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Assessing pedestrian exposure to fine particulates at fine levels of spatio-temporal resolution

By

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ABSTRACT: A compelling body of international evidence now exists suggesting a causal link between exposure to airborne particulate matter (PM) and adverse health consequences. Travel microenvironments have come under particular scrutiny because PM levels are known to be substantially higher than ambient levels from Fixed Site Monitors (FSMs) on which air quality assessments are based and because people significant proportion of time travelling (e.g., 80 minutes/day in Sydney). Over the last two years, we have developed and tested an approach for assessing the risk of exposure to PM at fine levels of temporal and spatial resolution while travelling by various modes of transport. The approach combines the capabilities of personal Global Positioning System (GPS) technology, portable particle monitors, and voice-recorded information on unusual events, to shed new light on the inherent variability in PM and importantly the location, duration and magnitude of 'hotspots'. The current paper addresses the critical issue of pedestrian exposure along a busy mixed-use roadway environment in Sydney. We present descriptive and statistical evidence of the key factors impacting overall exposure while walking, the most important of which are general traffic conditions, ambient weather conditions (particularly wind-speed), and time-of-day (worse in the morning). We then conduct a 'hotspot' analysis in which elevated readings are cross-compared to the information on the tape-recorder. It is clear and striking that particular vehicles (buses, trucks) and events (other pedestrian's smoking) are highly significant and cannot be ignored if we are to accurately assess and minimise exposure in the future.

KEY WORDS: ***Pedestrian exposure, GPS technology, $PM_{2.5.}$***

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1 Introduction

The connection between exposure to airborne particulate matter (PM) and adverse health consequences is a topic of hot debate (Kappos et al., 2004). Of particular focus recently have been the finer fractions, particularly those with an aerodynamic diameter of less the 2.5 microns ($PM_{2.5}$), because of their deeper penetration into the gas exchange region of the lung. This in turn has been associated with increasing the risk of lung cancer and other respiratory-related problems (Greaves, 2006). Although current regulatory standards for $PM_{2.5}$ (shown together with standards for PM_{10} in **Table 1**) reflect a maximum concentration not to be exceeded over one day and one year[1], recent epidemiological evidence suggests peak exposures of one hour or less may be more relevant from a health perspective (Michaels and Kleinman, 2000). The implications are that it has become increasingly important to know with greater precision the microenvironments in which higher levels of particulate concentrations occur and how long individuals spend in these microenvironments (and therefore potentially at risk of higher exposure) as they go about their daily business.

Table 1: Current Regulatory Standards for Fine Particulate Matter

Pollutant	Averaging Times	Maximum concentration (µg/m^3)			EPHC goal for maximum allowable exceedences within 10 years
		Australia	U.S.	Europe	
PM_{10}	Annual		revoked	40	
	24-hour	50	150	50	5 days a year
$PM_{2.5}$	Annual	8	15		
	24-hour	25	35	25	Not fixed as yet

Source: Environmental Protection and Heritage Council (EPHC) http://www.ephc.gov.au
U.S. Environmental Protection Agency (EPA) http://www.epa.gov

Over the last year, we have developed and tested an approach for assessing the risk of exposure to $PM_{2.5}$ at fine levels of spatial and temporal disaggregation while travelling by various modes of transport (Greaves, 2006; Greaves and Hamers, 2006). The approach combines the capabilities of personal Global Positioning System (GPS) devices and portable particle monitors to shed new light on the inherent variability in pollution levels in different travel microenvironments and identify the location, magnitude and duration of $PM_{2.5}$ 'hotspots'. The focus of the current paper is pedestrian exposure to $PM_{2.5}$, something we argue is highly topical given i) walking is something most of us do on regular basis – for instance, 17% of all trips in Sydney are made by walking, making it the second most frequently used mode behind the car, ii) there have been several recent newspaper/magazine articles alerting pedestrians to the

[1] A review of the latest year for which annual summaries are available (2004) show that New South Wales failed to meet both the annual and 24-hour standards for $PM_{2.5}$
(http://www.ephc.gov.au/pdf/Air_Quality_NEPM/Monitoring2004/nsw_compliance_rpt_2004_final.pdf

'hazards' of walking/jogging in close proximity to traffic, and iii) there is currently a strong push for walking on health grounds, primarily in response to the growing obesity epidemic (Pucher and Djikstra, 2003). Specifically, we report here on the results of a monitoring campaign conducted on a busy mixed-use arterial in Sydney's Inner West, which experiences high pedestrian and vehicular flows throughout the day. The aim of the campaign was to identify and assess the impact of the major factors affecting pedestrian exposure to $PM_{2.5}$, identify and attribute reasons for specific instances within trips (hotspots) where levels were significantly elevated, and provide guidance to pedestrians and public health authorities on what could be done in the future to reduce exposure.

