I T L S

WORKING PAPER
ITLS-WP-06-06

Variability of Personal Exposure to Fine Particulates for Urban Commuters inside an Automobile

By

Stephen P Greaves & Tony Bertoia

April 2006

ISSN 1832-570X

INSTITUTE of TRANSPORT and LOGISTICS STUDIES
The Australian Key Centre in
Transport and Logistics Management

The University of Sydney
Established under the Australian Research Council's Key Centre Program.

NUMBER: Working Paper ITLS-WP-06-06

TITLE: Variability of Personal Exposure to Fine Particulates for Urban Commuters inside an Automobile

ABSTRACT: Over the last decade, a growing body of evidence has emerged to suggest a causal link between short-duration exposure to elevated levels of fine airborne particulate matter and adverse health consequences. It is believed much of this 'peak' exposure occurs in transport microenvironments both because of the higher levels of fine particulates associated with road traffic, primarily from diesel exhaust emissions, and the fact people spend a significant amount of time traveling (for instance, 80 minutes/day for residents of Sydney). While previous studies have suggested substantial differences in exposure rates due to factors such as choice of mode, route, in-vehicle conditions, and meteorological factors, current measurement techniques have restricted insights to fairly coarse sampling intervals (e.g., every half hour, every trip). As a consequence, little tangible evidence is available on how pollution varies over a trip and most critically about the location, duration, and magnitude of peak excursions within trips. The current paper reports on a study in which the capabilities of Global Positioning Systems (GPS) and real-time particle monitors are combined to address this problem for an urban commute trip in Sydney. This ability to precisely spatially reference pollution data and in particular identify 'hotspots' holds considerable promise for both our understanding and reporting of such data in the future.

KEY WORDS: ***GPS, personal exposure, fine particulates, travel microenvironments***

AUTHORS: Stephen P Greaves & Tony Bertoia

CONTACT: Institute of Transport and Logistics Studies **(C37)**
An Australian Key Centre
The University of Sydney NSW 2006 Australia

Telephone: +61 9351 0071
Facsimile: +61 9351 0088
E-mail: itlsinfo@itls.usyd.edu.au
Internet: http://www.itls.usyd.edu.au

DATE: April 2006

1. Introduction

Over the last fifty years, a compelling body of international evidence has emerged suggesting a causal link between exposure to airborne particulate matter (PM) and adverse health consequences (*1*). Of particular focus recently has been the role of finer particulate fractions, particularly those with an aerodynamic diameter less than 2.5 microns ($PM_{2.5}$), because of their deeper penetration into the gas-exchange region of the lung[1]. This in turn has been associated with an increased risk of cardiopulmonary and lung cancer mortality, reduced lung growth and function, and as a potential trigger for existing respiratory problems such as asthma (*2*).

While 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 possibly one year, recent epidemiological evidence suggests peak exposures of one hour or less may be more relevant from a health perspective (e.g., *3, 4*). The implications are that it has become increasingly critical 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 period	Maximum concentration (μg/m³) Australia	U.S.	Europe	EPHC goal for maximum allowable exceedences within 10 years
PM_{10}	1 day	50	150	50	5 days a year
	1-year			40	
$PM_{2.5}$	1 day	*25**	65	25	Not fixed as yet
	1-year	*8**	15	-----	

Source: Environmental Protection and Heritage Council (EPHC) http://www.ephc.gov.au
**Note these are proposed standards for Australia, which have yet to be finalised*

Transport microenvironments have received particular scrutiny both because of the higher concentrations of fine particulates associated with road traffic, primarily from diesel exhaust emissions, and the fact people spend a significant amount of time traveling (for instance, 80 minutes/day for residents of Sydney according to the latest figures from the Sydney Household Travel Survey). As a consequence, several experimental studies have been conducted to assess what factors pertaining to travel are most critical in influencing exposure to fine particulates (e.g., *5, 6, 7, 8, 9*). While comparisons between the studies are hampered by different protocols and collection devices, it is clear a wide range of factors impact particulate levels including meteorological conditions, traffic levels, fuel quality, emission rates of the preceding vehicle, travel mode, and the ventilation systems of the individual vehicles themselves.

[1] Particulates are currently classified into four size groups, with the smaller the particle the greater the potential for deeper penetration into the lung: 1) Non-inhalable (>10 microns), 2) Inhalable (< 10 microns, referred to as PM_{10}), 3) Respirable (< 2.5 microns, referred to as $PM_{2.5}$), and 4) Ultrafine particles (<0.1 microns)

Most of the reported studies have employed fairly coarse sampling intervals (e.g., every half hour, every trip) dictated by the use of gravimetric methods in which samples are collected on filters and later weighed. While this provides an accurate indication of total particulates across the sampling interval, it is not able to provide data at the time-resolution required to identify peak excursions within a journey or associate this with specific elements of that journey. For instance, while intuition suggests that traveling through a tunnel, idling in heavy traffic, or traveling behind a diesel truck might all contribute disproportionately high amounts of particulate exposure, such excursions would be unidentifiable with an aggregate analysis of that journey. Similarly, it does not enable differentiation of modes on multi-modal journeys, which could be an issue in studying exposure in using public transportation in particular, as this typically involves a walk trip at either end.

Recently, small, portable devices capable of monitoring and logging particle concentrations at highly disaggregate temporal levels (second-by-second if required) have become widely available. Although the primary market for these devices has been in-door Occupational Health and Safety applications, their portability makes them intuitively appealing for collecting particulate data while traveling. The few studies that have employed this measurement technique have demonstrated the flexibility this permits for collection and analysis, and support the conjecture of significant intra-trip variability in particulate levels (*8*). Unfortunately, however, this only tells half the story, because unless it can be associated with what is happening on the trip at the same time, then it is still only possible to speculate about the reasons for observed fluctuations. One obvious answer is to simply have the data collectors' verbally record locations and events, which could be associated with marked change in levels. This is cumbersome, error-prone, problematic to process, and with demands now at an intra-route level, simply infeasible.

