1984
	Auckland	<2 mm	431	315	504	3	2	1992
	Waitakere	**<0.063 mm**	723	267	2,690	38	-	2002
	Auckland	<0.047 mm	431	315	504	3	2	1992
	Auckland	<0.036 mm	420	305	811	3	2	1992
	Wellington	<0.036 mm	-	303	2,377	16	1	1978
	Auckland	<0.036 mm	-	395	4,246	34	3	1983-84

Notes: [1] Kennedy unpublished. [2] ARC (1992). [3] Kennedy et al. (1988). [4] Fergusson & Ryan (1984).

Figure 3.5 provides illustrates the frequency distribution for Cu, lead and Zn concentrations in the Waitakere samples. Figures 3.6 and 3.7 provide a comparison of the concentrations measured in <63 µm and <2000 µm samples collected from intersection and straight road sites within the traffic volume bands. The data presented in the two figures are medians and the error bars are one standard deviation. The results of a comparison of the various sets of metal data between the two types of sites are presented in Table 3.4.

The statistical comparison of metal data for samples collected from intersections and straight roads indicated that for roads with greater than 5,000 VPD, the intersections had statistically higher concentrations of metals than the corresponding straight roads. This trend was seen for Pb and Zn but not for Cu. For Pb and Zn a difference was seen in the mid traffic volume band for both fractions (when the two samples from each intersection were kept as independent pieces of data). For Zn a difference was identified in the highest traffic volume sites for the <2,000 µm fraction but for the <63 µm fraction the difference was not statistically significant. A difference was also detected for Pb in the <2,000 um fraction in the lowest traffic volume band (1,000-5000 VPD).

An examination of the entry and exit data for the intersection sites (9 sites in 3 traffic bands) (paired t-test, log-transformed data) revealed that the concentration of Pb and Zn was higher at the entry sites compared to the exit (p=0.028 and 0.029 respectively). The exit sites are all affected by stop signs or traffic lights within the section of road sampled. At this stage the observed difference between the two sections of the intersection has not been resolved as the exit location is an area of braking and stopping and acceleration whereas the entry is an area of acceleration following a start from an ‘exit’ point at the other side of the intersection. The corresponding pattern seen in the Pb concentration that appears to follow the Zn concentration cannot be explained as the concentration of Pb in tyres and other sources such as brake dust are typically low (Kennedy & Gadd 2000). The lack of any difference for Cu between the sections of road may be related to the way that the brake dust is dispersed to the road environment from the wheel/brake housing.

Table 3.4 - Summary of comparison of metal concentrations in samples from straight roads and intersections for three traffic volumes.

Intersection entry and exits not combined

T-Test (2-tail unequal variance)

VPD	Cu		Pb		Zn	
	<63 um	<2 mm	<63 um	<2 mm	<63 um	<2 mm
1,000-5,000	0.534	0.144	0.136	0.020	0.469	0.106
5,001-10,000	0.720	0.058	0.008	0.002	0.010	0.0002
>10,000	0.999	0.307	0.438	0.852	0.092	0.0147

Intersection entry and exits averaged

T-Test (2-tail unequal variance)

VPD	Cu		Pb		Zn	
	<63 um	<2 mm	<63 um	<2 mm	<63 um	<2 mm
1,000-5,000	0.607	0.217	0.108	0.101	0.373	0.091
5,001-10,000	0.663	0.062	0.012	0.002	0.091	0.014
>10,000	0.771	0.332	0.355	0.916	0.086	0.018

Notes: Values in tables are p values, those values with p<0.05 are shaded yellow.

3.4 Polyaromatic hydrocarbons

Table 3.4 provides a comparative summary of the concentrations of PAHs measured in the <2,000 µm fraction of samples collected from the surface of roads in Waitakere City. The PAH fingerprint from the Waitakere samples is very similar to that present in the earlier samples collected from Auckland (ARC 1992). The differences observed when compared to the roadside soil sample from Brisbane are likely to be related to the greater amount of organic matter present in the soil sample compared to the road-surface samples and the greater length of time involved in accumulation of PAHs.

Figures 3.8 and 3.9 illustrate the relative concentrations of individual PAHs measured in road surface samples collected from straight road sites and intersection sites in Waitakere City. The data in the two figures show that the relative concentrations (the individual site fingerprints) are very similar in all samples collected.

Examination of the data in Table 3.4 shows that the concentrations of total PAH measured in the Waitakere City samples is similar to that measured in similar samples collected elsewhere in Auckland. Given that the concentration of PAH in exhaust emission particulates or the airborne particles within the road air-corridor are much higher, the concentrations observed are a function of the amount of material containing low concentrations of PAH with the depositing particles sourced from vehicle exhausts and other vehicle derived particles that will contain some PAH (e.g., tyre wear particles).

Concentrations of PAH in vehicle exhaust particles are high. Lee et al. (1995) reported a mean particle bound PAH concentration of 15.4 mg/kg (5.21-29.2 mg/kg) at a road intersection in Taiwan and Oda et al. (2001) measured 20-25 mg/kg in fine dust deposited in the Kojouike tunnel in Kurashiki Japan.

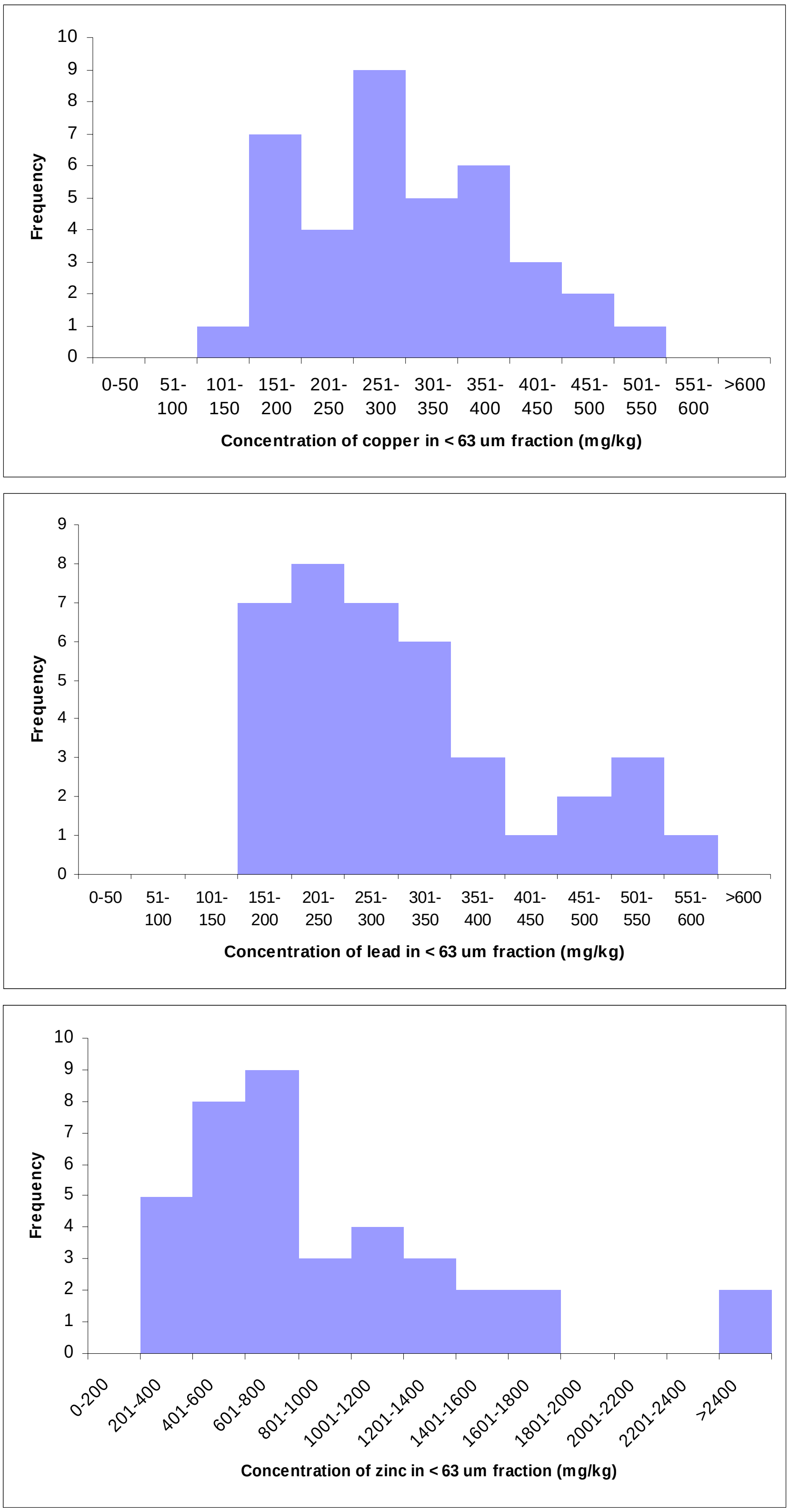


Figure 3.5 - Copper, lead and zinc in <63 µm fraction material from Waitakere City road surface samples.

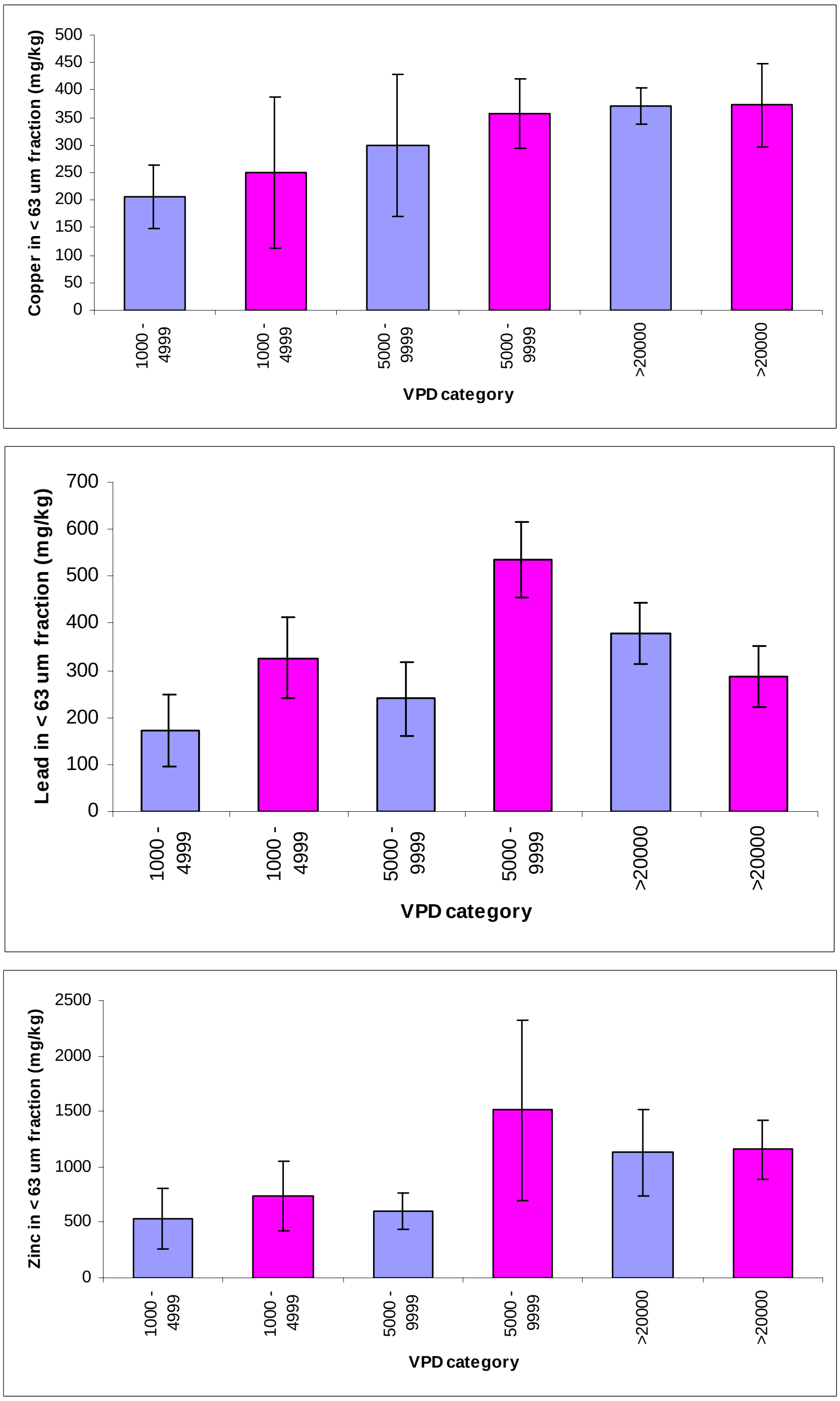


Figure 3.6 - Comparison of copper, lead and zinc concentrations in <63 µm sediment fraction between straight (blue) and intersection sites (purple) with similar vehicle counts.