2 Study Methods

The study focused on King Street and Missenden Road in the suburb of Newtown, located in Sydney's Inner West (Figure 1). King Street is a major 4-lane arterial famed for its vibrant mix of restaurants, cafes, and shops as well as providing a primary conduit from the south of Sydney to the CBD. It attracts high numbers of pedestrians throughout the day and night and experiences heavy traffic flows including a significant proportion of heavy goods vehicles. Missenden Road is also a four-lane arterial, which intersects with King Street as shown. It provides access to one of Sydney's major hospitals, the Royal Prince Alfred Hospital (RPAH), and points north. It is characterised by much lower volumes of traffic than King Street, but has reasonably high pedestrian activity during the day, largely associated with accessing King Street.

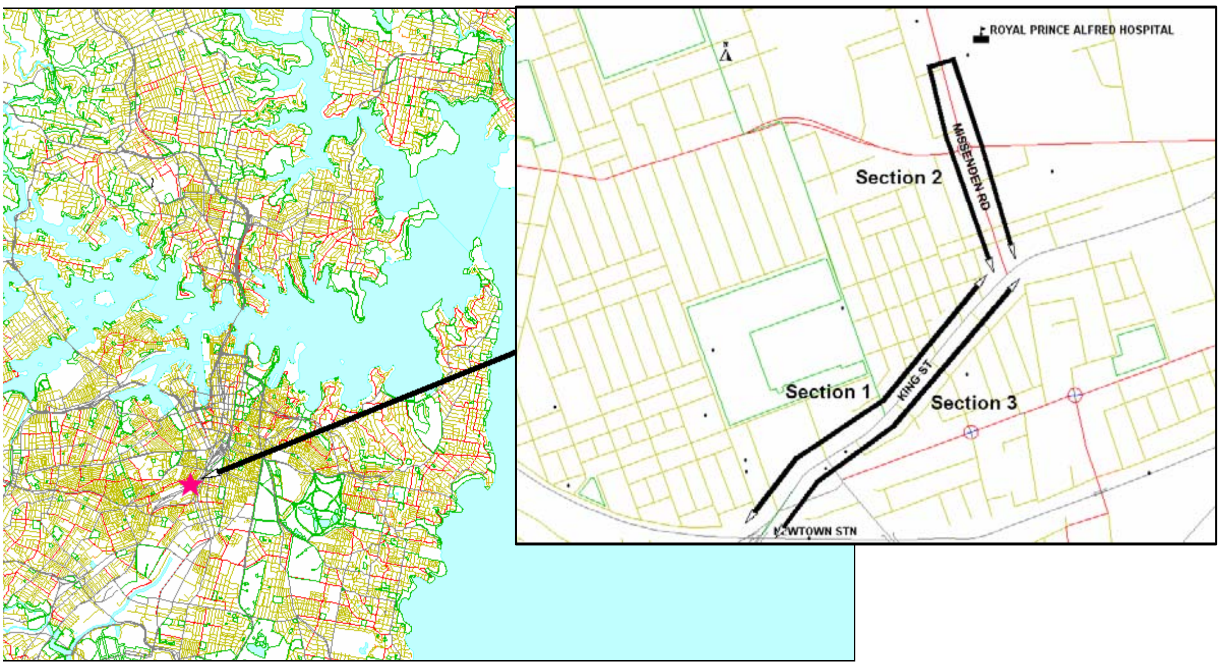

Figure 1: Study Area and Walking Route

The study route was designed as a circuit between Newtown Station and the RPAH comprising the most representative part of King Street and a distinct section of Missenden Road. The circuit was approximately two kilometres long, taking around thirty minutes to walk. The route was broken into three distinct 'segments' based on the built environment, traffic volumes, and the operation of clearway hours (**Table 2)**. The issue with clearway times is that in non-clearway times, on-street parking is permitted, effectively reducing the capacity to one lane in that direction. This causes congestion and delay and of most concern for the current study (we hypothesise), greater pollution.