Automated recording of personal travel has recently been revolutionised by the advent of light-weight, low-cost, portable, Global Positioning Systems (GPS) data loggers. Such devices are able to record and store second-by-second positional and velocity information to accuracies of a few metres, which can later be integrated within Geographical Information Systems (GIS), permitting powerful spatial analysis and display options. The other intrinsic appeal of GPS is that it can be linked to any device, which provides data by time, permitting those data to then be referenced spatially. This provides the rationale behind the current study, namely that combining GPS and a portable pollution monitor provides a simple method for collecting such data and permits analyses at a highly disaggregate temporal and spatial level. As such, this provides a powerful tool for assessing intra-trip variability and in particular identifying both the location and magnitude of peak levels of $PM_{2.5}$ experienced while travelling.

2. Study methods

Initial testing of the concept and development of the processing algorithms focussed on an urban commuting trip from Liverpool in the Western suburbs to a workplace in central Sydney (Figure 1). The selected route was 30.1 kilometres long and was known by the driver to take an average of one hour each way. Data were collected over several days during November and December of 2004, which mark the start of the summer months in Sydney. The rationale for selecting this route was that in addition to encompassing a variety of residential, commercial, and industrial environments, the route was typified by a range of road traffic operational conditions that might be typically encountered on a commuting trip in the city. These are summarised in Table 2.

Figure 1: The Study Route

Table 2: Details of the Route

Section	Section Length (km)	Built Environment	AADT*	No. of Traffic Lights	Signal Density
1. Liverpool city boundary	1	Residential	8983	1	1
2. Hume Highway (Liverpool to Villawood)	5.7	Parks and reserves	51740	11	1.9
3. Hume Highway (Villawood to Chullora)	10.4	High density residential and industrial area	59201	25	2.4
4. Hume Highway (Chullora to Ashfield	7.4	High number of medium-sized commercial buildings	35454	18	2.4
5. Parramatta Road (Ashfield to Camperdown)	3.9	Heavily congested, high number of steep ascents and descents.	69945	14	3.6
6. Missenden Road (Parramatta Road to King Street)	0.9	Hospital, some medium-sized residential apartment buildings	n/a	3	3.3
7. King Street to Burren Street	0.8	High density residential	4000	0	N/A
TOTAL	30.1		229323	75	2.5

* *Figures presented here are the Annual Average Daily Traffic (AADT) averaged from the stations within each section and should only be used as an indication of traffic conditions. Source: RTA Traffic Volume Data at: http://www.rta.nsw.gov.au/trafficinformation/downloads/aadtdata_dl1.html.. Accessed 1/3/05.*

Particle measurements were made with a SidePak™ personal aerosol monitor, manufactured by TSI Inc. (Figure 2). The device works by drawing air into the sensing chamber in a continuous stream, upon which the sensing mechanism (consisting of a laser diode) illuminates the aerosol stream with a laser light. Scattered light is then detected at 90° to the light beam. The intensity of the light scattering output is then converted to particle mass by calibration against the aerosol of interest. The device is factory calibrated to the respirable fraction of ISO test dust, which has the following characteristics; specific gravity of 2.6 g/cm^3, a refractive index of 1.5, and a mass median diameter of 2-3 μm (ISO Fine Test Dust, 12103-1, A2; Powder Technology Inc., Burnsville, MN). This is standard practice for these types of devices, because ISO fine test dust allows for detection of most aerosols of importance in personal exposure to particulates. The flow rate was set to the recommended 1.7 L/min (specified for measuring $PM_{2.5}$) in order to maximise performance and to ensure the exclusion of unknown particle size fractions. In addition, the monitor was zero calibrated on the morning of each test day to maintain the accuracy of the unit.

Figure 2: The Portable Aerosol Monitor and GPS Data Logger Used in the Study

It is widely reported these nephelometric (light-scattering) techniques tend to overestimate $PM_{2.5}$ in comparison to gravimetric methods, particularly at higher concentrations (*10, 11, 12*). The reason is that aerosols comprise a mixture of aerodynamic shapes with different light-scattering properties with the result that estimation results based purely on size fraction will tend to vary (*13*). The implications are the readings need to be calibrated against gravimetric measurements within each particular microenvironment (*14*). For the current study, logic dictates this is inside a vehicle while in traffic. Unfortunately, the myriad of studies and subsequent lack of universal calibration factors, highlight such calibration is highly non-trivial. In addition to the properties of the particles themselves, comparisons are affected by climatic conditions such as relative humidity (*15*) and errors in gravimetric measurements due to volatilization of semi-volatile materials and chemical reactions of gases with collected particles (*16*). For all these reasons, it was deemed appropriate to report and analyse the results directly from the device with the caveat that the results should be used as an indication of those instances on a trip requiring further scrutiny.

The GPS data were recorded using the Geostats® data logger shown in Figure 2. This unit is a relatively low-cost, portable unit, which requires no intervention from the user and is capable of storing data for up to one month based on four hours of use per day. The processing of the data comprised various stages. First, data were downloaded from both the GPS device and the SidePak monitor. Second, the GPS data were processed within the TransCAD GIS environment to create trips and link points to the underlying Sydney street system. Third, in situations where GPS points were missing or clearly inaccurate due to multi-path and other errors, a program was developed to infer the missing points based on the location of the known points before and after the missing point(s). This step was taken because we did not want to exclude $PM_{2.5}$ readings simply because no GPS record was recorded. Finally, another program was written to time-match the GPS and $PM_{2.5}$ records to create the final database for statistical analysis.