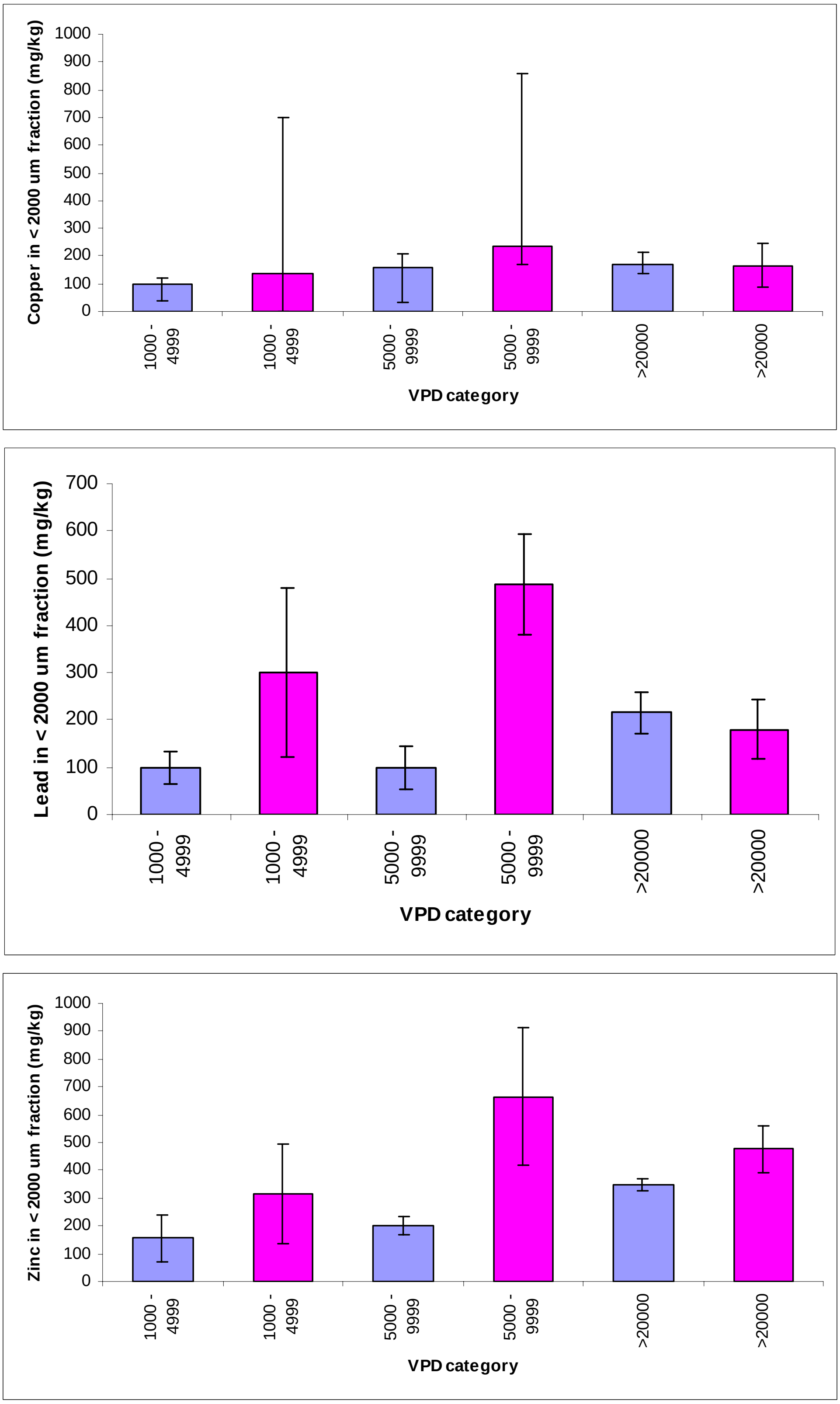


Figure 3.7 - Comparison of copper, lead and zinc concentrations in <2,000 µm sediment fraction between straight (blue) and intersection (purple) sites with similar vehicle counts.

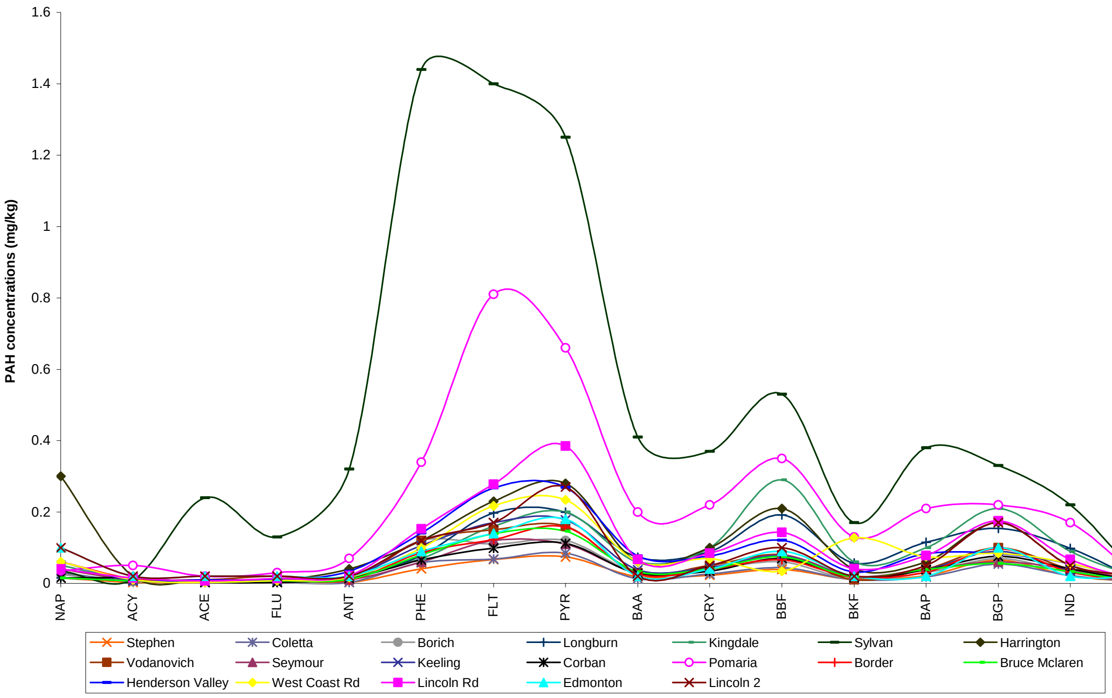


Figure 3.8 – Relative individual PAH concentrations for road surface material samples from straight road sites in Waitakere City.

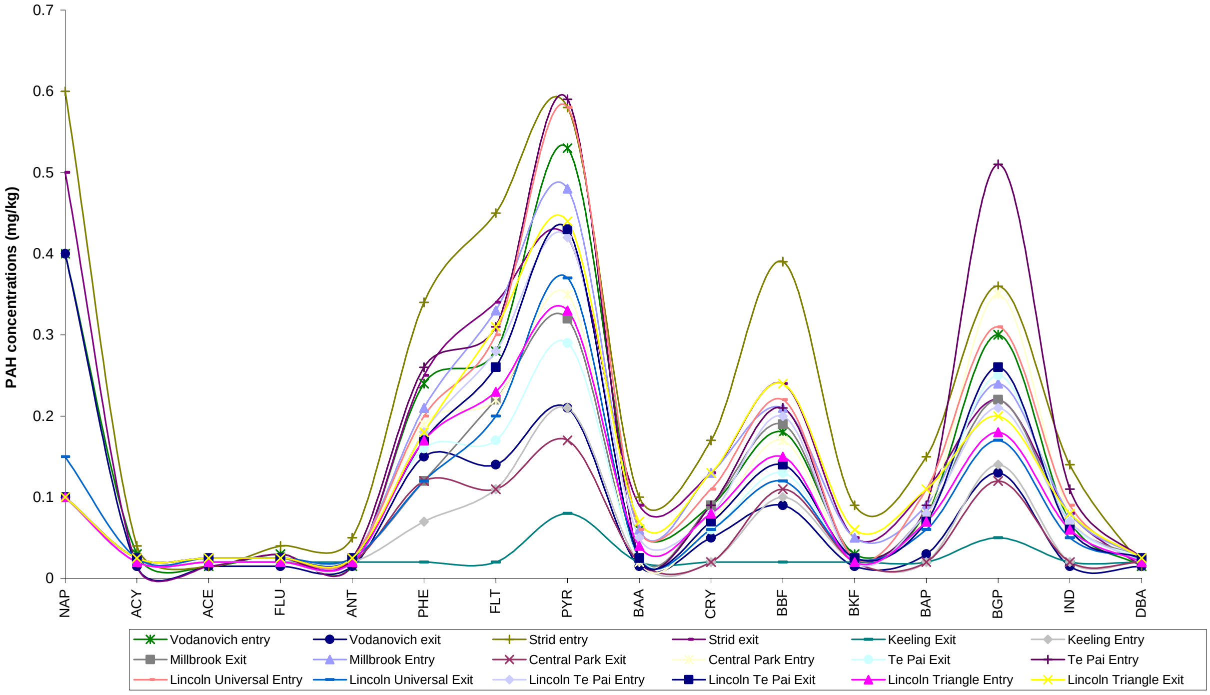


Figure 3.9 - Relative individual PAH concentrations for road surface material samples from intersection sites in Waitakere City.

Table 3.4 - Summary of PAH concentrations in Waitakere City road surface samples and Auckland gutter dust samples and Brisbane roadside soil (all data µg/kg, dry weight).

Location	Waitakere City	Pakuranga[1]		Southdown[1]		Brisbane[2] Roadside soil
Size Fraction (mm)	**<2000 (median)**	**0.047-0.12 mm**	**<0.047 mm**	**0.047-0.12 mm**	**<0.047 mm**	
Naphthalene	<200					
Acenapthene	175					
Acenaphthylene	<40					
Phenanthrene	120	-	-	-	-	715
Anthracene	<40	22	20	10	10	27.8
Fluoranthene	208.5	335	545	210	230	174
Fluorene	<40					
Pyrene	275	315	560	220	240	214
Chrysene/benz[a]anthracene	101.5	290	445	110	120	572
Benzo[b]fluoranthene	135	180	270	90	10	-
Benzo[k]fluoranthene	<50	70	105	35	40	201
Benzo[a]pyrene	70	155	210	75	85	363
Dibenzo[a,h] anthracene	<30	40	55	20	20	-
Indeno[1,2,3-cd]pyrene	58	-	-	-	-	584
Benzo[g,h,i]perylene	170	260	280	170	230	598
Coronene	-	-	-	-	-	98.6
Total PAH	1,462	1,617	2,490	920	1,085	3,346

Notes: 1 From ARC (1992) 2 From Yang et al. (1991).

Assuming that deposited particles within the road corridor have a similar composition as evident in these studies, the PAH deposited on the road is diluted by a factor of about 5-10 times by coarser particles containing lower concentrations of PAH. In the current study no analysis of any fraction finer than 2000 µm was carried out. However work by ARC (1992) did not identify large differences in the concentration of total PAH in fractions greater in size than 0.5 mm compared to those less than 0.5 mm (a factor of about two times). It is probable that isolation of very fine particles in road dust would reveal higher concentrations such as those found by Oda et al. (2001) in tunnel dust.

Phenanthrene, fluoranthene, pyrene, benzo[b]fluoranthene and benzo[ghi]perylene dominated the total PAHs measured. A number of samples contained detectable concentrations of naphthalene. Three were located at intersections and 1 was located in a straight section of road. Phenanthrene appears to be present in higher (but not statistically significant ($p>0.05$)) concentrations in samples collected at intersections sites compared to straight sections of road.

4. MODEL OUTPUT AND VERIFICATION

4.1 Vehicles emissions

As discussed by Kennedy et al. (2002) and Moncreiff & Kennedy (2002), the emission of contaminants from motor vehicles is dependent principally upon the source of the contaminant and the driving conditions. For example:

- Contaminants sourced from the exhaust system (e.g., PAHs) will be influenced by cold start and by stop-go conditions (congestion) and acceleration patterns.

- Contaminants sourced from tyres (e.g., Zn, Pb etc.,) will be influenced by road surface type, the physical parameters of the road (grade, curves etc.,) and acceleration/deceleration patterns (degree of congestion).

- Contaminants derived from brake pad wear (e.g., Cu, Pb etc.,) will be influenced by the nature of the vehicle braking cycle (e.g., degree of congestion, presence of intersections, lane changing, roundabouts etc.,).

If all of these factors were constant and the external factors that affect the build-up of materials on road surfaces and in gutters were similar then the concentration/load of contaminants would probably be well related to the average number of vehicles using a given road. This is however, not the case and these factors result in roads with similar traffic numbers having very different contaminant concentrations/loadings.

4.2 Emissions model and output

The VFEM-Water uses emission factors to estimate the amount of contaminant emitted from specific sources. The primary sources are, brake wear; tyre wear and exhaust emissions. There are other sources such as wear of road surface, loss of coolants, loss of oil. These sources and the emission factors for contaminants emitted from these sources are discussed in detail in Kennedy et al. (2002). That report describes the available emission factor data and its overall quality in relation to its use for modelling of contaminant emissions.