Table 2: Details of the Route

	Built Environment	Two-way Average Hourly Traffic Volumes During Monitoring Times**			Section	Clearway Time*
		AM	LUNCH	PM		
King Street	High density residential and commercial	2,161	1,533	2,213	1 [North Side]	6:00-10:00, Mon-Fri
					3 [South Side]	15:00-19:00, Mon-Fri
Missenden Road	Low density, hospital	826	814	887	2	N.A.

**During non-clearway times on-street parking is allowed, effectively reducing capacity to one-lane in that direction.*
***Computed from RTA-provided, SCATS counts.*

The equipment involved the AM510 SidePak™ personal aerosol monitor, the Neve GPS data logger and a digital voice recorder (all shown in Figure 2). The AM510 SidePak™ personal aerosol monitor estimates second-by-second concentrations of $PM_{2.5}$ using nephelometric (light-scattering) techniques (see Greaves, 2006 for more details). The sampling tube of the pollution monitor was clipped to the collar of the pedestrian to ensure samples was collected as near as possible to the breathing zone. The Neve GPS data logger is ideal for this study given its small size and light weight (103 grams). The voice recorder was added to the set-up for the analyst to record events or circumstances, which were perceived to increase $PM_{2.5}$, such as heavy vehicles, bus stops, pedestrians smoking etc.

Figure 2: The portable pollution monitor (left), GPS logger (middle) and digital voice recorder (right) used in the study

The experimental design represented a compromise between available resources (one student, five weeks to collect the data), previous studies (e.g., Kaur et al., 2005) and our knowledge of the area. We selected three time-periods, namely morning (8:00am~9:30am), lunch (12:00pm~1:30pm) and evening (5:00pm~6:30pm) and two directions, clockwise (with traffic, higher $PM_{2.5}$ anticipated) and anti-clockwise (against traffic) making a total of six strata. Every trip started and ended at Newtown Station (see Figure 1) and the aim was to complete at least five circuits within each stratum. Two major sources of $PM_{2.5}$ were defined: 'traffic sources' attributed to specific network situations such as intersections, congestion, particular vehicles, most notably buses and trucks, and 'non-traffic sources' attributed to restaurants and other pedestrians smoking cigarettes.

The number of runs/samples required for statistical validity is a *critical* issue, which receives little/no mention in previous studies of this type. Clearly, it should be set based on the variance of the $PM_{2.5}$, the statistical error we are willing to tolerate and the level of confidence required. $PM_{2.5}$ is highly variable across trips, implying large numbers of trips are required – in our case we estimate we would need approximately 50 trips *per stratum* to achieve +/- 5 microns with 95% confidence (300 in all). One of the intrinsic appeals of using GPS, is that we can now gather 'samples' at much finer scales of temporal resolution (e.g., every second, every minute) providing a potentially much larger usable sample. In our case, we treated the previously-identified sections as independent observations, which in effect gave us a sample size of three times the number of runs completed. Clearly, one has to be cautious about the impacts of autocorrelation, when using data in such a manner, something we tackle in a companion paper at this conference (Issarayangyun and Greaves, 2006).

3 Results

Data collection was undertaken from 31 August, 2006 to 12 October, 2006 which marks the transition from winter to spring in Sydney. This time of year is marked by fluctuating temperatures and occasional days of heavy rainfall. The average temperature was 19.0^{o}C and ranged from 14.7^{o}C to 27.1^{o}C. In total, 34 weekday trips were conducted with five trips on the week-end, which gave a combined total of around 20 hours of walking. The breakdown is provided in **Table 3.**

Table 3: Summary of trips by Stratum

	Total Number of trips	**Clockwise**	**Anti-clockwise**
Morning	10	5	5
Lunch	12	5	7
Evening	12	5	7
Weekend Trips	5	5	0
Sum	39	20	19

Table 4 provides summary statistics for the 34 weekday trips. The average $PM_{2.5}$ exposure on King Street was approximately 13 μg/m^3, well within the 24-hour standard shown in **Table 1.** Average $PM_{2.5}$ concentrations in the morning were found to be substantially higher (more than double) those at lunch or in the evening, which is in line with other findings (Kaur et al., 2005; Greaves, 2006). In terms of directional effects, walking with the traffic (clockwise) resulted in notably higher average levels in line with our expectations. Walking on King Street with its heavier traffic volumes resulted in substantially higher (double) average $PM_{2.5}$ exposure than Missenden Road. Average $PM_{2.5}$ exposure on weekdays was marginally higher than on weekends.