All vehicle trips were conducted in a 1995 Hyundai Excel coupe, which has a 4-cylinder 1.5 litre engine, automatic transmission, and runs on unleaded fuel. The same driver conducted all vehicle trips in order to reduce inter-driver variability in driving styles, which may potentially confound the results. In all trips, the GPS device was placed in a shoulder bag, and was hung around the head of the passenger seat, with the satellite receiver facing the passenger side window. The SidePak Monitor was placed on the passenger seat, with the sample tube attached to the GPS strap near the head of the passenger seat. The sample tube was positioned in this way (i.e. at face-level) to enable us to investigate the actual exposure level within an individual's normal breathing zone.

Each trip was designed to sample $PM_{2.5}$ during peak-hour traffic conditions. As such, each morning trip began between 7:30am and 9:00am while the afternoon trips began between 4:30pm and 6:00pm. We also experimented with different combinations of vent position (open/closed) and air-conditioning (on/off) as the in-vehicle environment is known to have a major impact on particulates entering the vehicle (*17*). In addition to the in-vehicle manipulations, the driver recorded any events throughout the trip, which could contribute disproportionately to elevated levels of particulates such as whether the vehicle was following a smoky vehicle, or whether there was unusual congestion or smells entering the vehicle. We also recorded the wind speed, relative humidity, pressure, and temperature from the Bureau of Meteorology website for each trip.

3. Results

In all, while data were collected for 33 trips, three had to be excluded because the device became obstructed for a significant proportion of the trip, leading to no data being recorded during those times. Exploratory data analyses of the $PM_{2.5}$ data revealed that while general trends were discernible, the data were very 'spiky', testament to both the characteristics of what we were measuring combined with the use of a one second time increment. While we considered the possibility of defining rules for deleting extreme values this was deemed to be a dangerous strategy as there was no way of determining if they were genuine or not. We therefore experimented with taking moving averages of the prior five, ten, and fifteen seconds before deciding ten seconds represented an appropriate compromise. The impacts of this are demonstrated in Figure 3 using a segment from one of the sample trips.

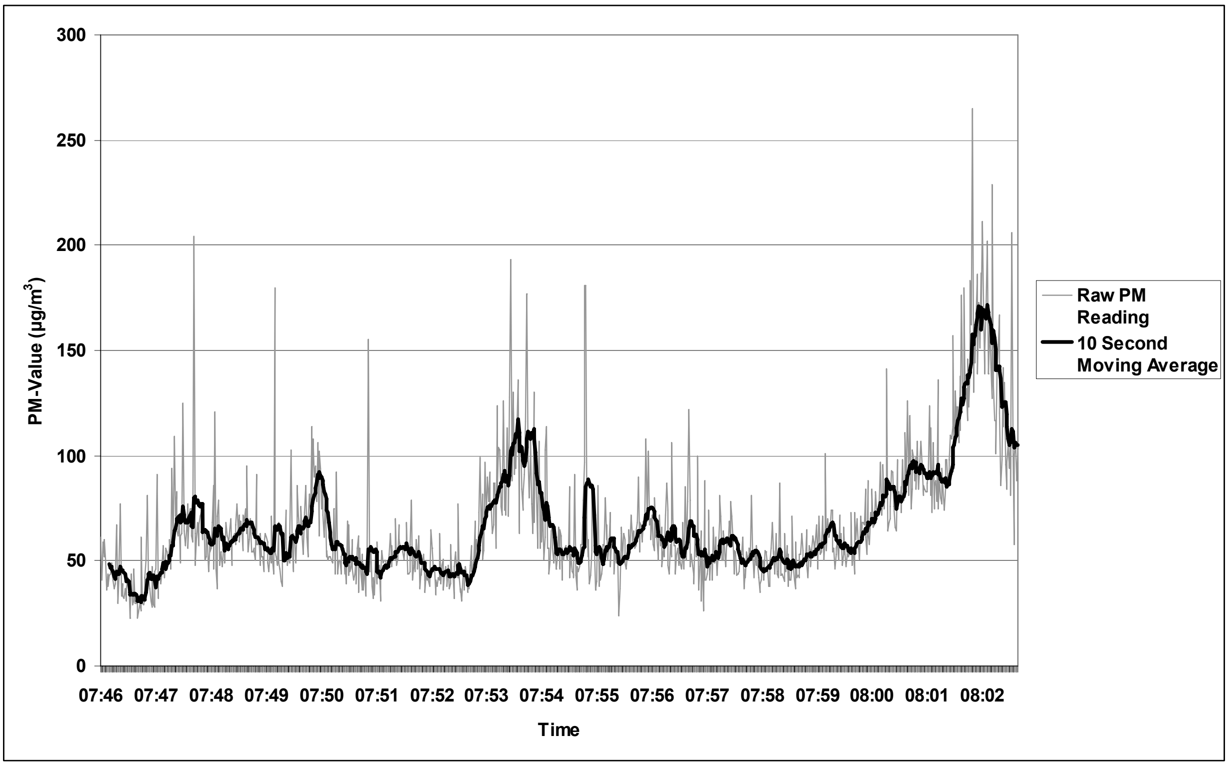


Figure 3: Comparison of Second-by-Second (raw) $PM_{2.5}$ Readings and Smoothed Data using a 10-second Prior Moving Average

3.1 Inter-trip Variability

Table 3 provides information for the 30 complete trips summarised by different combinations of vent position, air-conditioning and time-of-day – note, we did not consider the scenario of air-conditioning off with the vent closed as this resulted in intolerable operating conditions for the driver, particularly as this was conducted during the summer in Sydney. The results show that under the most controlled conditions (A and B), in which the vents were closed and the air-conditioning was on, the average $PM_{2.5}$ concentrations were well below levels that Table 1 suggests would be deemed hazardous[2]. The situation changed dramatically for those trips where the vent was opened with average $PM_{2.5}$ concentrations increasing by approximately three to four times depending on whether the air-conditioning was turned on or off. The results in Table 3 also show that $PM_{2.5}$ levels were 30 to 50 percent higher for the morning runs than the afternoon runs depending on condition. This could be a factor of time-of-day or a reflection of greater congestion during the morning runs as indicated by the lower average speeds.