Airborne contaminants within the air road corridor

Contaminant concentrations in the air of the road corridor are affected by a range of factors. These include the emission rate of the contaminant; the local wind speed and its direction; thermal heat effects from the road surface and vehicles; mixing and dispersion caused by vehicle movement and turbulence that is caused by the interaction of local winds and structures adjacent to the road corridor (Karim & Marsiu 1998, Rao et al. 2002). The authors examined the nature of vehicle wake effects within the road corridor.

Initial inertial movement of contaminants from vehicle exhausts are greater when ambient winds have lower velocities (Benson 1992). Wind speed determines the initial dilution of emissions from vehicles within the road corridor. Karim et al. (1998) identified that this could be treated as an inverse relationship between wind speed and concentration. This was readily observed for the key gaseous vehicle emission components in Nagoya Japan and also suspended particles. Overall, vehicle movement is considered to influence contaminant concentrations significantly within the air corridor at least 100 m of the roadway.

The VFEM-Water is able to accommodate any number of emission sources and is able to utilise simple emission factors (e.g., a single factor for all vehicle types) or complex factors (emission factors for all vehicle classes etc.). The emission factors used in the first assessment of the model were those identified in Kennedy et al. (2002). As described in that report, emissions can be calculated per day for any given fleet and traffic LoS. As emissions from motor vehicles are dispersed in the road corridor and then into the local and regional air system, a factor is then applied to account for the proportion of contaminants that are dispersed away from the sealed road corridor. The model output is presented as the mass of contaminant deposited to the road corridor, per metre length of road, per day for the given traffic volume and fleet composition at that location.

The factors used in the current assessment should be regarded as preliminary factors. In many cases the factors are simple with one factor being used across all vehicle classes. In addition, there are considerable "uncertainties" associated with most factors.

These uncertainties were not quantified by Kennedy et al. (2002) but are likely to be large. Minimum uncertainties in the estimation of contaminant emission loads for the key vehicle particulate contaminants should be considered to be of the order of 20-50% and in some cases

100% or higher (as they are the sum of errors of a number of factors). The estimates identified in that report will be refined over time.

The model output is also adjusted for the proportion of contaminant that is not deposited within the road corridor. These adjustment factors are again based upon a number of published studies of the accumulation or deposition of contaminants in and adjacent to the road corridor.

It should be noted that many contaminants present in urban road surface dusts are derived from sources other than motor vehicles, therefore some degree of non-correlation might be expected between model output and measured road surface loadings. Those contaminants that have strong signatures from motor vehicles would tend to exhibit stronger correlations with vehicle number (e.g., the PGMs and Pb where Pb is present in petrol.

4.3 Contaminant concentrations and loadings and traffic volumes in Waitakere City

4.3.1 Contaminant Concentrations and loadings

The investigation of metal (Cu, Pb and Zn) and PAH concentrations on Waitakere City road surfaces has shown that the concentrations present are typical of what would be expected for an urban area of the size and nature of Waitakere City. With the exception of Pb, contaminant concentrations are similar to those reported previously in New Zealand urban areas. Material loadings on road surfaces are also similar to those reported for other large urban areas (e.g., Melbourne, Paris). Average contaminant loadings on road surfaces in Waitakere City are summarised in Table 4.1.

Table 4.1 - Summary of Cu, Pb, Zn and PAH loads (mg/m^2) on road surfaces in Waitakere City.

	VPD	Number of samples	Copper	Lead	Zinc	PAH
All roads		38	3.16	2.75	5.78	0.026
Straight roads	<120 VPD	3	1.97	1.62	5.64	0.017
	120-499	3	2.67	2.32	3.88	0.025
	500-999	2	2.69	4.53	9.09	0.054
	1,000 – 4,999	3	7.27	5.56	16.36	0.048
	5,000 – 9,999	3	4.39	2.70	5.16	0.021
	10,000 – 19,999	3	4.94	7.49	5.47	0.038
	>20,000	3	2.82	3.49	5.28	0.014
Intersection sites	1,000-4,999	6	5.01	11.70	12.02	0.076
	5,000 – 9,999	6	2.43	4.19	5.84	0.0094
	>10,000	6	2.13	1.86	5.27	0.021
Paris, whole street[1]			2.2	18.4	21.7	-

Note: 1 – Bris et al. (1999).

Comparison with data such as that of Bris et al. (1999) for Paris shows that Pb loads in Waitakere City are only 15% of those present in cities where Pb is still present in petrol. Cu loads are similar but Zn loads are considerably higher in Paris. Bris et al. (1999) noted that the Zn loads were very high and attributed this to corrosion of Zn from Zn surfaces.

Figures 4.2 and 4.3 illustrate the changes in concentration present in <63 and <2,000 μm road surface material as the ADT (straight road sites only) increases at the sites sampled. Examination of the trends shows that for some elements a significant increase with traffic (ADT) is present (e.g., Cu, <63 μm $p<0.05$). For intersection sites shown in Figure 4.4, the difference in concentration between the three different bands of ADT varied between the three elements. For Zn, the lowest ADT grouping had lower concentrations in both fractions analysed. For Pb, the second ADT band had the highest concentration in both fractions. For Cu, the differences between sites were less evident.

If the metal loading data in Table 4.1 is compared with the information in Figure 4.3, it is evident that the loading data does not follow the same trends. This is particularly so for the zinc loading data which does not indicate much difference between low and high ADT roads. The difference between the lowest and highest average loading data in Table 4.1 for all three elements is 4.2-4.56 times. The reasons for this lack of difference are discussed further below.

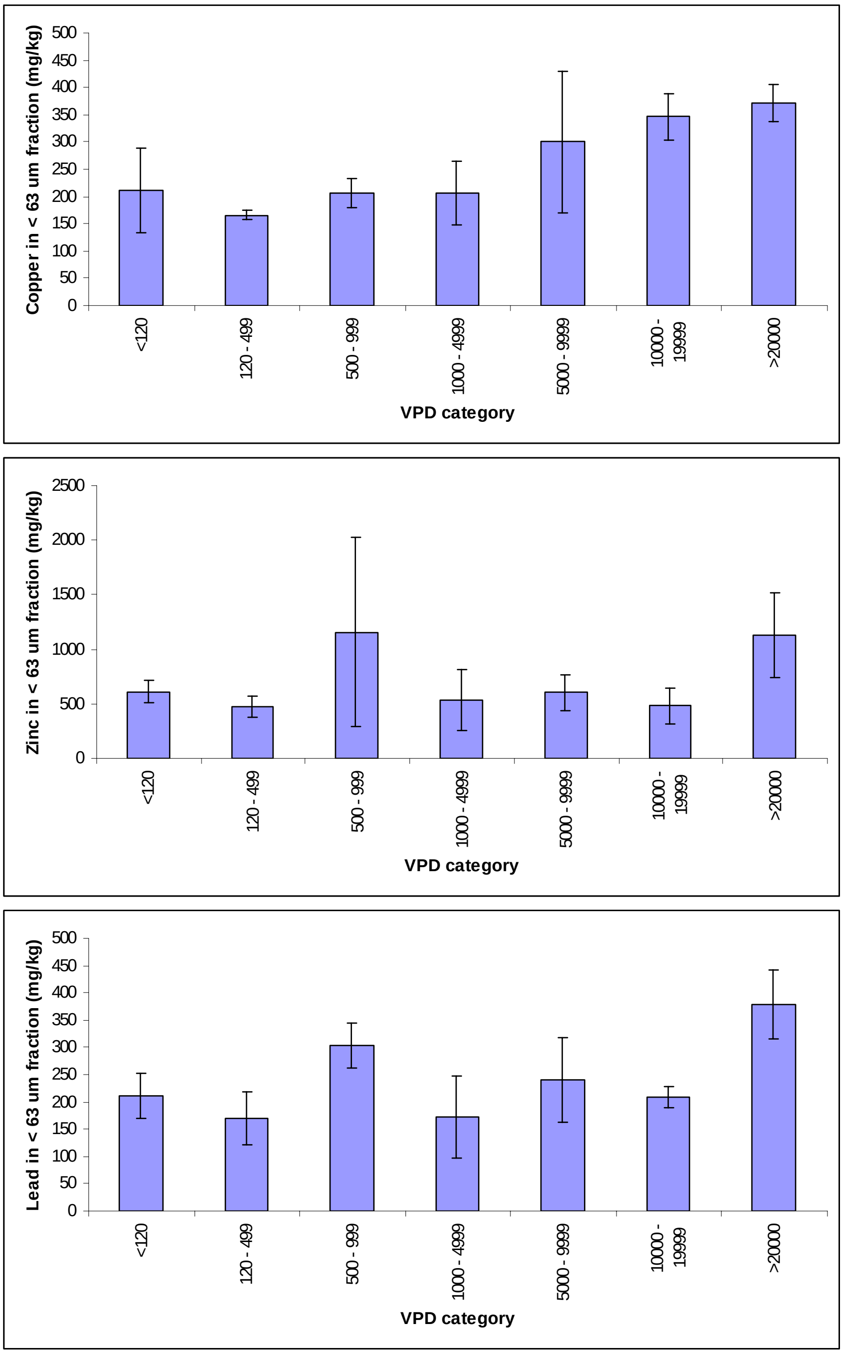


Figure 4.2 - Comparison of copper, lead and zinc concentrations in <63 µm sediment fraction at straight road sites grouped by VPD.

4.3.2 Traffic Volumes

As noted in the introduction to this section, the relationship between contaminant emissions and vehicle driving behaviour is moderately complex. However, as vehicle numbers increase emissions would be expected to increase proportionally such that differences would be expected in loadings for road surfaces with significantly different vehicle numbers.

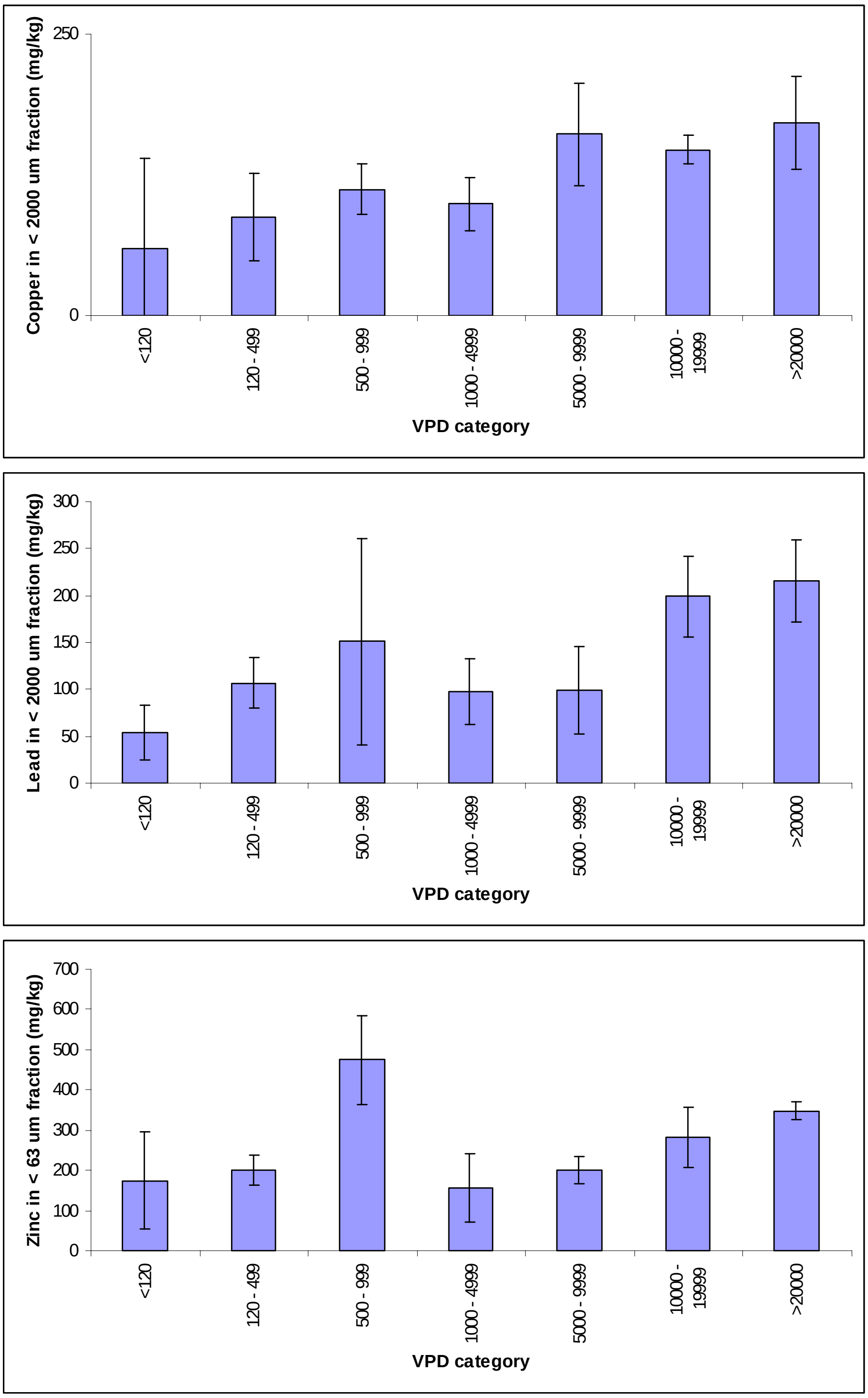


Figure 4.3 - Comparison of copper, lead and zinc concentrations in <2,000 µm sediment fraction at straight road sites grouped by VPD.