Table 4: Summary Statistics of the 39 Complete Runs

	PM2.5 Value (μg/m3)				
	No. of Trips	**No. of Seconds of GPS Data**	**Mean**	**Std. Dev.**	**Maximum**
All Weekday samples	34	66916	12.8	20.8	997
Weekends	5	9787	10.8	25.7	711
Period					
Morning	10	19639	20.3	24.8	553
Lunch	12	23221	9.7	19.9	997
Evening	12	24056	9.7	15.7	434
Direction					
Clockwise	15	29786	15.9	21.3	529
Anti-clockwise	19	37130	10.3	20.0	997
Location					
North side of King St	34	22090	15.8	25.2	861
South side of King St	34	20469	14.7	20.5	997
Missenden Rd	34	24357	8.5	15.1	474

We computed Pearson correlation coefficients to gain a preliminary idea of the strength of the relationship between traffic and meteorological variables and $PM_{2.5}$. Note that we took the Log_{10} of $PM_{2.5}$ to try to mitigate the impacts of what is a highly positively skewed data set (Greaves, 2006). It should be noted also that we were able to get traffic volumes for the times at which the monitoring was done, rather than relying on averages, which most studies have had to do. This enabled us to produce the correlations shown. The results, shown in **Table 5**, confirmed our expectations that higher traffic volumes are strongly associated with higher $PM_{2.5}$ concentrations and windier conditions are associated with lower $PM_{2.5}$ (Adams et al., 2001; Greaves, 2006). Relative humidity, temperature and pressure were found to have insignificant impacts on $PM_{2.5}$.

Table 5: Pearson Correlation Coefficients for Traffic and Weather Variables and $PM_{2.5}$ (Log_{10})

n_s=102	Hourly Traffic Volumes	Log_{10} Wind speed (km/h)	Temperature (°C)	Relative humidity (%)	Pressure (hPa)
$PM_{2.5}$ (Log_{10})	**0.534 (0.00)***	**-0.420 (0.00)**	-0.013 (0.89)	0.164 (0.10)	0.177 (0.08)
Wind speed (km/h)		1	-0.123 (0.22)	0.062 (0.54)	-0.186 (0.05)
Temperature (°C)		…..	1	**-0.684 (0.00)**	**-0.290 (0.00)**
Relative humidity (%)		…..	…..	1	**0.366 (0.00)**
Pressure (hPa)		…..	…..	…..	1

**p-value=observed significance level, (bold indicate significance at p=0.05 level); 30 minute average of minute-by-minute wind speed, temperature, relative humidity, and pressure information during the times when monitoring was done.*

One of the more intriguing issues to emerge from this preliminary analysis was the time-of-day findings and whether these can be explained by traffic conditions. **Table 6** shows a breakdown by roadway and time-period, which shows this is clearly *not* the case – if it were, the $PM_{2.5}$ levels in the morning and evening peaks would have been similar with lunchtime much lower (on King Street in particular) according to the traffic information provided in **Table 2.** The reasons why could be due to wind speed differences (also shown in **Table 6**) and potentially other atmospheric conditions, such as the lower inversion layer in the morning, which tends to 'trap' pollution (Adams et al., 2001). We also anticipated lunch time may have been higher, because this marks the time when both directions of King Street are down to one lane and there is significant on-street parking activity, which causes serious congestion. Interestingly, while the data collector reported that it seemed to be worse at this time of day, they later acknowledged that the parked vehicles in effect extended the distance between the moving traffic and pedestrians, which may explain this lower than expected value.

Table 6: Summary Statistics by Road and Time Period

Road	PM2.5 Value (µg/m3)					
	AM		LUNCH		PM	
	Mean	Std Dev.	Mean	Std Dev.	Mean	Std Dev.
King Street	22.9	26.1	11.8	23.3	12.4	18.0
Missenden Road	15.5	21.6	6.1	11.0	5.2	9.2
Average Wind Speed During Monitoring Period	19 km/h	13 km/h	28 km/h	13 km/h	28 km/h	11 km/h

3.1 Statistical Analysis

To investigate the combined effects of these independent variables on $PM_{2.5}$, we employed general linear modelling (GLM) techniques. GLM involves both regression analysis and analysis of variance (ANOVA), allowing the testing of two or more independent variables on one dependent variable. In our case, we employed an Analysis of Covariance, because were particularly interested in establishing whether there were significant differences across the levels of the fixed factors (time-period, clearway, direction of walk) while holding traffic and weather constant (i.e., treating them as covariates). We also ran models with and without data points that included high elevations due to non-traffic factors (as identified on the tape recorder) to try to remove this 'noise' from the analysis.