[2] While the issue of an **hourly** standard for $PM_{2.5}$ is an ongoing debate it is likely concentrations for such a standard would be higher than those in Table 1, which reflect daily averages.

Table 3: Summary Trip Statistics

Condition	AM/ PM	Air-Con	Vent	No. of Trips	Mean Speed (km/hr)	$PM_{2.5}$ Mean ($\mu g/m^3$)	$PM_{2.5}$ SD ($\mu g/m^3$)	$PM_{2.5}$ Range ($\mu g/m^3$)
A	AM	On	Closed	6	26.9	20.6	8.1	13.9-28.0
B	PM	On	Closed	4	29.2	16.3	6.1	13.8-19.7
C	AM	Off	Open	5	26.9	85.6	45.6	65.0-114.8
D	PM	Off	Open	5	31.2	57.6	37.1	47.4-68.53
E	AM	On	Open	5	27.5	60.4	30.6	41.6-73.2
F	PM	On	Open	5	35.5	46.0	52.0	26.3-56.3

The other notable issue arising from this summary of results is the wide range of average $PM_{2.5}$ concentrations. To gain some handle on the reasons behind this, simple linear regression was used to predict $PM_{2.5}$ – note, the Log_{10} was taken to try to mitigate the impacts of what was a highly positively skewed data set (*6*) and the dichotomous variables (vent position, air-conditioning, am/pm) were dummy coded.

Table 4 presents a summary of the linear regression modelling. Before drawing any inferences, the first thing we looked for was any evidence of multicollinearity between the independent variables, indicated here by a Variance Inflation Factor (VIF) greater than five (*18*). Having satisfied this test, the results can be interpreted. All the variables shown are statistically significant in the prediction of $PM_{2.5}$ concentrations and overall these seven factors explained just over half (53 percent) the variation– note a positive sign indicates that factor is associated with increasing $PM_{2.5}$ concentrations. The most critical factor was confirmed as being whether the vent was open, which alone explained 39 percent of the variability in $PM_{2.5}$ concentrations. The next most important factor was time-period, which explained an additional five percent, followed by air-conditioning (additional three percent), and speed (two percent).

Table 4: Regression Results for Predictors of $PM_{2.5}$ Concentrations

Dependent Variable: $PM_{2.5}$ (LOG_{10})		Unstandardised Coefficients		Standardised Coefficients	t	Sig.	Variance Inflation Factor (VIF)	Adj. R-Square
		B	Std. Error	Beta				
	(Constant)	.527	.014		38.360	.000		
1	Vent	.452	.002	.612	224.868	.000	1.577	.392
2	AMPM	-.216	.002	-.304	-98.407	.000	2.034	.443
3	Air_Con	-.059	.002	-.080	-26.887	.000	1.883	.475
4	Speed (km/h)	-.002	.000	-.141	-64.734	.000	1.014	.495
5	Relative Humidity (mBar)	.006	.000	.258	70.904	.000	2.819	.506
6	Temp (^oC)	.019	.000	.216	65.375	.000	2.317	.523
7	Wind Speed (km/h)	.003	.000	.092	26.709	.000	2.504	.526

It may come as a surprise perhaps that the weather variables explained very little of the variability once the other factors were included with wind speed in particular standing out in this regard. Referring to other recent studies, results while inconclusive appear to corroborate what was found here. For instance, Alm et al., (1999) regressed wind speed against average concentrations of particulates sized between one and ten microns for 24 car trips and showed there was no relationship with R^2 = 0.001 (*19)*. By contrast, Adams et al., (2001) reported an R^2 of 0.12 for a similar comparison in London (*6)*. Interestingly, however, in assessing the specific impacts of wind speed on bus particulate levels, they only report an R^2 of 0.01, while for the London Underground they report an R^2 of 0.36. These results seem to suggest something was inconsistent in how their assessment was made.

3.2 Intra-trip Variability

Overall, the results presented show that we can explain approximately half of the variability in $PM_{2.5}$ exposure levels with knowledge of one or two basic variables. However, equally apparent is that half of the variability *cannot* be explained in such simplistic terms. In addition, while the use of averages and variances gives us some overall impression of what is going on, it does not enable detection of the magnitude and duration of short-term high excursions within trips, which could be critical for fully understanding the health implications. With this in mind, this section presents readers with examples of the types of insights permissible using the GPS/particle logger approach.

Examples of time-series graphs and GIS plots are presented for two of the trips in Figures 4 and 5. Trip 11 experienced by far the highest average $PM_{2.5}$ readings even acknowledging the fact the vent was open. Breaking this down into the previously identified sections (Table 5), most of the high excursions occurred in the heavily congested sections of Hume Highway and Parramatta Road (sections 4-6). In addition the driver reported being behind a smoky vehicle in Camperdown, which is shown as an annotation on the time-series plot. The GIS plot demonstrates visually what is going on and also helps pin-point hotspots of particulate concentrations such as at intersection approaches.