The concentrations of contaminants Cu and Pb in gutter dusts (not road surface material) were found to have a correlation ($p<0.05$) with average traffic flow at 12 locations in Wellington and Lower

Hutt (commercial, residential and industrial land-uses,) (Kennedy 2003). Figure 4.5 shows that relationship for Cu and Pb concentrations for traffic flows up to near 20,000 vehicles per day for gutter dust samples collected from a range of sites (residential, commercial and industrial) in the Wellington region. One site (Tory Street in Wellington) was omitted from the Figure as the higher Pb concentration of 6,421 mg/kg was considered to be attributable to renovation work on an adjacent building. Schafer et al. (1999) identified a relationship between the concentration of Pt and Rh in urban-road dusts in Karlsruhe with the concentration of Pt and Rh increasing by a factor of 10 times from 0-10,000 up to 50,000-70,000 vehicles per day.

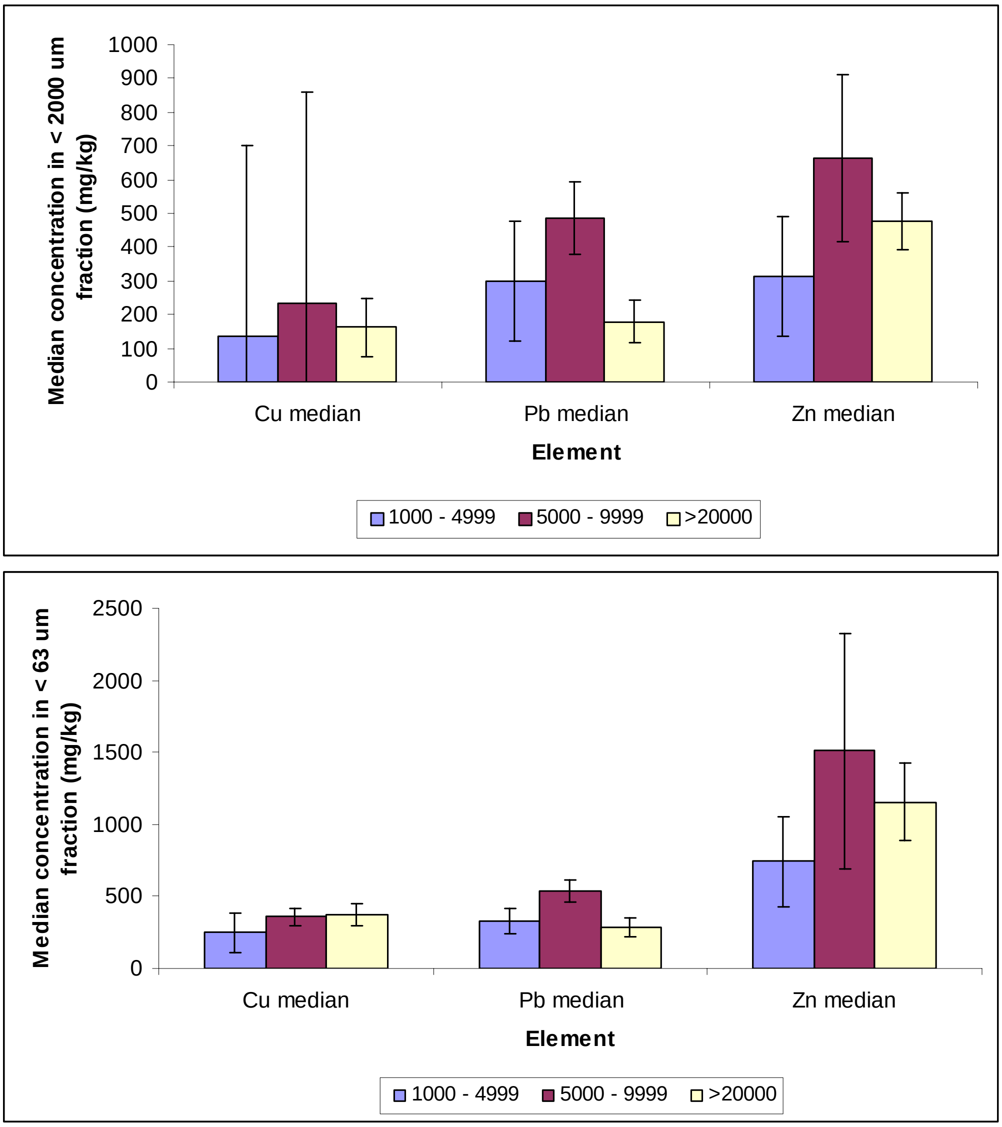


Figure 4.4 - Comparison of copper, lead and zinc concentrations in < 63 and 2,000 µm fractions of road surface material between intersection sites of different traffic volumes.

Relationships that might be observed between contaminant concentration and traffic volume are assumed to reflect a generally similar bulk material mass at each location but may represent a changing contaminant loading (derived from the increasing vehicle numbers) resulting in an increasing contaminant concentration within the material on the road surface. Waitakere City road surface Cu concentrations although slightly lower than those observed in Figure 4.5, follow the same general trend as seen in the figure with the lower VPD sites having concentrations of about 60 mg/kg and the highest VPD having concentrations around 160 mg/kg.

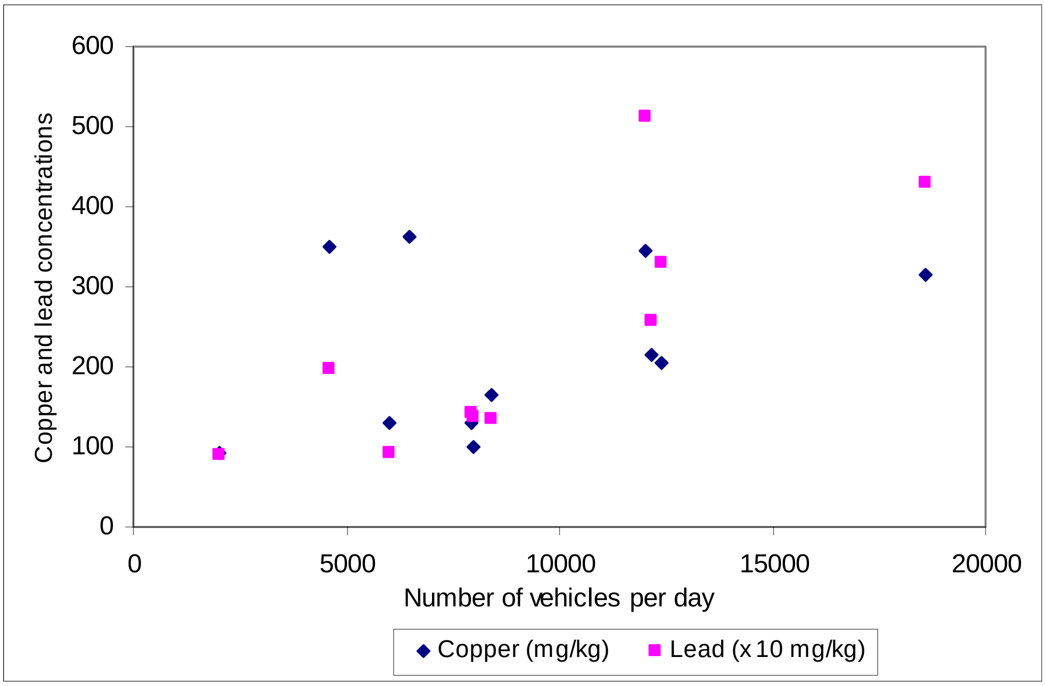


Figure 4.5 - General relationship between copper and lead concentration in Street gutter dusts sampled in Wellington and Lower Hutt in 1978 (Kennedy unpublished).

4.3.3 Re-suspension of particulates

As deposited contaminants are re-distributed following deposition, their movement within the road corridor is important. Early work by Sartor & Boyd (1972) showed that contaminants such as Pb tend to accumulate in the first metre of the road (beside the gutter) due to the redistribution of particles by vehicles. It has been recognised for some time that vehicle movement on roads influences the amount of particulate material in the air above the road surface. Venkatram et al. (1999) identified that there is considerable uncertainty in the estimation of re-suspended PM_{10} material from road surfaces (e.g., using models such as AP-42) and reviewed methods of estimating emission rates from paved roads. The authors identified an initial dispersion height of 3.5 m for re-suspended particulates, which will be dependent upon factors such as vehicle speed. The authors also suggested that material loading on the road surface was not necessarily a good estimator of the amount of re-suspended material. Re-suspended PM_{10} was expected to be present within a ‘bubble’ created by the moving vehicle. This ‘bubble is similar to that described by Rao et al. (2002) for vehicle wakes.

Kuhns et al. (2001) also examined paved road particle emissions and found through the use of on-road emissions measurement that aerosol concentrations behind the vehicle tire increased exponentially with vehicle speed. Using tunnel studies, Sternbeck et al. (2002), examined the contribution of traffic to re-suspension of metals and found that there were differences between estimated emission rates and measured airborne loads. The authors concluded that the re-suspension of dust on the road derived from soil adjacent to the road (contaminated with metals etc.,) results in over-estimates of vehicle derived airborne contaminant emission rates (in large particles).

However, one complicating factor (especially when dealing with vehicle contributions to respirable particle contamination) is that a significant proportion of the contaminant present on those additional soil derived particles may also be vehicle derived.

4.3.4 Estimated versus predicted loadings

The emission factors from VFEM-W were used to predict the loadings for contaminants on the roads studied in Waitakere City. These estimates were based on an average vehicle fleet composition from the overall New Zealand fleet. This may not be appropriate for the lower ADT roads where the fleet is likely to be further dominated by smaller vehicles. The emission factors for the average New Zealand fleet as used in the predictions in the following sections are shown in Table 4.2 below. These factors take into account the proportion of emissions that are expected to leave the road corridor.

Table 4.2 – Comparison of Cu, Pb, Zn and PAH emission factors from various New Zealand studies (all data mg/vehicle km).

	Copper	Lead	Zinc	PAHs
VFEM-W				
Normal driving conditions *	0.086	0.0035	1.2	0.079
Congested driving conditions *	0.12	0.0043	2.3	0.098
Timperley 2003	0.0593	0.0473	0.447	-
ARC 1999	0.16	-	0.70	-
This study				
25%	0.017	0.024	0.049	0.004
Median	0.16	0.11	0.18	0.014
75%	0.50	0.62	1.0	0.059

Note: * Based on average NZ vehicle fleet.

When estimating the contaminant loads emitted from motor vehicles and comparing the loads with the loads observed on the road surface, it should be noted that the estimations of emitted loads from motor vehicles are based on emission factors with relatively high levels of uncertainty associated with them. Although there is data for contaminant concentrations in material emitted, the rates or emission factors should be identified as having large errors associated with them. However, the emission factors identified in Kennedy et al. (2002) are in most cases similar to or are based upon international/published emission factors. These factors are used to identify the total load of contaminant emitted to the road corridor.

Recently vehicle emission factors have been published based on stormwater modelling studies in Auckland City (Timperley et al. 2003). The concentration of dissolved and particulate metals was measured in a large number of stormwater samples from two separate roads. The total load of metals collected was used to calculate an emissions factor per vehicle per kilometre (the emission factors include any contributions from other sources to the road surface). These are shown in Table 4.2.

The loads measured on Waitakere roads in this study were also used to back-calculate emission factors. This was undertaken by dividing the on-road measured load by the length of road studied and the number of vehicles on the road at the point of sampling. These ‘emission factors’ are also provided in Table 4.2 and are generally similar to the values calculated by Timperley et al. (2003).

The loads on the road as measured in this study were adjusted to account for the number of days accumulation of material on the road surface that has occurred prior to the sampling event occurring (or removal mechanism such as a storm event). The number of contaminants accrual days was calculated based upon the number days prior to sampling on which at least 7 mm of rain was recorded. Timperley et al. (2003) provided accrual information for a series of storm events that were roughly 8 days between significant events.

It should be noted that the on-road loads estimated in this study are based upon the removal of road surface material from the entire width of road to estimate the average loading on the road surface.