Summary results for the GLM analysis are shown in **Table 7.** By way of clarification, the sample size of 81 is based on our treatment of the three sections as independent observations and the fact that we only had contiguous traffic information for 27 of the circuits. The results of the ANCOVA (upper part of the table) show traffic volumes and wind-speed are highly significant in explaining $PM_{2.5}$ levels, while time-period, direction and clearway are non-significant. Excluding these variables and running (in effect) a simple regression (lower part of table), the final model comprising wind speed and traffic volumes explained 43 percent of the variability in $PM_{2.5}$. The results also suggest that each additional 500 vehicles increases $PM_{2.5}$ levels by 35 percent, while a 5 km/h increase in wind-speed decreases $PM_{2.5}$ levels by 15 percent.

Table 7: Results of GLM Analysis

	df	MS	F value	p	h_p^2
Traffic volume (1000 vehicles/hr)	1	1.13	24.65	0.000	0.263
Wind speed (km/h) (log10)	1	0.53	11.64	0.001	0.144
Period (Morning=1, Lunch=2, Evening=3)	2	0.10	2.23	0.115	
Direction (Clockwise=0, Anti-clockwise=1)	1	0.03	0.69	0.410	
Clearway (yes=1, no=0)	1	0.05	1.15	0.286	
aGLM Univariate procedure. Dependent variable is log10 (exposure level). Period, direction, clearway fixed factors, Log10(wind speed), traffic volume covariates. Df=degree of freedom, MS=mean squares, F value= F test, p=significance value for F test, β =regression co-efficient, hp2=ratio of the effect variance to the sum of effect and error variance.					
Including non-traffic factors, n_s=81, R^2=0.428, p=0.000					
	β	p	95% Confidence Interval		
			Lower Bound	Upper Bound	
Intercept	1.28	0.000	0.90	1.67	
Traffic volume (1000 vehicles/hr)	0.26	0.000	0.18	0.35	
Wind speed (km/h) (log10)	-0.53	0.000	-0.79	-0.27	

3.2 Micro-level Insights

The aggregate statistical analysis shows that over half the variability in $PM_{2.5}$ levels remains unexplained.

One of the clear appeals of using the GPS/particle logger/tape recorder approach is the capability to investigate how $PM_{2.5}$ varies within trips and of particular interest, the location, duration and ultimately the reason for 'hotspots'. One example of the many time-series plots and graphics we have produced is shown in Figure 3. Clearly, there appear to be a number of traffic-related and non-traffic related hotspots, which in many cases are unpredictable. Perhaps ironically, the most notable source was fellow pedestrians smoking cigarettes either in the many al fresco restaurants on King Street, at bus stops or simply walking down the street. In these cases, $PM_{2.5}$ values were generally distributed around 200-300 $\mu g/m^3$, well above safe standards. While there has been a raft of anti-smoking legislation in New South Wales as with most of Australia, this does not cover many public spaces or al fresco dining.