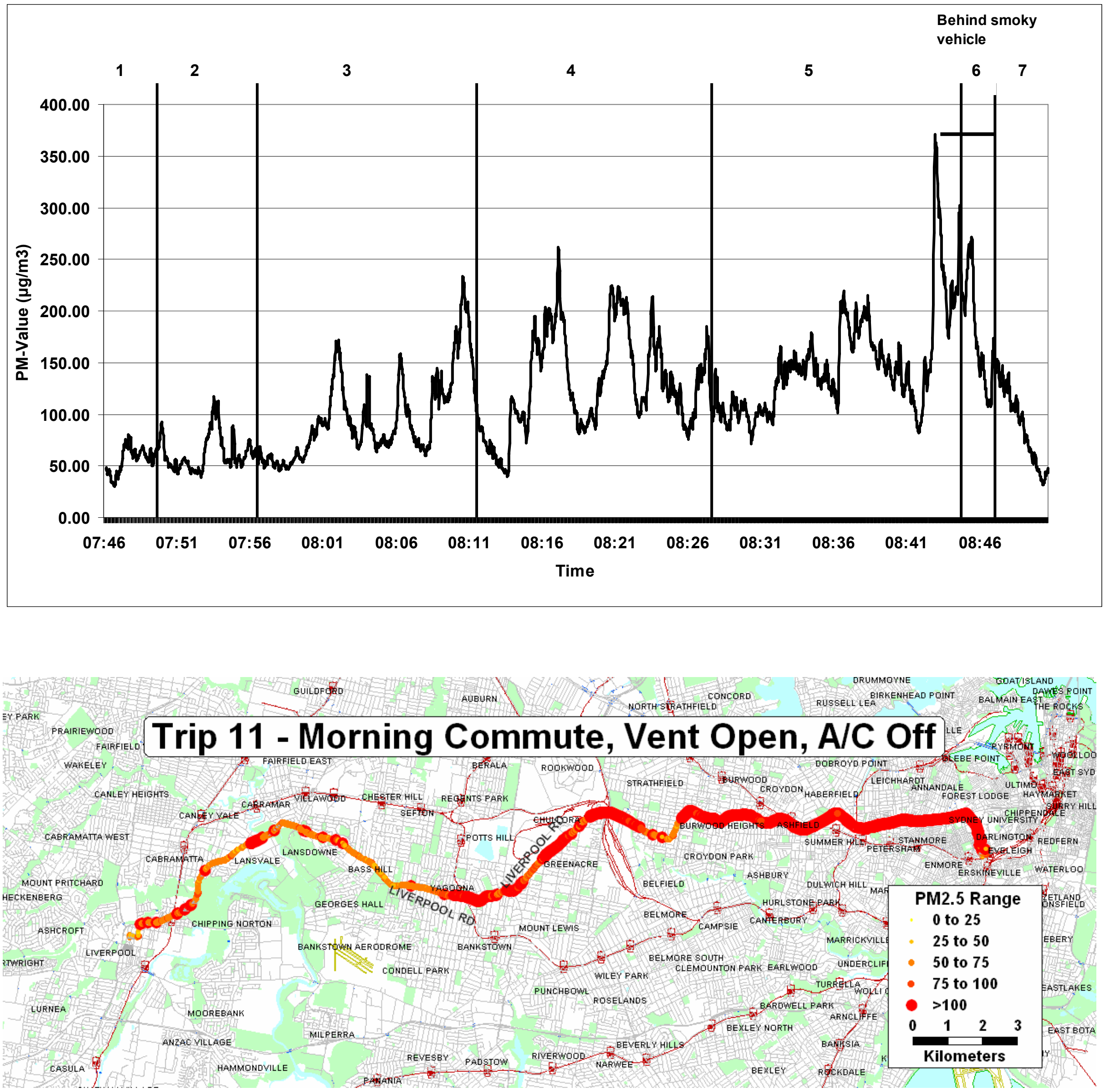
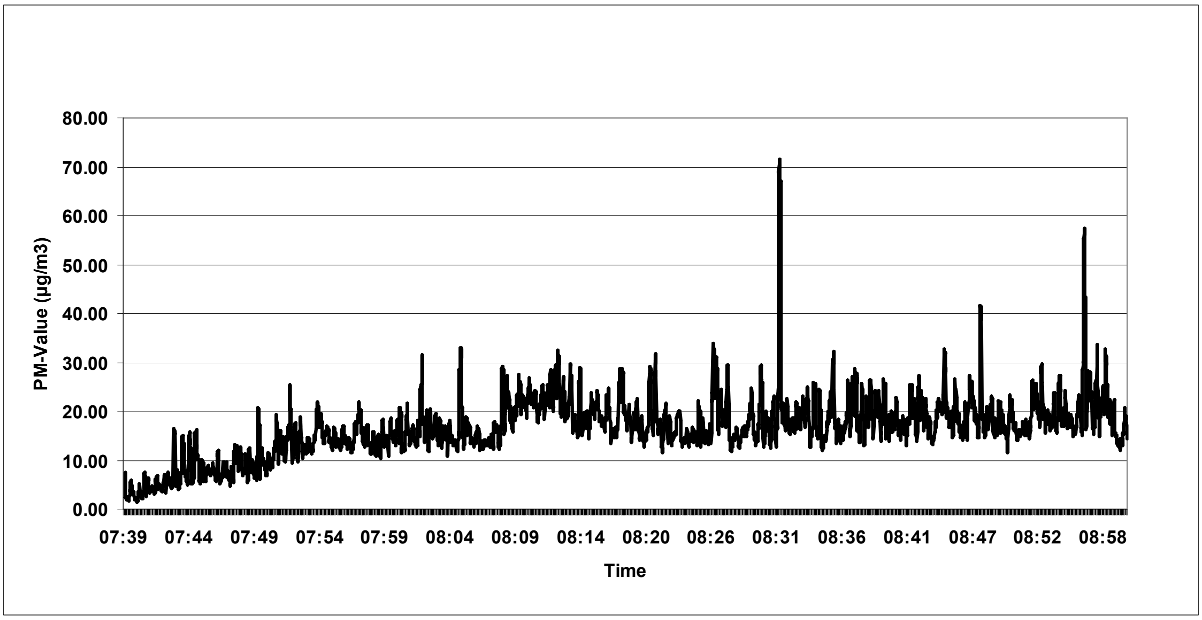


Figure 4: Example of Time-series and GIS Plot for Trip 11 [morning commute, vent open, A/C off].