Loadings change across the road surface as a result of a number of factors including accumulation within the gutter and deposition arising from the impaction of particles on parked cars within the road corridor. The deposition and hence loading measured on the road surface also changes somewhat depending upon the width of the road and the volume of vehicles on the road. As such, a road of constant width with increasing traffic volume would be expected to have higher concentrations of contaminant and increasing loads as the traffic volume increased. However, increases in road width for the same volume will result in the same deposition pattern and load but with more contaminant collected through deposition to the road surface the total contaminant load available for stormwater runoff will increase. Typically lower ADT roads are narrow and higher ADT roads (e.g., Lincoln Road in Waitakere City) are wider. In this study, the road width varied from 6 m up to 15 m.

4.3.5 Copper

Given that brakes are identified as the predominant source of Cu contributing to the road surface Cu load, then the behaviour of Cu emissions generated by the brake system on the vehicle is important. The wear of brake pads was discussed in Kennedy et al. (2002). In tunnel studies reported by Sternbeck et al. (2002), they identified that their estimated brake wear emissions were 10 times greater that their measured emissions. The difference was attributable to accumulation of wear particles containing Cu on the vehicle wheel rim or the formation of non-suspendable particles.

In this study, some retention within vehicle brake housing would be expected and non-uniform loss of brake pad wear dust would be expected when accumulated dust is lost from the housing. In addition, it should be noted that some brake wear dust may be contributed to the road surface when it rains and the rain washes a proportion of the accumulated particles from the rims. Figure 4.6 compares the measured Cu loads on roads in Waitakere City with the amount predicted based on the VFEM-W.

The load measured per m^2 on Waitakere City road surfaces does not follow the predicted loads in this preliminary assessment. For many sites the average load on the road appears to be independent of VPD. For some sites the measured Cu concentration is much greater proportionally than other sites. It is possible that the road surface sample included some metallic Cu from an unknown source in it. This is shown in Figure 4.6. Figure 4.7 shows the data with lower Cu concentrations (note the different scale on the y-axis).

The predicted load for Cu is determined by the median Cu concentration in the particulates worn from the brake pads. In a limited study of contaminants in brake pads (Kennedy & Gadd 2000), it was reported that the median concentration may be of the order of 280 mg/kg. If that concentration is used in the estimation of loads generated by use of brakes on vehicles then the overall predicted load is very low, with all sites <0.1 mg/m^2. The use of this concentration figure produces a very low Cu emission rate (of the order of 12.6 µg/km). Other studies reported in Kennedy et al. (2002) utilise high Cu concentrations in wear particles and consequently wear rates of the order of 1,200 µg/km have been used in those studies (e.g., in Sternbeck et al. 2002).

As noted in Kennedy et al. (2002), the appropriate concentration data to use to calculate fleet averaged emission data is dependent upon the nature and type of pads used by the various classes of vehicles in the New Zealand vehicle fleet. Of the studies reported in Kennedy et al. (2002), most have a significant number of high Cu containing brake pads within the suite of pads examined (e.g., containing 100,000 mg/kg Cu). Given the significant discrepancy between the measured loads and the initial predicted loads (using the median data reported for New Zealand pads – refer Kennedy et al. 2002), a nominal figure of 5,000 mg/kg has been used in this first order estimation of predicted loads using VFEM-W.

The predicted amount of Cu on the road surface is also dependent upon the number of accrual days. In addition, as noted earlier, the fixed load on the road may represent 40-50% of the total load on the road surface. As the rainfall (and intensity) prior to collection may not have been sufficient to remove all of the Cu, the number of days contaminant accumulation significantly influences the predicted load. For the predictions in Figure 4.6, the measured loads are divided by the number of days since the last 7 mm rainfall.

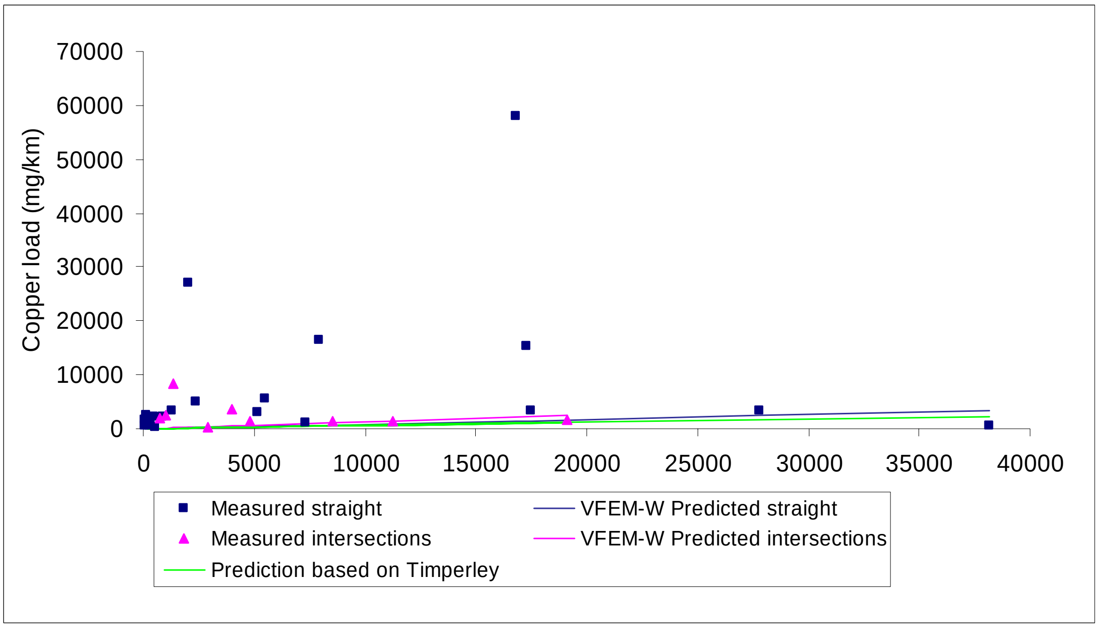


Figure 4.6 - Measured and predicted copper loading on Waitakere City road surfaces (all data shown).

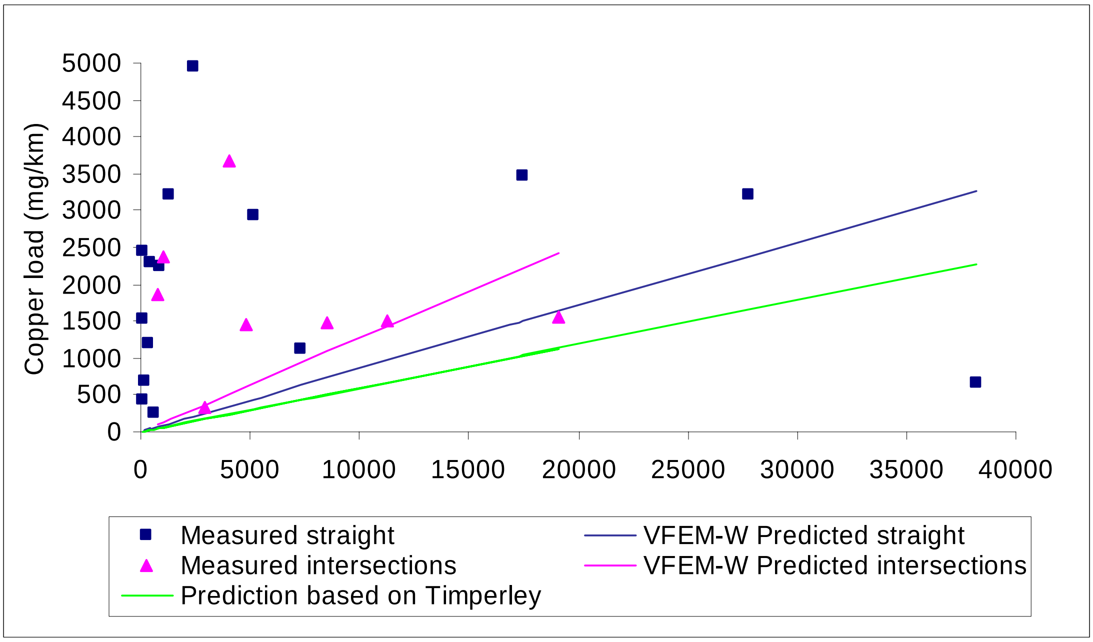


Figure 4.7 - Measured and predicted copper loading on Waitakere City road surfaces (not all data shown).

The predicted VFEM-W output for Cu based upon the emission factors identified above show that on straight roads and intersection entries, brakes wear contributed 96% of the emitted Cu. At intersection exits this figure was 97.2%. Exhaust emissions were identified as contributing 3.9 and 2.6 % and tyres contributed only a minor amount at 0.2%.

Overall, the assessment of Cu predictions by VFEM-W is completely dependent upon the Cu emission rate, which is dependent in turn on the concentration of Cu in the particles worn from brake pads. Comparison of the VFEM-W emission estimates with the back-calculated emission rates from this study and Timperley et al. (2003) (Table 4.2) shows that they are generally within a factor of two of each other. To refine the estimates of Cu emissions using the VFEM-W, the following is required:

1. Improvements in the certainty in the fleet weighted Cu concentrations (primarily in brake pad wear particles) used in the calculation of predicted loads.

2. Refinement of the on-road deposition factor (the proportion of Cu reaching the road).

3. Refinement of the wear rate factors for brakes under different driving conditions).

Because of the extremely highly variable nature of Cu in brake pads and between types of pads used by different vehicle classes an accurate assessment of Cu emissions using the model will only be possible using fleet weighted average concentrations that take into account the range of pads on the current market and used by the different vehicle classes (used by VFEM-W).

4.3.6 Lead

Figure 4.8 illustrates the measured Pb load on road surfaces in Waitakere City and the loads predicted using VFEM-W. The measured load of Pb on Waitakere roads is much higher than the predicted loads. The predicted loads were calculated using generic emission factors for Pb which do not reflect the use of Pb free petrol currently in New Zealand petrol. One of the most significant factors that needs, to be taken into account is assessing what proportion of the Pb in the measured load is derived from historic vehicle contributions and arriving on the road surface by deposition on dust entrained from roadside areas. The contribution can be potentially estimated from the silt load on road and information on the average concentration in soils in road-side areas.

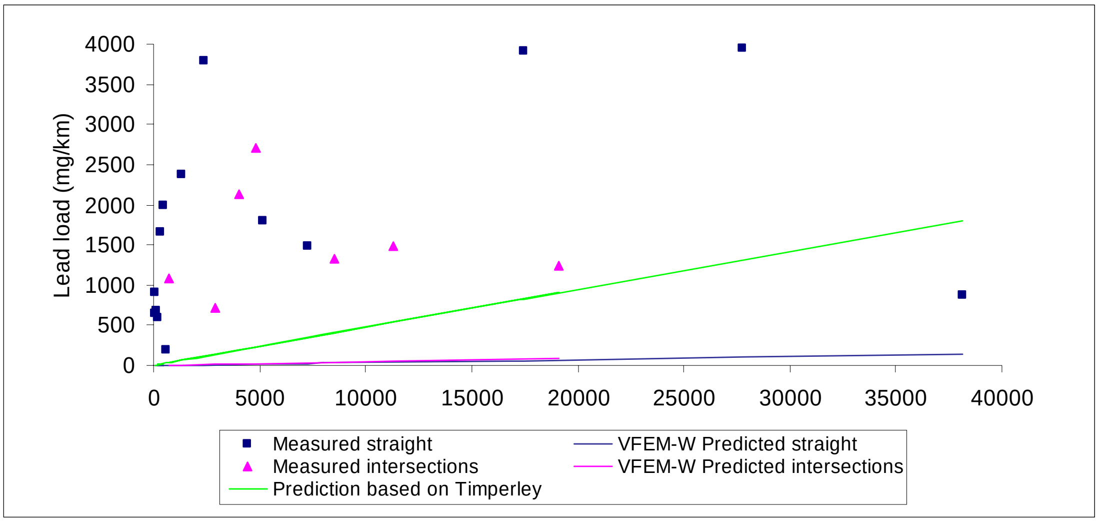


Figure 4.8 - Measured and predicted lead loading on Waitakere City road surfaces.

The concentration of Pb in soil adjacent to roads in New Zealand has been relatively well studied and provides an indication of the likely concentration of Pb associated with soil particles deposited on road surfaces from adjacent areas. Kennedy et al. (1988) reported that Pb concentrations in <36 um dust in roadside gutters in the Auckland area had geometric mean concentrations ranging from 1,093 mg/kg in Mangere to 2,564 mg/kg in Clover Park (30,000 VPD).

The soil adjacent to busy roads also contains high concentrations of Pb as a result of past emissions. Concentrations in bulk soils immediately adjacent to most busy roads are likely to be of the order of 1,000 mg/kg (and Pb concentrations in re-suspendable particles).

The examination of Waitakere road surfaces has shown that about 10% of the material on the road surface is of silt size. This material if derived from the environment adjacent to the road is likely to contribute Pb. If it is assumed that this contributed silt contained 1,000 mg/kg Pb (the actual typical concentration in Waitakere soils is not known) then the silt load would contribute at least 50% of the Pb measured in the Pb load present on the surface of Waitakere roads. The silt load on Waitakere road surfaces is closely related to the overall Pb load (which was calculated from the <2 mm material load and concentration) ($R^2 = 0.806$).