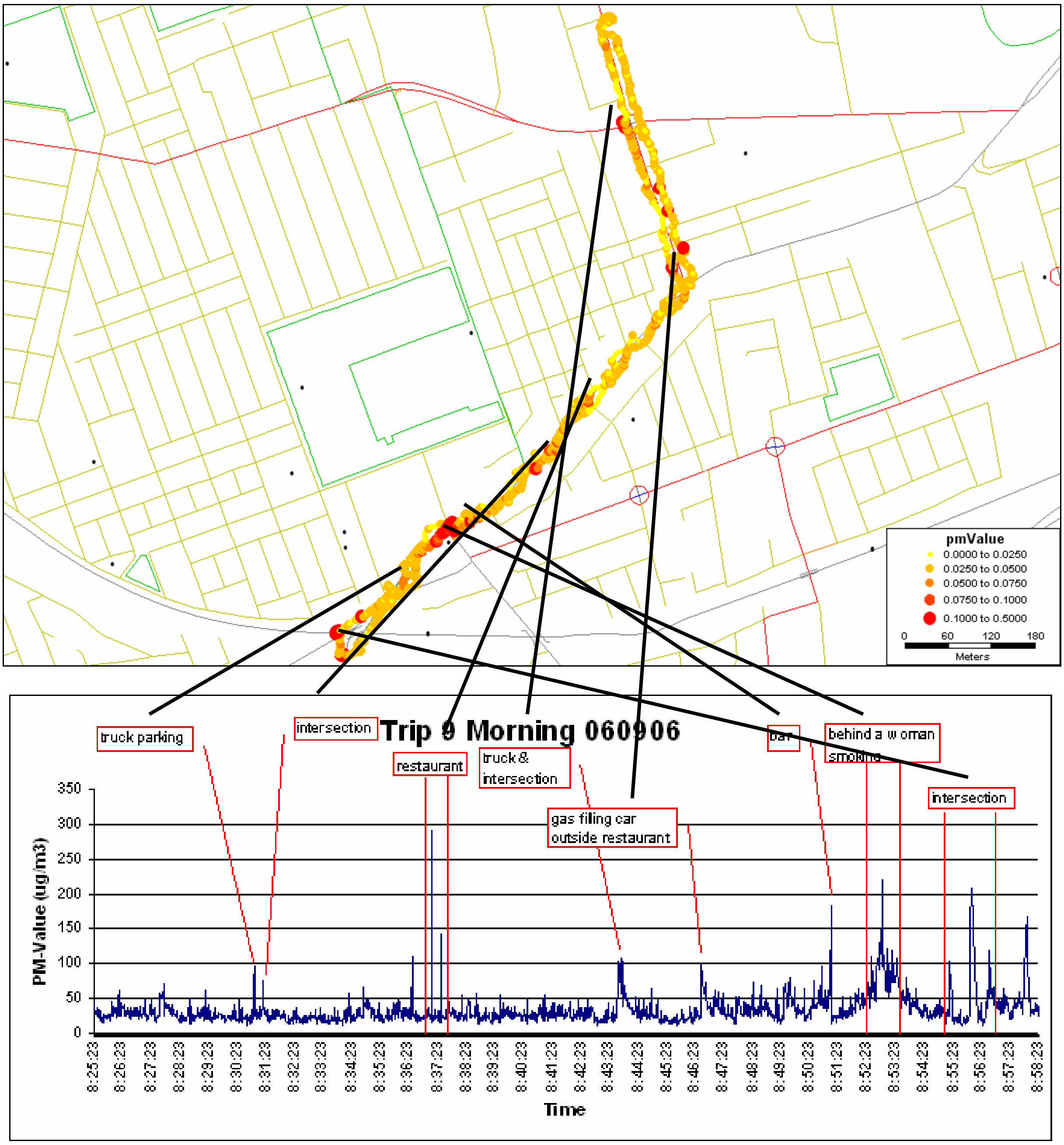

Figure 3: Combination of GIS Map and Time Series Chart for a Typical Trip

Other notable instances of $PM_{2.5}$ hotspots occurred at intersections, where pedestrians had to wait to cross the road, bus stops, and specific vehicles, such as buses, trucks and ‘smoky’ vehicles – one clear example is shown in Figure 4. In all cases, though it should be noted that hotspots generally lasted a few seconds, and were generally quite random in their occurrence, supporting a previous notion, that much of the very high exposures are simply a function of chance (Greaves and Hamers, 2006).