Table 5: Exposure Summary for Trip 11 for Each Section

Section	Mean Speed (km/hr)	$PM_{2.5}$ Mean (µg/m^3)	$PM_{2.5}$ SD (µg/m^3)	Total Exposure	% of Time	% of Exposure
1	20.1	47.0	11.8	4893	2.2%	0.9%
2	37.9	62.6	16.3	31463	12.5%	6.8%
3	41.1	91.5	37.1	83011	23.4%	18.4%
4	26.5	130.8	48.3	129498	25.6%	29.0%
5	13.2	149.7	50.4	160062	27.6%	35.8%
6	12.6	149.0	47.5	33373	5.9%	7.6%
7	22.0	58.0	20.0	6723	2.9%	1.5%
TOTAL	26.6	114.8	54.2	449023	100%	100%

By way of contrast, Trip 3 recorded one of the lowest average concentrations of $PM_{2.5}$ readings, despite the fact it was the longest and most congested of the 30. Even here, however, it is notable that the heavily congested sections contribute disproportionately to the overall exposure for the trip. The implications are that even with the closing of the vents, fine particulates are able to enter the vehicle.



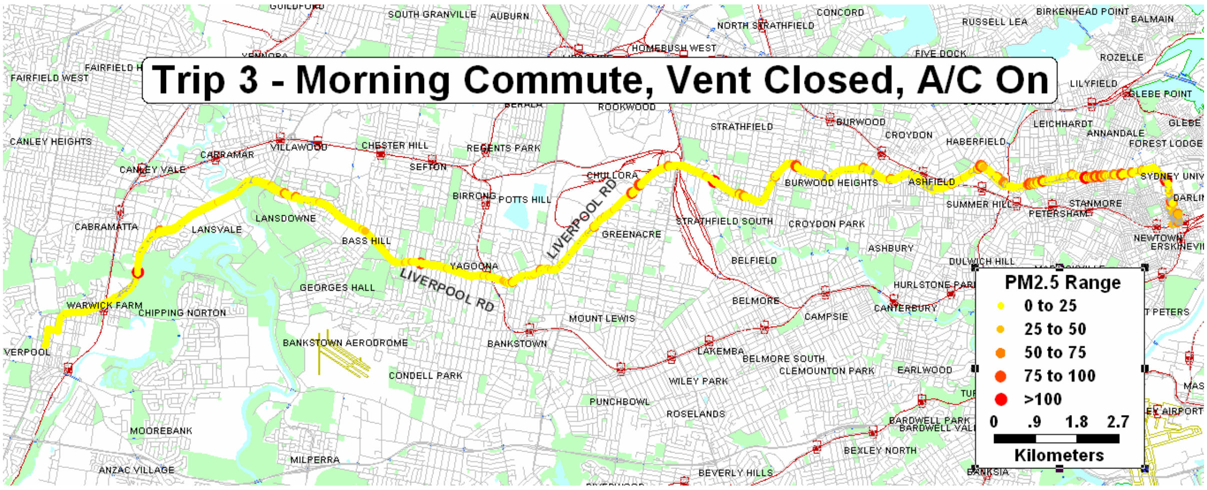


Figure 5: Example of Time-series and GIS Plot for Trip 3 [morning commute, vent closed, A/C on].

Table 6: Exposure Summary for Trip 3 for Each Section

Section	Mean Speed (km/hr)	$PM_{2.5}$ Mean (μg/m^3)	$PM_{2.5}$ SD (μg/m^3)	Total Exposure	% of Time	% of Exposure
1	7.5	4.2	5.9	190	0.8%	0.2%
2	32.0	7.7	9.9	4734	13.3%	6.1%
3	29.7	15.8	10.6	19430	26.3%	24.6%
4	21.5	8.9	11.3	21208	22.3%	25.4%
5	9.9	19.4	17.5	26512	28.5%	33.0%
6	5.7	21.3	20.0	7535	6.7%	8.5%
7	7.8	17.9	10.7	3078	2.1%	2.2%
TOTAL	20.3	16.9	14.3	82687	100%	100%

3.3 Intra-trip Exposure

While the time-series plots and graphical displays are useful for understanding the spatio-temporal variation in particulate concentrations, there is still the critical issue of what the implications are for assessing short-duration exposures. In the absence of short-duration exposure standards, to give the reader some idea of what these numbers actually mean, the device records around 10-20 μg/m^3 in an air-conditioned office. Outdoors away from traffic, the readings may even be lower dependent on wind. By contrast, the device in the vicinity of an extreme event such as cigarette smoke, will record 200 – 300 μg/m^3. Feedback from the driver in this study seemed to suggest discomfort was felt if the levels exceeded 100 μg/m^3 with mild discomfort experienced if the levels exceeded 75 μg/m^3.

The pie-charts illustrate the proportion of time for which various levels of $PM_{2.5}$ were experienced for some of the conditions specified earlier. Keeping the vent closed resulted in less than one percent of the time being spent above 50 μg/m^3 for both the morning and afternoon trips. There is also a distinct time-of-day difference with just over one quarter of the time being spent in the 25-50 μg/m^3 range for the morning trips compared to eight percent of the time for the afternoon trips. As with comparisons of average concentrations, opening the vent has a dramatic effect on increasing the proportion of time spent at higher levels. For the morning runs, over half the time was spent at levels above 75 μg/m^3 while one third of the time was spent above 100 μg/m^3. The situation was not as dramatic for the afternoon runs, but never-the-less still resulted in over one quarter of the time being spent at levels above 75 μg/m^3. These numbers have more impact when put in the context of time. Given the trip takes approximately one hour, the implications are that the driver would spend thirty minutes on average at levels above 100 μg/m^3 if they had their vent open and air-conditioning off.