If this “existing contribution” is removed from the measured loads, there is still a relatively significant difference between the measured and predicted loads. This difference may be the result of:

1. The certainty in the fleet weighted Pb concentrations in brake and tire wear particles used in the calculation of predicted loads.

2. Utilisation of appropriate data for metals in exhaust emissions using New Zealand fuels.

3. Refinement of the on-road deposition factor (the proportion of Pb reaching the road).

4. The need to further account for the Pb contributed by soil adjacent to roads.

Given the relatively low predicted loads based compared to the measured loads, the number of days accrual has little effect on the comparison of predicted and measured loads. The back-calculated emission factors from this study and those calculated by Timperley et al. (2003) are within a factor of about two. Both factors are higher by than the VFEM-W factors by a factor of 10. This could imply that the VFEM-W emission factors are under-estimating the proportion of Pb reaching the road surface from vehicles or there is a significant amount on non-current vehicle derived Pb reaching the road surface from areas adjacent to the road. It is likely that the answer is a combination of these factors.

4.3.7 Zinc

Figure 4.9 provides a comparison of the measured zinc load measured on Waitakere City roads and the loads assessed using the VFEM-water. The measured zinc loads is higher than the predicted zinc loadings. Zinc in tire wear is the most significant source of zinc contributing to the road surface loading of zinc. As with Cu the predicted estimates are very dependent upon the identification of concentration data that reflects the concentration present within the on-road tyre fleet. The tyre zinc concentration used in the VFEM-W is an average concentration (8,310 mg/kg, range 1,190-18,300) based upon limited examination of New Zealand tyres (Kennedy & Gadd 2000; Kennedy et al. 2002). This produced an emission rate for zinc derived from tire wear of 1 mg/km (using an average tyre wear rate of 120 mg/km). In comparison Sternbeck et al. (2002) utilised a concentration of 16,000 mg/kg zinc and a wear rate of 150 mg/km to produce an emission rate of 2.4 mg/km (which when compared to their tunnel based measurements of zinc was considered high). They noted that the emission factor lacked confidence citing the USEPA PART5 model which uses 5 mg/km for a four wheel passenger vehicle. They noted that both brakes and tyres would be expected to contribute to the zinc load.

Figure 4.8 summarises the measured and predicted zinc loading data for the sampling sites in Waitakere City. The comparison shows that there appears to be little relationship with vehicle numbers at the sites samples. In Table 4.2, it can be seen that the back-calculated Zn emission rates for vehicles from this study and Timperley et al. (2003) are within a factor of two. These factors are about five times lower than the emission rates calculated by the VFEM-W. There are a number of factors that influence the measured and predicted loads of zinc on the road. These factors need to be investigated further to refine the predicted loads further:

1. The certainty in the fleet weighted tire zinc concentrations used in the calculation of predicted loads.

2. Refinement of the on-road deposition factor (the proportion of zinc reaching the road).

3. Refinement of the wear rate factors.

4. Refine the estimate of accrual period for contaminants.

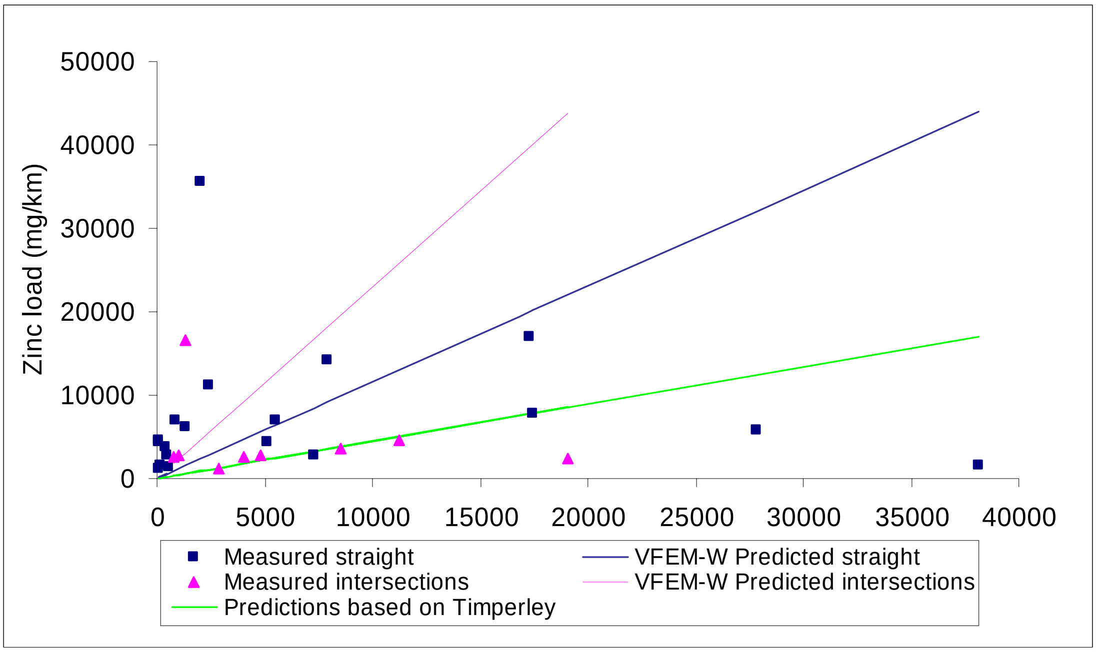


Figure 4.9 - Measured and predicted zinc loading on Waitakere City road surfaces.

4.3.8 PAHs

Concentrations of PAH measured in particles on road surfaces in Waitakere City are similar to those measured in earlier work undertaken in Auckland (ARC 1992). Figure 4.10 illustrates the predicted and measured loads of PAH on road surfaces at the sites sampled in Waitakere City. Unlike the estimates and measured loads of the three metals, the predicted PAH load was substantially greater than the measured loads.

The calculation of emission loads from vehicles at each of the sites has shown that 61.5 and 75.9% of the emitted load was derived from the exhaust system at intersections and on the straight sections respectively. Brakes were an insignificant source (<0.5%). Tyres accounted for 23.7% of the PAH load on the straight sections of road and 38.2% at intersections. Traffic emissions account for virtually all of the PAH present in the air above the roadway surface (e.g., -90% - Nielson 1996) and as such, vehicles are likely to be the primary source of PAHs deposited on Waitakere City roads. Consequently, the relationship between what is observed on the road surface will be a function of particle deposition processes, re-suspension of particles and chemical processes that influence the concentration associated with particles on the road surface.

The PAH emission factor for the tyres is based on the data of Rogge et al. (1993) who measured a total PAH concentration in tyres of 226 mg/kg. Gadd & Kennedy (2000) examined PAH concentrations in New Zealand tyres and found total PAH concentrations in the order 11-123 mg/kg. However, the data of Gadd & Kennedy (2000) included a limited number of PAHs, many were not detected (10 mg/kg). As such the Kingett Mitchell data is likely to underestimate the concentrations present. In addition, Rogge et al. (1993) included a range of methylated PAHs in their analytical scheme. The analysis of the Waitakere road surface material included some 16 PAHs, of which, 12 were included by Rogge et al. (1993). To allow comparison of the Rogge data and data from this study, the concentration of PAHs that were not in the Waitakere study were removed from the Rogge total resulting in the 226 mg/kg reducing to 89 mg/kg. This concentration was used in the assessment of predicted loads. The figure is higher than the median from the Gadd & Kennedy (2000) study but is considered to be in the correct order of concentration.

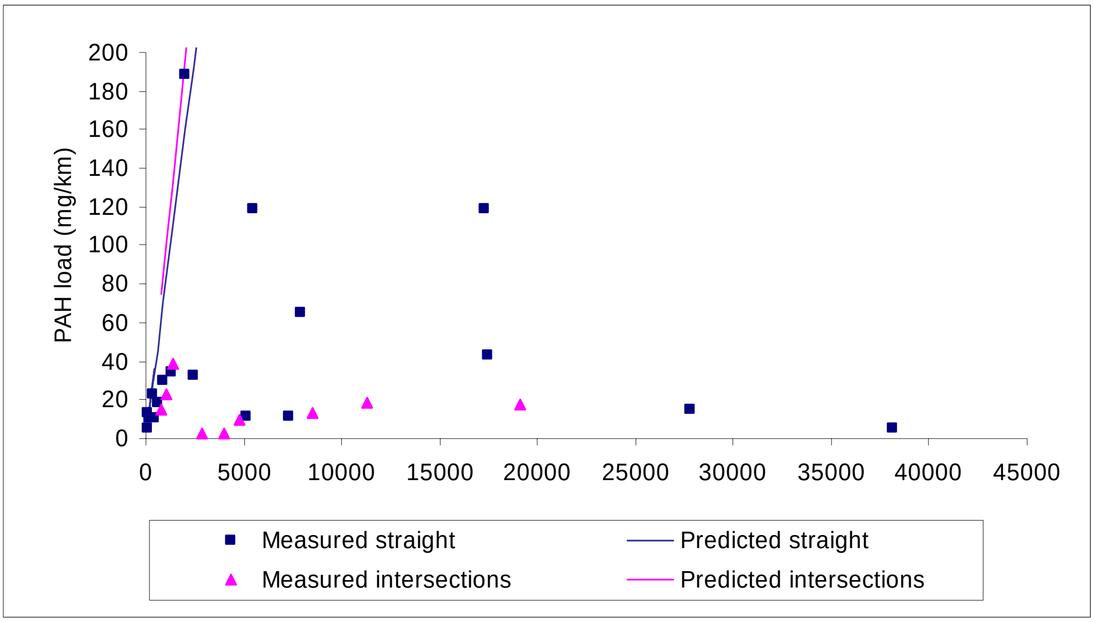


Figure 4.10 - Measured and predicted PAH loading on Waitakere City road surfaces.

Given the contribution that tires potentially make to the on-road loading then the concentration used in the emission loading estimates is important. Two key refinements will be required to improve the resolution of the PAH emission outputs from the VFEM-W. The first is the wear rate factors for different vehicle classes and for different driving styles/road conditions has the potential to vary the emitted load considerably. As noted by Kennedy et al. (2002) modelled output such as that from the tyre wear model HDM4 will be required to reduce the uncertainty that arises from the affect of road geometry and driving habits. The second is the concentration of PAH in tyres needs to be refined given the variation identified amongst brands of tyres and between different types (PC versus HD vehicles).

5. OVERVIEW

The measurement of contaminant concentrations and loadings of contaminants on road surfaces with differing traffic volumes has shown that:

1. Road surfaces in Waitakere City carry loads of material (soil, dust and debris) that are similar to those reported in other urban areas (e.g., in Australia).

2. The proportion of fine dust (e.g., silt and clay) is also similar to that observed else where.

3. The concentrations of the key motor vehicle sourced contaminants Cu and zinc are present on road surfaces in concentrations similar to those recorded previously in New Zealand.

4. The concentration of Pb in road surface material is considerably lower than measured prior to the removal of Pb from petrol. Pb is still present in high concentrations.

5. PAH concentrations have been measured in concentrations similar to previous measurements made in 1992 elsewhere in Auckland. The PAH fingerprints are also similar to previous road dust characterisation.

The concentrations present in road surface materials showed some general relationship with traffic volume. Differences were also identified in the concentrations present for Zn at intersection entry lanes compared to exit lanes.

For each site sampled in Waitakere City the VFEM-W was used to identify the load of each contaminant deposited on the road surface. This first run of the model utilised contaminant emission factors presented in Kennedy et al. (2002). The calculated emission loads (using the VFEM-W) differed to the loads measured on road surfaces in Waitakere City. The degree of difference was dependent upon the contaminant involved. Examination of the loads predicted using the model identified a series of limitations within the present model that will need to be refined to allow the model to estimate loadings to road surfaces with less uncertainty. The following points were identified:

1. As the primary source of Cu emissions from motor vehicles is the wear of brake pads, improvements in the particle wear estimates (for vehicle classes in particular) and the concentration of Cu in wear particles is needed. The Cu concentration data for vehicle classes requires that concentrations be obtained using a fleet weighted brake pad sampling approach.

2. As the primary source of zinc emissions from motor vehicles is the wear of tires, improvements in the particle wear estimates and the concentration of zinc in wear particles is needed. The zinc concentration data for vehicle classes requires that concentrations be obtained using a fleet weighted tyre sampling approach. Such improvements in the data source used for emission factors should improve the predictions of zinc loads.

3. For Pb, further work is required to identify the proportion of Pb on roads sourced from non-road sources (which include historic Pb deposition from alkyl Pb use). The current prediction using the VFEM suggest that off-road sources may be a significant source of Pb.

4. New data is required on the emission rates from Pb free fuels. Any data on the emission rates of particulate metals collected at the same time would result in improvements to metal emission factors.

