MOVEMENT OF PEOPLE AND AIR POLLUTANTS: EXPOSURE ASSESSMENT USING DYNAMIC POPULATION DATA

Sean Walsh[1], Stephen Roddis[2], Mark Bannister[1],
Joshua Stewart[2], Martin Cope[3], Sunhee Lee[3]

[1] EPA Victoria, Ernest Jones Drive, Macleod, VIC, 3085, Australia
[2] Department of Transport, 121 Exhibition St, Melbourne, VIC, 3000, Australia
[3] Centre for Australian Weather and Climate Research, PMB 1, Aspendale, VIC 3195, Australia

Abstract

Calculating population exposure to air pollutants requires a knowledge of the spatial and temporal patterns of air pollution in relation to the exposed population. Population data are often treated as if everyone remained at their residences all day; this is clearly not the case. Furthermore, peak air pollutant concentrations do not always occur where people are most concentrated; this is especially true for secondary pollutants which may develop many kilometres downwind of source areas.

In order to build improved estimates of population exposure in Melbourne, the 2007 Victorian Integrated Survey of Travel and Activity (VISTA) was used to construct twenty-four maps of the urban population, one for each hour of the day. This data was combined with air pollutant concentrations from a CSIRO grid-based chemical transport model to estimate exposure of the population, accounting for typical daily movements on weekdays and weekends. A further refinement was to separate the population data into age groups, since younger and older residents travel less than those of working age; with the aim of improving exposure estimates for those with increased vulnerability to air pollution.

The results are compared with the more conventional approaches of assuming either a single population total for the city, or a map of fixed residential population. It was found that average dynamic exposure estimates were slightly higher than estimates based on residential population, whilst peak dynamic exposure estimates were significantly higher.

Keywords: Exposure, Population, Air Pollution, Time-Activity Study

1. Introduction

Common air pollutants may impact on human health, with the extent of harm dependent on the extent of exposure or dose. However, quantifying exposure remains a challenge, due to a number of reasons, for example:

- The full spatial and temporal pattern of concentrations across an urban area is extremely difficult to determine;
- Measurements and models evaluate outdoor air pollution, but most of the time people are either indoors or in vehicles;
- During a typical day, people may be far from their point of residence, which means that using census population for exposure calculations is problematic.

This project seeks to address the third issue, using a travel survey for Melbourne to construct twenty-four population maps for Melbourne, one for each hour of the day. These maps are combined with modelled air pollutant concentrations, to create population exposure estimates. Results are compared with two simpler but commonly used representations of population.

2. Literature

A number of travel/activity surveys for Melbourne were undertaken between 1993 and 1997 (Victorian Activity and Travel Survey; Roddis & Richardson, 1998). To create full time-dependent population maps, the sample population patterns were scaled up so that the total population matches a total derived from census data. Trip data are used to determine the surveyed person's location at each time of the day, and known demographic patterns of age and gender are used in the scaling process.

Marquez *et al*. (2001), used this dynamic population data with ambient air pollution measurements to obtain local estimates of time-varying exposure. The study contrasted daily population patterns of a residential area (Bayside) and an industrial area (Dandenong). During the day, there was an influx of people into Dandenong but an exodus of people from Bayside, causing significant differences in the hourly profile of pollutant exposures between the two areas.

This study uses modelled concentrations instead of measurements. Although there will be some errors associated with model accuracy, this approach has the advantages of covering a wider range of pollutants and providing far greater spatial detail.