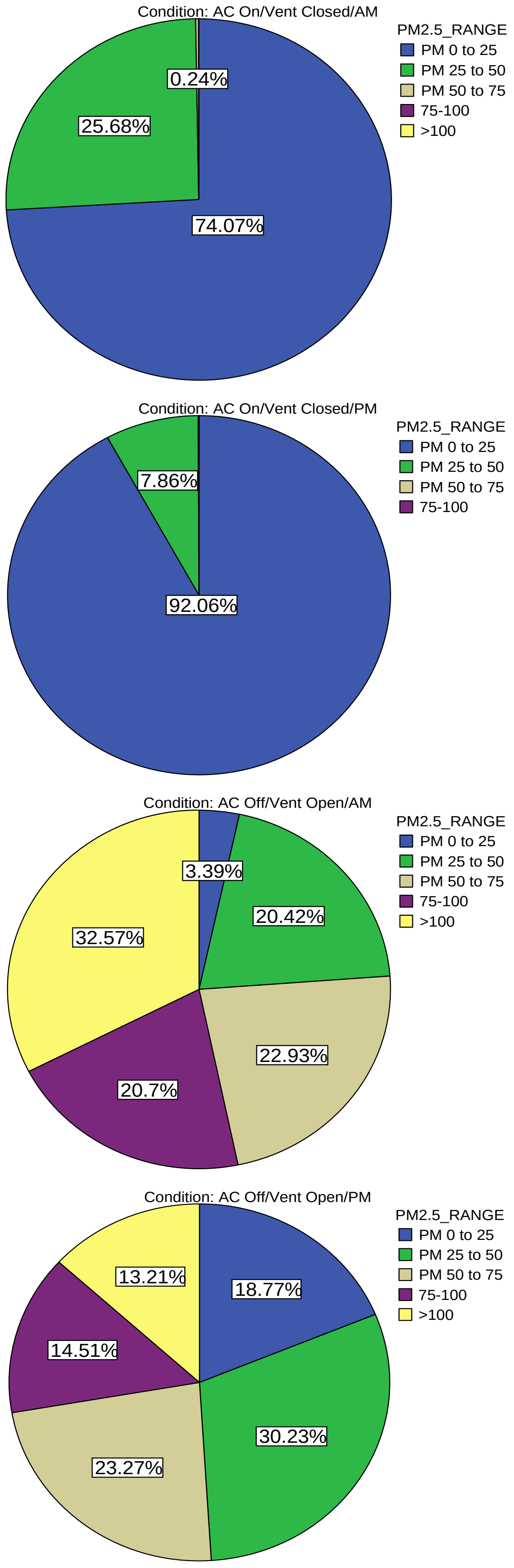


Figure 6: Proportion of Time for Various Levels of $PM_{2.5}$

4. Conclusion

Establishing the link between personal activities, exposure to pollution and ultimately short and long-term health ramifications is one of the most pressing public health issues of today. Currently, this assessment is made through tenuous correlations between averaged readings from fixed site ambient pollution monitors (of which there are currently 18 in Sydney, not all of which monitor $PM_{2.5}$) and aggregate medical statistics such as hospital admissions. While the provision of time-averaged ambient data is indicative of general air quality trends it does not reflect the fact that certain pollutants can vary markedly at a local scale as demonstrated here. Gaining a handle on pollution levels at finer levels of temporal and spatial resolution has been restricted by the use of gravimetric methods, which although reasonably accurate, have restricted analyses to coarse sampling intervals and are somewhat inflexible due to the requirement for specialised equipment to weigh and analyse the results.

The current study addresses some of these measurement issues by combining the capabilities of more flexible particle monitoring devices with the automated spatial referencing capabilities of GPS. As a data collection method in itself, the approach is intrinsically appealing to all those collecting air quality data, whether it is for research purposes or to complement an existing local air quality monitoring program. The portability of both devices makes them appealing for study of other modes (bicycle, walk, bus, train) something, we are currently investigating in Sydney.

It is also important to understand the limitations and caveats of this method. As was explained in an earlier section, estimates of particulate concentrations from nephelometric methods generally do not confer with those from gravimetric methods and calibration is non-trivial. In addition, the measurements say nothing about the composition of the particulates, which is in itself a whole other area of investigation. The question this raises is what the numbers coming off the device mean in terms of standards (the bench-marks linked to health outcomes), which are based on other measurement methods. One possibility could be to identify 'hotspots' of particulate elevations for more detailed study using more rigorous measurement tools (*20*). In terms of the GPS, while this opens up a whole new world of spatial analytical possibilities, there are still many issues surrounding the collection, management, and processing of the data. While we have developed software routines to overcome some of these problems, the processing of one vehicle trip in this study still takes in the order of thirty minutes. With walking and other 'off-network' trips, the problems are even more challenging.

These issues aside, the study demonstrated that even for this relatively simple case, we were able to gain considerable insights into the magnitude and location of intra-trip excursions (hotspots), which were not discernible from aggregate trip analyses. Overall, the most critical issue was vent position with average concentrations well below hazardous levels when closed even in heavily congested traffic. This finding is corroborated by others. For instance, in a study of fine particulates in state trooper vehicles in California, Riediker et al., (2004) found that levels of $PM_{2.5}$ levels in state trooper vehicles were not only lower than might be deemed hazardous, but actually lower than levels from roadside monitors (*12*). Clearly, the extent to which this occurs is dependent on the filtration system of the vehicle, which is likely to differ markedly by make, model and year. An additional issue here is that filtration systems are likely to be less effective in blocking ultrafine particles (less than 0.1 microns), which in addition to being strongly associated with road traffic are thought to pose an even greater health hazard because of their deeper penetration into the bronchioli (*17*).