5. Improvements are required in the vehicle exhaust PAH emission rates in New Zealand to provide better estimates of on-road PAH concentrations.

6. REFERENCES

ARC, 1992: An assessment of stormwater quality and the implications for the treatment of stormwater in the Auckland region. Report prepared by Kingett Mitchell & Associates Ltd. Auckland Regional Council, Environmental Planning Division Technical Report No 5. April 1992.

Ball, J. E.; Jenks, R.; Auborg, D. 1998: An assessment of the availability of pollutant constituents on road surfaces. The science of the total environment 209: 243-254.

Benson, P. E.; A review of the development and application of the CA-LINE3 and 4 models. Atmospheric environment 26B: 379-390.

Bris, F-J.; Garnaud, S.; Apperry, N.; Gonzalea, A.; Mouchel, J-M.; Chebbo, G.; Thevenot, D. R. 1999: A street deposit sampling method for metal and hydrocarbon contamination assessment. The science of the total environment 235: 211-220.

Brockbank, C. I.; Batley, G. E.; Ball, J. E.; Tilley, J. H. 1999: Metals and hydrocarbons in stormwater runoff from urban roads. CSIRO Division of Energy Technology, Centre for Advanced Analytical Chemistry Investigation Report ET/IR98R. Prepared for the Roads and Traffic Authority of New South Wales, January 1999.

Ellis, J. B.; Revitt, D. M. 1982: Incidence of heavy metals in street surface sediments: solubility and grain size studies. Water air and soil pollution 17: 87-100.

Fergusson, J. E.; Ryan, D. E. 1984: The elemental composition of street dust from large and small urban areas related to city type source and particle size. The science of the total environment 34: 101-116.

Gadd, J.; Kennedy, P. 2000: Preliminary examination of organic compounds present in tyres, brake pads and road bitumen in New Zealand. Prepared by Kingett Mitchell Ltd for Ministry of Transport, November 2000, revised October 2003.

Heaney, J. P.; Pitt, R.; Field, R. 1999: Innovative urban wet-weather flow management systems. EPA/600/R-99/029.

Karim, M.; Matsui, H. 1998a: A mathematical model of wind flow, vehicle wake, and pollutant concentration in urban road microenvironments. Part 1: model description. Transportation research 3(2): 81-92.

Karim, M.; Matsui, H.; Guensler, R. 1998b: A mathematical model of wind flow, vehicle wake, and pollutant concentration in urban road microenvironments. Part 2: model results. Transportation research 3(3): 171-191.

Kennedy, P. C. Kjellstrom, T. K.; Farrell, J. 1988: Environmental lead and lead in primary and pre-school children's blood in Auckland New Zealand. New Zealand Energy Research and Development Committee. Report No. 169. February 1988.

Kennedy, P. C.; Gadd, J. 2000: Preliminary examination of trace elements in tyres, brake pads and road bitumen in New Zealand. Report prepared for New Zealand Ministry of Transport by Kingett Mitchell Limited, November 2000, revised October 2003.

Kennedy, P. C.; Gadd, J.; Moncreiff, I. 2002: Emission factors for contaminants released by motor vehicles. Report prepared for Infrastructure Auckland and New Zealand Ministry of Transport. December 2002.

Kennedy, P. C. 2003: Metals in particulate material on road surfaces. Prepared for New Zealand Ministry of Transport by Kingett Mitchell Limited, October 2003.

Kuhns, H.; Etyemezian, V.; Landwehr, D.; MacDougall, C.; Pitchford, M.; Green, M. 2001: testing re-entrained aerosol kinetic emissions from roads (TRAKER): a new approach to infer silt loading on roadways. Atmospheric environment 35: 281502825.

Lau, S. L.; Stenstrom, M. K. 2001: Metals and PAHs adsorbed to street particles, pp 122-134. In Rain – the forgotten resource. Second South Pacific stormwater conference, 27-29 June 2001, Auckland.

Lee, W-J.; Wang, Y-F.; Lin, T-C.; Chen, Y-Y.; Lin, W-C.; Ku, C-C.; Cheng, J-T. 1995: PAH characteristics in the ambient air of traffic source. The science of the total environment 159: 185-200.

Legret, M.; Pagotto, C. 1999: Evaluation of pollutant loadings in the runoff waters from a major rural highway. The science of the total environment 235: 143-150.

Li, X.; Poon, C-S.; Liu, P. S. 2001: Heavy metal contamination of urban soils and street dusts in Hong Kong. Applied geochemistry 16: 1361-1368.

Malmquist, P. A. 1978: Atmospheric fallout and street cleaning – effects on urban stormwater and snow. Progress water technology 10 (5/6): 495-505.

Moncreiff, I.; Kennedy, P. C. 2002: Road Transport Impacts on Aquatic Ecosystems, Issues and Context for Policy Development. Report prepared for Ministry of Transport by Fuels & Energy management Limited and Kingett Mitchell Limited, February 2002.

Nielsen, T. 1996: Traffic contribution of polycyclic aromatic hydrocarbons in the centre of a large city. Atmospheric environment 30(20): 3481-3490.

Oda, J.; Nomura, S.; Yasuhura. A.; Shibamoto, T. 2001: Mobile sources of atmospheric polycyclic aromatic hydrocarbons in a roadway tunnel. Atmospheric environment 35: 4819-1827.

Pitt, R. 1987: Small storm urban flow and particulate wash-off contributions to outfall discharges. Ph.D. dissertation submitted to the Department of Civil and Environmental Engineering. University of Wisconsin – Madison.

Rao, K. S.; Gunter, R. L.; White, J. R.; Hosker, R. P. 2002: Turbulence and dispersion modelling near highways. Atmospheric environment 36: 4337-4346.

Rogge, W. F.; Hildemann, L. M.; Mazurek, M. A.; Cass, G. R.; Simonelt, B. R. 1993: Sources of fine organic aerosol. 3. Road dust, tire debris, and organometallic brake lining dust: Roads as sources and sinks. Environmental science and technology 27: 1892-1904.

Sartor, J. D.; Boyd, E. B. 1972: Water pollution aspects of street surface contaminants. U.S. Environmental Protection Agency, EPA-R2-72-081.

Schafer, J.; Eckhardt, J-D.; Berner, Z. A.; Stuben, D. 1999: Time dependent increase of traffic emitted platinum-group elements (PGE) in different environmental compartments. Environmental science and technology 33: 3166-3170

Sternbeck, J.; Sjodin, A.; Andreasson, K. 2002: Metal emissions from road traffic and the influence of resuspension – results from two tunnel studies. Atmospheric environment 36: 4735-4744.

Timperley, M.; Bailey, G.; Pattinson, P.; Kuschel, G. 2003: Zinc, copper and lead in road runoff. 26th Australasian Transport Research Forum, Wellington, New Zealand, 1 - 3 October 2003.

Vaze, J.; Chiew, F. H. S. 2002: Experimental study of pollutant accumulation on an urban road surface. Urban water 4: 379-389.

Venkatram, A.; Fitz, D.; Bumiller, K.; Schuming, D.; Boeck, M.; Ganguly, C. 1999: using a dispersion model to estimate emission rates of particulate matter from paved roads. Atmospheric environment 33: 1093-1102.

Westerlund, K-G. 2001: Metal emissions from Stockholm traffic – wear of brake linings. Stockholm Environment and Health Protection Administration, April 2001. Stockholm Air Quality and Noise Analysis SLB Analysis No 3: 2001.

Yang, S. Y. N.; Connell, D. W.; Hawker, D. W.; Kayal, S. I. 1991: Polycyclic aromatic hydrocarbons in air, soil and vegetation in the vicinity of an urban roadway. The science of the total environment, 102: 229-240.

Yim, W. W. S.; Nau, P. S. 1987: Distribution of lead, zinc, copper and cadmium in dust from selected urban areas of Hong Kong. Hong Kong engineer, 7-14.

Appendices

Blank

Appendix A1 – Waitakere City Site Characteristics

Road Name	**Road Hierarchy Type**	**Landuse Left**	**Landuse Right**	**Lanes**	**Road Width**	**Road surface type (observed)**	**Speed Limit**	**Average Roughness (NAASRA)**	**Minimum Roughness (NAASRA)**	**Maximum Roughness (NAASRA)**	**Potholes**	**Litter on road**
POMELO RD	Local Road	Residential	Residential	1	6.7	Aggregate	50	100	83	118	none	Negligible
STEPHEN AVE	Local Road	Residential	Residential	1	7	Hot mix	50	174	159	190	none	Negligible
COLETTA LN	Local Road	Residential	Residential	1	5.5	Aggregate	50	100	99	102	none	Negligible
LONGBURN RD	Local Road	Residential	Residential	1	7.2	Aggregate	50	96	25	152	none	Mashed up paper, quite a bit in gutters
KINGDALE RD	Local Road	Residential	Residential	1	6.3	Aggregate	50	96	31	125	none	Negligible
BORICH RD	Local Road	Residential	Residential	1	8.2	Hot mix	50	75	65	85	1x5 cm diameter hole & 1x5 cm wide crack in gutter	Some dirt
SYLVAN CRES	Local Road	Residential	Residential	1	6.8	Aggregate	50	88	25	129	none	Negligible
HARRINGTON RD	Local Road	Residential	Residential	1	7	Aggregate	50	94	87	102	none	Negligible
HINDMARSH ST	Local Road	Residential	Residential	1	8.5	Aggregate	50	95	82	108		
KEELING RD	Local Road	Training centre	Factory offices	1	12	Hot mix & aggregate	50	59	44	74	none	2x bottle caps, 2x cigarette butts, paper
VODANOVICH RD	Local Road	Residential	Residential	1	7.9	Hot mix & aggregate	50	83	76	91	none	Broken glass
Road Name	Road Hierarchy Type	Landuse Left	Landuse Right	Lanes	Road Width	Road surface type (observed)	Speed Limit	Average Roughness (NAASRA)	Minimum Roughness (NAASRA)	Maximum Roughness (NAASRA)	Potholes	Litter on road
SEYMOUR RD	District Arterial Route	Residential	subdivision, earthworks	1	9.6	Aggregate	60	90	74	105	none	Sand, cigarette butts, foil, mud
CORBAN AVE	Distributor Road	Park/school	Park/school	1	11	Aggregate	50	61	25	105	none	Dirt, grass clippings, chewing gum
BORDER RD	District Arterial Route	Residential	Residential	1	10.1	Aggregate	60	51	44	59	none	Leaves, leaf litter
BRUCE MCLAREN RD	Distributor Road	Residential	Residential & disused orchard	1	9.7	Aggregate	60	77	55	131	none	Cigarette butts, leaves, grass
POMARIA RD	Distributor Road	Residential	Residential	1	8.6	Hot mix, aggregate & concrete	50	97	78	116	10 cm diameter	Cigarette butts, nails (removed)
HENDERSON VALLEY RD	Regional Arterial Route	Industrial	Park/school	1	14.7	Aggregate	60	83	65	117	none	Foil, plastic, grass in gutter, substantial dirt & dust in gutter
WEST COAST RD	District Arterial Route	Park	Residential	1	11.8	Aggregate	60	54	42	73	none	Negligible
LINCOLN RD	Regional Arterial Route	Residential	Commercial	2	12.3	Hot mix	50	77	59	97	none	Bubble gum, broken glass, dirt

Appendix A2 – Number of days prior to sampling for key rainfall events – days based on Henderson Meteorological Station data.