3. Methodology

Starting with a set of pollutant concentrations $C(x,y,t)$, we can define the pollutant exposure of any persons located at (x,y) for hour h to concentrations above a threshold T :

$$\overline{C}(x,y,h,T) = \int_{1\,hour} H\,[C(x,y,t) - T]\,dt \qquad \ldots(1)$$

Here the Heaviside step function $H[\ ]$ will give 1 when the concentration is above the threshold, and 0 otherwise. Now we introduce population exposure, using three different approaches:

<u>Uniform</u> Population Exposure

$$E_U(x,y,h,T) = \overline{C}(x,y,h,T) * P_U \qquad \ldots(2)$$

<u>Residential</u> Population Exposure

$$E_R(x,y,h,T) = \overline{C}(x,y,h,T) * P_R(x,y) \qquad \ldots(3)$$

<u>Dynamic</u> Population Exposure:

$$E_D(x,y,h,T) = \overline{C}(x,y,h,T) * P_D(x,y,h) \qquad \ldots(4)$$

Where:

P_U = uniform (spatially averaged) population
= P_{TOTAL} / (nx * ny)

$P_R(x,y)$ = residential population in grid cell (x,y)

$P_D(x,y,h)$ = dynamic (hourly) population in grid cell (x,y) and hour h

Hourly exposure values are in units of ppb-person-hours. This data can then be aggregated over a longer time period, for example:

$$E_R^{Annual}(T) = \sum_h \sum_x \sum_y [E_R(x,y,h,T)] \qquad \ldots(5)$$

$$E_R^{Max}(T) = \underset{h,x,y}{MAX}\,[E_R(x,y,h,T)] \qquad \ldots(6)$$

4. Case Study

Air pollution and population were examined over an area of 210 x 180 km, centred on Melbourne, Australia. Pollutant concentrations were taken from the TAPM-CTM model (Cope *et al*., 2008), using emissions from the year 2006 (Delaney & Marshall, in press). Whilst this combined inventory & model system is the subject of ongoing improvement, its accuracy in predicting air pollution in Melbourne is quite reasonable (Cope *et al*, in press). The model was run with a full year of meteorology data, using three nested grids, with the inner grid of 70 x 60 cells (3 km spacing) matching the study area.

Population data were prepared from the 2007 Victorian Integrated Survey of Travel Activity (VISTA) (Department of Transport, 2009), which involved a survey of 11400 households in Melbourne and a further 6000 households in nearby regional centres. The data were organised into three age groups, and processed into hourly weekday population and hourly weekend population, for each cell in the 70 x 60 model grid.

The survey provides detail on a range of typical daily activities, as can be seen in Figure 1. Note that the total Melbourne dynamic population increases slightly during the day as people commute in from regional towns.

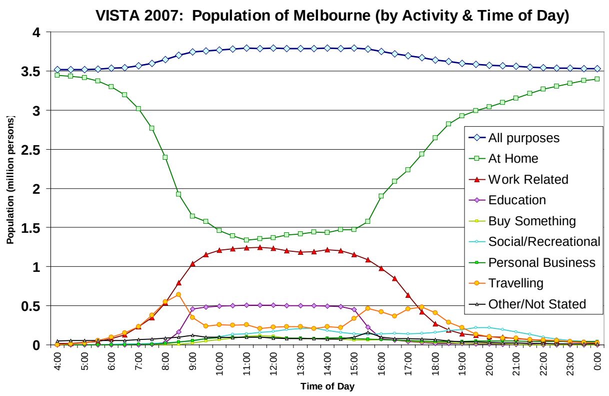

Figure 1: Weekday population & activity in Melbourne

Using trip data from the survey, origins and destinations were geo-coded to assign locations for each hour of the day. If a survey respondent was travelling at a given hour then the trip *origin* was used to define the location if they were less than half way through the trip, otherwise the *destination* was assigned. Respondents who recorded no travel on their survey day were assigned to their home location for the full 24 period. Respondents that were outside the study area for all or part of the day were excluded for the time they were absent. Weighting factors, based on the demographic representativeness of each respondent, were then used to scale up the survey results to provide total weekday and weekend population estimates for each hour of the day.