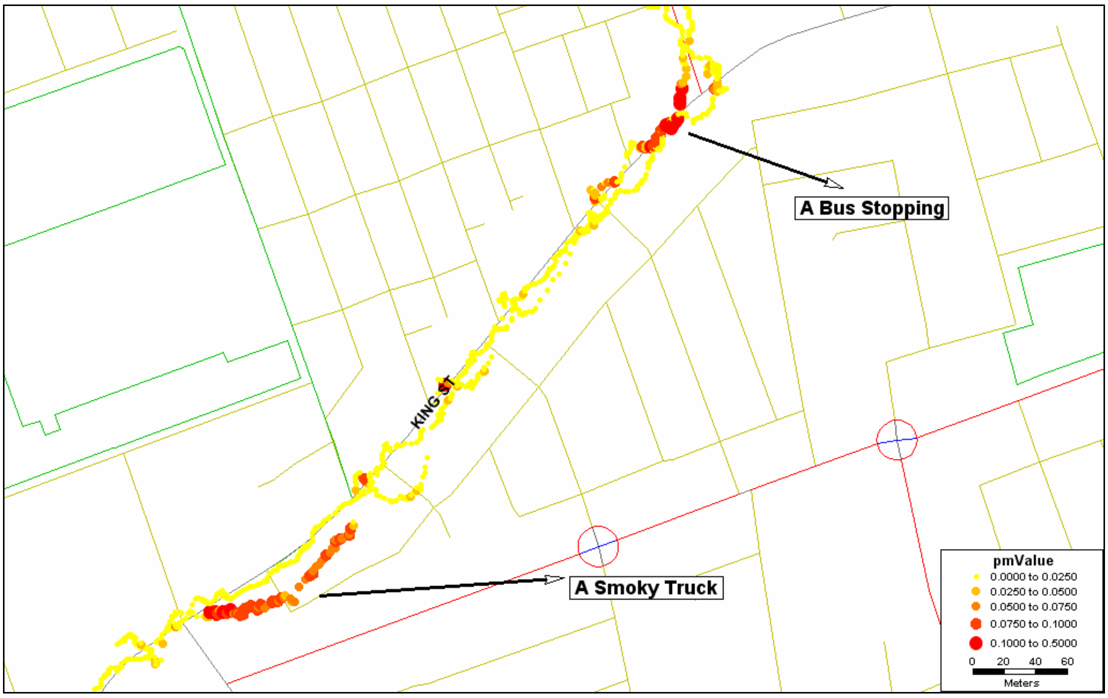

Figure 4: PM2.5 'Hotspots' Attributed to Heavy Vehicle Activity

3.3 Intra-Trip Exposure

While the plots and time-series graphs present many interesting insights, there is still the critical issue of assessing the implications for short-term exposures. The pie-charts shown in Figure 5 indicate the proportion of time attributed to different levels of $PM_{2.5}$ for the morning, lunch-time and evening trips. Even for the worse case (morning trips) over three-quarters of the time, levels were within the lowest range of 0-25 $\mu g/m^3$ with only a marginal amount of time spent above 100 $\mu g/m^3$.