Date	Sites Sampled	No. days previous to sampling that rainfall occurred			
		0 mm	1 mm	7 mm	15 mm
15-May	Pomelo Rd Coletta Ln Sylvan Cres	5	11	17	19
16-May	Longburn Rd Kingdale Rd Keeling Rd	6	12	18	20
17-May	Harrington Rd Corban Ave Border Rd	7	13	17	17
16-Jul	Bruce McLaren Rd West Coast Rd Henderson Valley	4	4	4	5
30-Jul	Pomaria Rd Vodanovich Rd Seymour Rd	4	7	8	8
1-Aug	Stephen Ave Borich Rd Lincoln Rd	6	9	10	10
2-Aug	Strid Rd Vodanovich Rd	7	10	11	11
2-Dec	Keeling Rd Milbrook Rd	5	5	16	31
3-Dec	Te Pai Place Central Park Dr Lincoln Rd 2	6	6	17	32
4-Dec	Edmonton Rd Lincoln/Te Pai	7	7	18	33
5-Dec	Lincoln/Universal Lincoln/Triangle	8	8	19	34

Appendix B – Waitakere City road surface sample texture and metal concentrations

		Texture			< 63 µm Metal concentrations			< 2 mm metal concentrations		
Sample Name	**Total mass of sample**	**> 2 mm**	**>63 µm <2 mm**	**< 63 µm**	**<63 um Cu**	**<63 µm Pb**	**<63 µm Zn**	**<2 mm Cu**	**<2 mm Pb**	**<2 mm Zn**
	g	g	g	g	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Pomelo	707	331	349	26.1	210	212	612	60	86.7	175
Stephen	1454.1	491.3	570.13	42.11	297.0	236	697	48	28.2	137
Coletta	732	81.3	591	57.5	142	155	485	192	53.8	363
Borich	544.6	82.33	401.49	60.52	174.0	151	363	149	129	176
Longburn	637	214	384	45.7	166	170	474	87	76	201
Kingdale	988	147	766	72	156	242	564	77	107	249
Sylvan Sweeps	348	220	100	15	226	274	1770	96	72.6	553
Harrington	1270	371	767	138	187	332	547	128	229	396
Vodanovich	4940	4000	851	82.9	187	172	535	82	60.7	157
Seymour	8800	2240	6010	539	207	165	267	99	130	130
Keeling Sweeps 1-4	2983	896	1928	153	296	300	816	128	97.9	288
Corban Sweeps 1-4	1454.3	513.1	885.3	46.8	303	251	750	159	97.1	239
Pomaria	1150	342	718	85.7	297	364	493	163	178	208
Border 17/5/02	995	256	665	68.6	251	228	709	78	102	194
Bruce McLaren	1560	458	1040	56	539	182	418	179	68.7	155
Henderson Valley	5230	498	4330	392	346	198	483	147	199	303
West Coast Rd	1460	226	1110	112	383	209	372	149	226	165
Lincoln Rd	959.5	134.18	685.38	139.53	297	236	697	126	142	281
Edmonton	1290	424	812	50	348	424	855	200	246	363
Lincoln 2	316	77	222	16.8	395	334	1400	142	185	332

		Texture			< 63 µm Metal concentrations			< 2 mm metal concentrations		
Sample Name	**Total mass of sample**	**> 2 mm**	**>63 µm <2 mm**	**< 63 µm**	**<63 µm Cu**	**<63 µm Pb**	**<63 µm Zn**	**<2mm Cu**	**<2mm Pb**	**<2mm Zn**
	g	g	g	g	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Strid Rd 2/3 + Strid Entry 1	1435.87	747.19	307.07	28.66	426	323	1030	114	160	319
Strid Rd Exit + Strid Exit 2/3	692	312.58	349	30.04	479	247	798	161	94.6	226
Vodanovich School Intersection entry	386.7	94.11	252.4	40.13	298	482	1110	114	409	460
Vodanovich School Intersection exit	394	93.88	249.5	50.28	160	241	340	261	584	307
Keeling Exit	5740	1980	3440	589	202	338	400	107	254	212
Keeling Entry	2400	731	1500	164	170	331	683	1520	347	686
Te Pai Exit	99.4	24.6	67.1	7.3	404	543	2690	226	483	865
Te Pai Entry	142	42.9	84.7	13.8	282	489	2420	237	391	983
Central Park Exit	229	72	146	10.4	322	559	1360	1190	695	845
Central Park Entry	218	69.5	136	11.8	392	549	1660	143	541	482
Millbrook Exit	340	34	264	42	317	349	626	228	426	425
Millbrook Entry	554	76.9	421	55.4	448	527	925	1600	492	459
Lincoln Triangle Entry	827	263	528	35.9	470	394	1440	173	158	582
Lincoln Triangle Exit	623	105	459	57.8	261	258	736	164	147	388
Lincoln Universal Entry	327	92.3	206	27.7	290	299	1440	160	201	537
Lincoln Universal Exit	847	227	557	62.2	386	277	1070	138	136	417
Lincoln Te Pai Exit	325	93.2	208	24.3	383	256	1240	365	290	540
Lincoln Te Pai Entry	677	217	411	47.3	362	397	1050	152	258	409

Appendix C – Waitakere City road surface material PAH concentrations

Sample Name	Naphthalene	Acenaphthylene	Acenaphthene	Fluorene	Anthracene	Phenanthrene	Fluoranthene	Pyrene	Benzo[a]anthracene	Chrysene
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Pomelo	0.15	0.084	0.446	0.261	0.67	3.72	11.6	5.87	3.1	2.93
Stephen	< 0.03	< 0.006	< 0.006	< 0.006	< 0.006	0.041	0.067	0.074	0.019	0.023
Coletta	0.03	0.006	< 0.006	< 0.006	< 0.006	0.058	0.068	0.085	0.013	0.026
Borich	< 0.05	< 0.01	< 0.01	< 0.01	0.01	0.12	0.11	0.12	0.03	0.04
Longburn	< 0.03	0.008	0.009	< 0.007	0.015	0.078	0.197	0.199	0.073	0.089
Kingdale	< 0.1	< 0.02	< 0.02	< 0.02	0.02	0.07	0.16	0.2	0.06	0.1
Sylvan	< 0.07	0.01	0.24	0.13	0.32	1.44	1.4	1.25	0.41	0.37
Harrington	0.3	0.02	< 0.02	< 0.02	0.04	0.12	0.23	0.28	0.06	0.1
Vodanovich	< 0.08	< 0.02	< 0.02	0.02	< 0.02	0.12	0.15	0.16	0.03	0.05
Seymour	< 0.08	< 0.02	< 0.02	< 0.02	< 0.02	0.06	0.12	0.11	0.03	0.04
Keeling	< 0.03	0.007	< 0.006	0.007	0.019	0.106	0.17	0.178	0.038	0.045
Corban	< 0.03	0.015	< 0.006	< 0.006	0.014	0.066	0.099	0.112	0.028	0.034
Pomaria	< 0.07	0.05	0.02	0.03	0.07	0.34	0.81	0.66	0.2	0.22
Border	0.06	0.012	< 0.007	0.009	0.009	0.086	0.123	0.158	0.026	0.04
Bruce Mclaren	< 0.03	0.007	< 0.006	0.007	0.011	0.08	0.139	0.146	0.033	0.041
Henderson Valley	0.06	0.009	0.01	0.01	0.034	0.141	0.267	0.269	0.077	0.077
West Coast Rd	0.06	0.01	< 0.006	0.008	0.017	0.099	0.217	0.234	0.061	0.069
Lincoln Rd	0.04	0.015	0.007	0.014	0.022	0.153	0.278	0.385	0.067	0.085
Edmonton	< 0.2	< 0.04	< 0.04	< 0.04	< 0.04	0.09	0.14	0.18	< 0.04	0.04
Lincoln 2	< 0.2	< 0.04	< 0.04	< 0.04	< 0.04	0.12	0.17	0.27	< 0.04	0.05

Sample Name	Naphthalene	Acenaphthylene	Acenaphthene	Fluorene	Anthracene	Phenanthrene	Fluoranthene	Pyrene	Benzo[a]anthracene	Chrysene
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Vodanovich entry	0.4	0.03	<0.03	0.03	<0.03	0.24	0.28	0.53	0.06	0.09
Vodanovich exit	0.4	<0.03	<0.03	<0.03	<0.03	0.15	0.14	0.21	<0.03	0.05
Strid entry	0.6	0.04	<0.03	0.04	0.05	0.34	0.45	0.58	0.1	0.17
Strid exit	0.5	<0.03	<0.03	0.03	<0.03	0.25	0.34	0.42	0.09	0.13
Keeling Exit	< 0.2	< 0.04	< 0.04	< 0.04	< 0.04	< 0.04	< 0.04	0.08	< 0.04	< 0.04
Keeling Entry	< 0.2	< 0.04	< 0.04	< 0.04	< 0.04	0.07	0.11	0.21	< 0.04	< 0.04
Millbrook Exit	< 0.2	< 0.05	< 0.05	< 0.05	< 0.05	0.12	0.22	0.32	< 0.05	0.09
Millbrook Entry	< 0.2	< 0.05	< 0.05	< 0.05	< 0.05	0.21	0.33	0.48	0.06	0.13
Central Park Exit	< 0.2	< 0.04	< 0.04	< 0.04	< 0.04	0.12	0.11	0.17	< 0.04	< 0.04
Central Park Entry	< 0.2	< 0.04	< 0.04	< 0.04	< 0.04	0.19	0.22	0.35	< 0.04	0.07
Te Pai Exit	< 0.2	< 0.05	< 0.05	< 0.05	< 0.05	0.16	0.17	0.29	< 0.05	0.06
Te Pai Entry	< 0.2	< 0.05	< 0.05	< 0.05	< 0.05	0.26	0.31	0.59	< 0.05	0.09
Lincoln Universal Entry	< 0.2	< 0.05	< 0.05	< 0.05	< 0.05	0.2	0.3	0.58	0.06	0.11
Lincoln Universal Exit	< 0.3	< 0.05	< 0.05	< 0.05	< 0.05	0.12	0.2	0.37	< 0.05	0.06
Lincoln Te Pai Entry	< 0.2	< 0.04	< 0.04	< 0.04	< 0.04	0.18	0.28	0.42	0.05	0.08
Lincoln Te Pai Exit	< 0.2	< 0.05	< 0.05	< 0.05	< 0.05	0.17	0.26	0.43	< 0.05	0.07
Lincoln Triangle Entry	< 0.2	< 0.04	< 0.04	< 0.04	< 0.04	0.17	0.23	0.33	0.04	0.08
Lincoln Triangle Exit	< 0.2	< 0.05	< 0.05	< 0.05	< 0.05	0.18	0.31	0.44	0.07	0.13

Sample Name	**Benzo[b]fluoranthene**	**Benzo[k]fluoranthene**	**Benzo[a]pyrene (BAP)**	**Benzo[g,h,i]perylene**	**Indeno[1,2,3-c,d]pyrene**	**Dibenzo[a,h]anthracene**
	mg/kg	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**
Pomelo	4.67	1.6	2.98	2.37	1.96	0.536
Stephen	0.039	0.011	0.022	0.065	0.021	< 0.006
Coletta	0.044	0.01	0.018	0.054	0.022	< 0.006
Borich	0.06	0.01	0.03	0.07	0.03	< 0.01
Longburn	0.192	0.057	0.115	0.154	0.098	< 0.007
Kingdale	0.29	0.06	0.1	0.21	0.09	< 0.02
Sylvan	0.53	0.17	0.38	0.33	0.22	< 0.01
Harrington	0.21	0.04	0.06	0.17	0.05	< 0.02
Vodanovich	0.08	< 0.02	0.04	0.10	0.04	< 0.02
Seymour	0.08	0.02	0.04	0.06	0.04	< 0.02
Keeling	0.077	0.018	0.039	0.09	0.035	< 0.006
Corban	0.07	0.016	0.038	0.076	0.041	< 0.006
Pomaria	0.35	0.13	0.21	0.22	0.17	< 0.01
Border	0.066	0.017	0.031	0.097	0.032	< 0.007
Bruce Mclaren	0.075	0.018	0.039	0.056	0.033	< 0.006
Henderson Valley	0.121	0.032	0.083	0.083	0.055	< 0.006
West Coast Rd	0.034	0.128	0.075	0.084	0.056	< 0.006
Lincoln Rd	0.143	0.041	0.078	0.175	0.067	< 0.007
Edmonton	0.09	< 0.04	< 0.04	0.1	< 0.04	< 0.04
Lincoln 2	0.1	< 0.04	0.05	0.17	0.05	< 0.04

Sample Name	Benzo[b]fluoranthene	Benzo[k]fluoranthene	Benzo[a]pyrene (BAP)	Benzo[g,h,i]perylene	Indeno[1,2,3-c,d]pyrene	Dibenzo[a,h]anthracene
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Vodanovich entry	0.18	0.03	0.08	0.3	0.07	<0.03
Vodanovich exit	0.09	<0.03	0.03	0.13	<0.03	<0.03
Strid entry	0.39	0.09	0.15	0.36	0.14	<0.03
Strid exit	0.24	0.05	0.11	0.22	0.08	<0.03
Keeling Exit	< 0.04	< 0.04	< 0.04	0.05	< 0.04	< 0.04
Keeling Entry	0.1	< 0.04	< 0.04	0.14	< 0.04	< 0.04
Millbrook Exit	0.19	< 0.05	0.08	0.22	0.07	< 0.05
Millbrook Entry	0.21	0.05	0.09	0.24	0.08	< 0.05
Central Park Exit	0.11	< 0.04	< 0.04	0.12	< 0.04	< 0.04
Central Park Entry	0.17	< 0.04	0.08	0.35	0.08	< 0.04
Te Pai Exit	0.13	< 0.05	0.07	0.25	0.07	< 0.05
Te Pai Entry	0.21	< 0.05	0.09	0.51	0.11	< 0.05
Lincoln Universal Entry	0.22	< 0.05	0.11	0.31	0.09	< 0.05
Lincoln Universal Exit	0.12	< 0.05	0.06	0.17	0.05	< 0.05
Lincoln Te Pai Entry	0.2	< 0.04	0.08	0.21	0.07	< 0.04
Lincoln Te Pai Exit	0.14	< 0.05	0.07	0.26	0.06	< 0.05
Lincoln Triangle Entry	0.15	< 0.04	0.07	0.18	0.06	< 0.04
Lincoln Triangle Exit	0.24	0.06	0.11	0.2	0.08	< 0.05