Other important factors were time-of-day (morning levels greater than afternoon) and the use of air-conditioning (off levels greater than on) and to a lesser extent, average speed (decreasing levels with increasing speed). Perhaps most perplexing here is why there is not a stronger relationship between declining speeds and increasing particulate levels. The issue is that speed is essentially a proxy for all the traffic and street environment factors we know influence particulate levels but are difficult to quantify. This is something we started to investigate here by initially subjectively defining seven sections as specified in Table 2 and comparing levels within those sections. Clearly, the advantage of the spatially-referenced data is we can build greater refinement into this process, which is something we are currently pursuing.

As a final point, the intra-trip analyses suggests that while we may be able to identify additional factors that contribute to $PM_{2.5}$ variability, much will remain a factor of random events. For instance, the example presented here showed the impacts of being behind a smoky vehicle. On other trips, the driver was able to associate unusual excursions with being behind a bus but in many cases it was simply inexplicable. With this method, while we can improve our understanding of where things happen there is still the fundamental issue of what might have caused a change in $PM_{2.5}$. One option we are currently pursuing is the potential to link the particle/GPS data with digital video footage for each trip. Clearly there are a host of additional issues involved here but this may be a bridge we have to cross if we are to get a true understanding of what causes elevated levels of fine particulates while travelling.

Acknowledgements

Qinjiang Jiang for developing the software processing routines used in this study.

References

Brunekreef and Holgate (2002). Air Pollution and Health. *Lancet, 360*, 1233-1242.

Kappos, A.D., et al, (2004). Health Effects of Particles in Ambient Air. *International Journal of Hygiene and Environmental Health, 207*, 399-407.

Michaels, R.A. and M.T. Kleinman (2000) Incidence and Apparent Health Significance of Brief Airborne Particle Excursions. *Aerosol Science and Technology* 32, 92-105.

Delfino, R.J., B.D. Coate, R.S. Zeiger, J.M. Seltzer, and D.H. Street (1998). Symptoms in pediatric asthmatics and air pollution: differences in effects by symptom severity, anti-inflammatory medication use and particulate averaging time. *Environmental Health Perspective* 106, 751-761.

Adams, H.S., M.J. Nieuwenhuijsen and R.N. Colville (2001) "Determinants of Fine Particle ($PM_{2.5}$) Personal Exposure Levels in Transport Microenvironments, London, UK,*" Atmospheric Environment,* 35, Issue 27, September, 2001, pp. 4557-4566.

Chan, L.Y., W.L. Lau, S.C. Zou, Z.X. Cao, S.C. Lai (2002) Exposure level of carbon monoxide and respirable suspended particulates in public transportation modes while commuting in urban areas of Guangzhou, China. *Atmospheric Environment* 36 (38), 5381-5840.

Gee, I.L. and D.W. Raper (1999) Commuter exposure to respirable particles inside buses and by bicycle. *The Science of the Total Environment,* 235, 403-405.

Gulliver, J. amd D.J. Briggs (2004) Personal exposure to particulate air pollution in transport microenvironments. *Atmospheric Environment,* 38, pp. 1-8.

Rank, J., J. Folke, and P.H. Jespersen (2001) Differences in cyclists and car drivers exposure to air pollution from traffic in the city of Copenhagen. *The Science of the Total Environment, 279*, 131-136.

Chang, L.T., Suh, H.H., Wolfson, J.M. *et al.* (2001). Laboratory and field evaluation of measurement methods for one-hour exposures to O3, $PM_{2.5}$, and CO. *Journal of the Air and Waste Management Association, 51,* 1414–1422.

Yanosky, J.D., Williams, P.L. & MacIntosh D.L. (2002). A comparison of two direct-reading aerosol monitors with the federal reference method for $PM_{2.5}$ in indoor air. *Atmospheric Environment, 36,* 107–113.

Riediker, Cascio, Griggs, Herbst, Bromberg, Neas, Williams and Devlin (2004). Particulate Matter Exposure in Cars Is Associated with Cardiovascular Effects in Healthy Young Men. *American Journal of Respiratory and Critical Care Medicine, 169*, 934-940.

Hinds, W.C. (1999). *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles,* Second ed. New York: John Wiley & Sons, Inc.

Quintana, P.J.E., J.R. Valenzia, R.J. Delfino, and L.S. Liu (2001) "Monitoring of 1-Min Personal Particulate Matter Exposures in Relation to Voice-Recorded Time-Activity Data", *Environmental Research Section A,* 87, 199-213.

Kim, J.Y., Magari, S.R., Herrick, R.F., Smith, T.J. & Christiani, D.C. (2004). Comparison of Fine Particle Measurements From A Direct-Reading Instrument and a Gravimetric Sampling Method. *Journal of Occupational and Environmental Hygiene, 1*, 707-715.

Patashnick, H, Rupprecht, G, Ambs, J L, Meyer, M B (2001) Development of a reference standard for particulate matter mass in ambient air *Aerosol Science and Technology 34* (1), 42-45.

Taylor, D and M. Ferguson (1998) The Comparative Pollution Exposure of Road Users – a Summary. *World Transport Policy and Practice,* 4 (2), pp. 22-26.

Levine at al., (2002) *Statistics for Managers Using Microsoft Excel*.

Alm, S., J. Jantunen and M. Vartianinen (1999) Urban commuter exposure to particle matter and carbon monoxide inside an automobile. *Journal of Exposure Analysis and Environmental Epidemiology,* 9, pp237-244.

Weijers, E.P., A.Y. Khlystov, G.P.A. Kos, and J.W. Erisman (2004) Variability of particulate matter concentrations along roads and motorways determined by a moving measurement unit. *Atmospheric Environment,* 38, pp. 2993-3002.