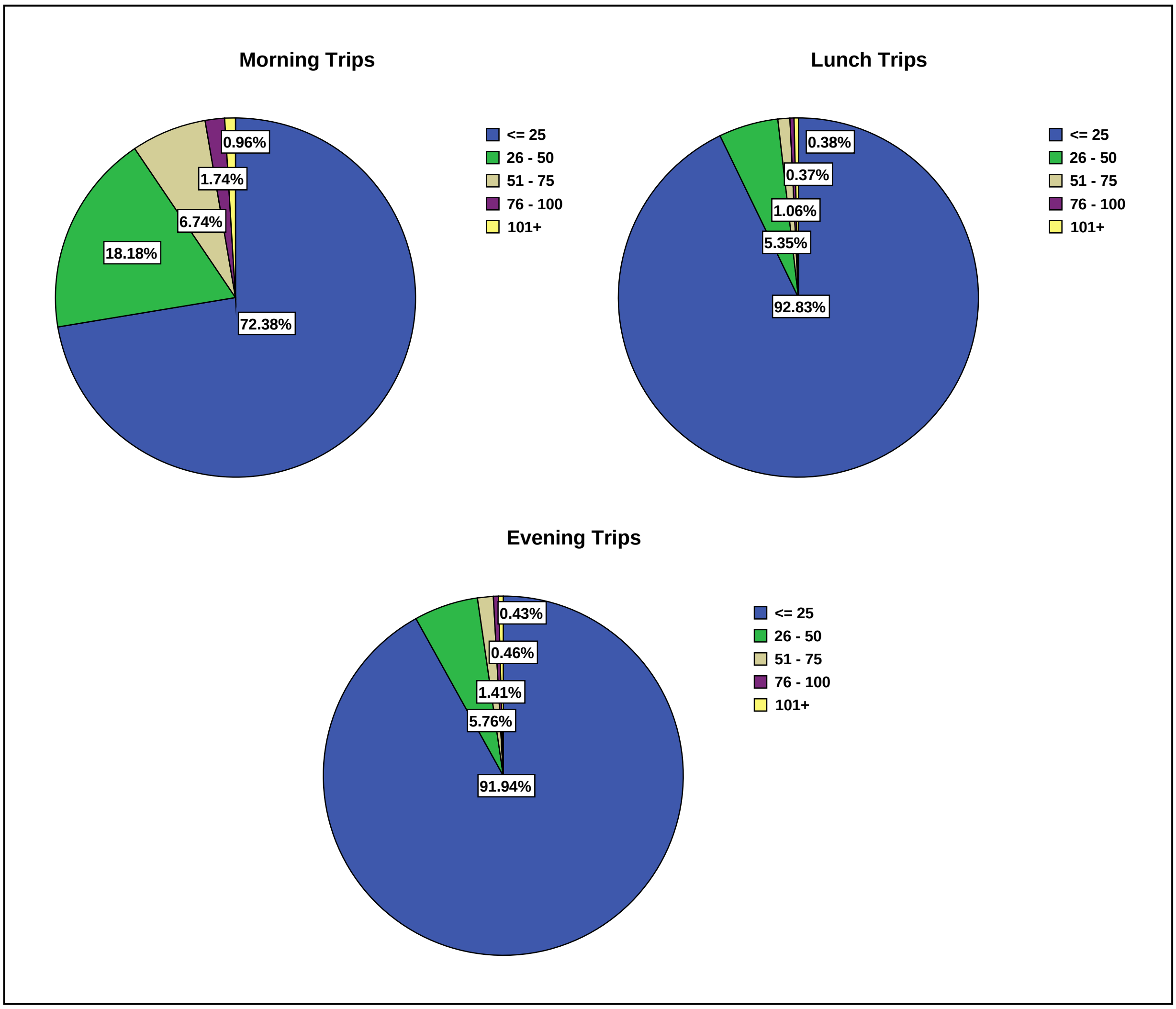

Figure 5: Proportion of time for various levels of $PM_{2.5}$

4 Conclusions

This paper addresses the important public health issue of pedestrian exposure to air pollution in areas of high pedestrian/vehicular activity and reveals many important insights. First, and perhaps surprisingly, average $PM_{2.5}$ levels (12.8 µg/m^3) were well within daily designated standards with only four of the 39 trips exceeding the current 24-hourly standard of 25 µg/m^3 – note, we acknowledge this is not a fair comparison, but currently there is no hourly standard against which to draw such a comparison. Comparing this to other studies (of which are few and far between), this is much lower – for instance, Kaur et al., (2005) reported the average $PM_{2.5}$ was 37.7 µg/m^3 on a busy road in London. Second, statistical modelling showed that almost half the variability in $PM_{2.5}$ was explained by knowledge of traffic volumes and wind-speed – based on this case study, each additional 500 vehicles was associated with a 35 percent increase in $PM_{2.5}$ levels, while each 5 km/h increase in wind-speed was associated with a 15 percent decrease in $PM_{2.5}$ levels. While time-period was found to be statistically insignificant, levels in the AM were almost double those in the PM, something attributed to the substantially lower wind speeds in the morning. The direction of walking, while statistically insignificant, showed that walking with vehicles resulted in higher average exposure than walking against them. Third, the aggregate trip-level analysis, hid many notable hotspots of $PM_{2.5}$, which were only discernible from the disaggregate analysis permitted by the use of GPS data. In particular, the impact of other pedestrians smoking and heavy vehicles emerged as a particularly alarming issue.

Overall, the statistical analysis was only able to explain around half the variability in $PM_{2.5}$. This largely stems from the fact we are not able to incorporate intra-trip factors through the use of an aggregate modelling exercise. We could of course simply re-run the model excluding those cases identified as unusual traffic events as we have done with non-traffic events. However, we argue this necessitates the need to employ a different approach to the statistical analysis, which raises some particular challenges – we address this issue in a companion paper at this conference (Issarayangyun and Greaves, 2006).

These issues aside, what messages can we relay on to the general public and policy-makers based on this work? One of the most poignant messages is that based on our previous work, which has applied a similar method to study exposure while commuting in a car (Greaves, 2006) the average values appear to be much lower for pedestrians – in the car study, which focused on commuting on busy road, average values ranged from 14.8 - 85.9 $\mu g/m^3$. As to reasons why, it is postulated that in a car, motorists are in fact sitting in a 'tunnel of pollutants', whereas pedestrians are out of the direct impact of exhaust fumes (Taylor and Ferguson, 1998). This should not be construed as pedestrians having little to worry about – the fact is that walking in close proximity to heavy traffic does apparently lead to an order of magnitude difference in exposure exacerbated by hotspots and the general ambient conditions. However, many of these effects can be mitigated with some common-sense – don't stand behind someone smoking, stand back from intersections, walk away from the road-side of the pavement etc. In terms of policy, there are specific issues that need addressing. First, there is the critical issue of regular monitoring and reporting of pollution levels in these micro-environments, something, which if done (rarely) is typically in response to a specific issue – our method could provide a flexible, relatively low-cost approach for local councils to conduct such monitoring. Second, there needs to thought given to imposing restrictions on heavy vehicle usage of facilities at high periods of congestion and pedestrian activity. Third, thought does need to be given to whether smoking laws have gone far enough and whether we should be following the lead of places such as California on further restrictions. The bottom line is if we are to encourage walking, we have to create a more pleasant as well as safe environment in which to walk!

5 References

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