Figures 2 and 3 show examples of the resulting population maps, for times 01:00 and 13:00 respectively. These maps show weekday population for ages 15-64, and clearly demonstrate the daily influx of workers towards the city centre. Note that there is some uncertainty in individual cell populations, as the data are derived from a survey, but it appears that the overall population patterns make sense in terms of typical daily urban activity.

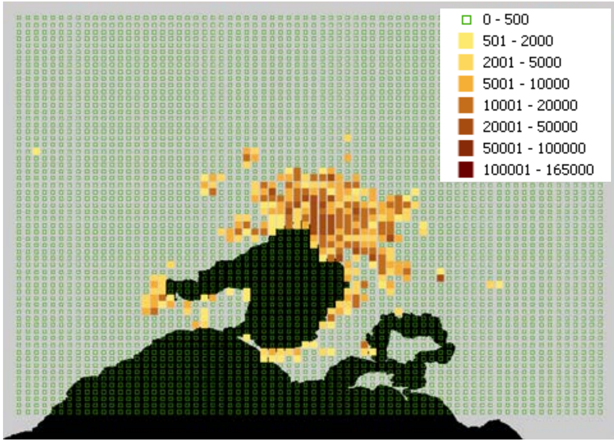

Figure 2: Weekday population at **1:00** **AM** (ages 15-64)

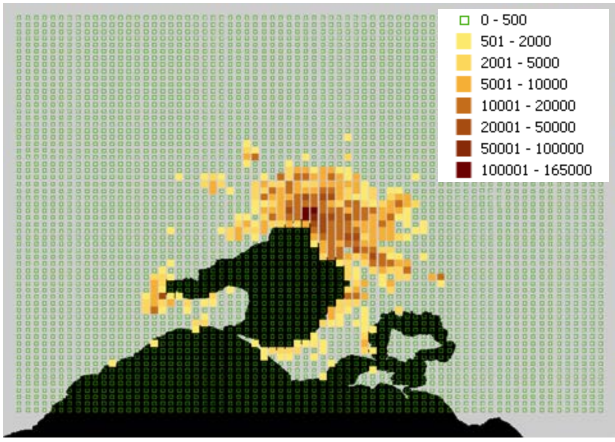

Figure 3: Weekday population at **1:00** **PM** (ages 15-64)

This study seeks to compare the use of dynamic population data with more conventional approaches. A conventional map of residential population for 2007 was prepared from the dynamic data by taking an average of the midnight to 3:00am weekday population values. In Australia, the census is taken on a weeknight, thus night time weekday population should provide a census-like population dataset for comparison purposes. Table 1 shows the residential population totals for each age range.

Table 1. Residential population (millions)

Age Range	**Population**
0 - 14	0.715
15 - 64	2.544
65 +	0.460
All ages	**3.719**

Custom software was developed to perform exposure calculations using TAPM-CTM concentration fields. The software was configured to provide exposure statistics over the whole domain, subsets of the domain, or individual grid cells.

5. Results & Discussion

Calculations of total annual exposure for a range of pollutants were undertaken using equation (5). A selection of results is presented below, comparing the three approaches to exposure.

Table 2. Total annual exposure for gaseous pollutants (ppb- person-hours x 10^9), threshold = 0

Pollutant	**Uniform Exposure** $E_U^{Annual}(0)$	**Residential Exposure** $E_R^{Annual}(0)$	**Dynamic Exposure** $E_D^{Annual}(0)$
CO	3011	7583	7950
O_3	750	543	555
NO_2	59	275	288
SO_2	17	33	36
HCHO	20	30	32
Toluene	2.5	17	18
Xylenes	1.5	12	12
Benzene	1.3	7.9	8.4

Recently, Cope *et al.* (in press) have extended the TAPM-CTM model to simulate various components of $PM_{2.5}$. Table 3 shows exposures to total fine particles and also to each modelled component.

Table 3. Total annual exposure for $PM_{2.5}$ and its components (µg/m^3-person-hours x 10^9), threshold = 0

Pollutant	**Uniform Exposure**	**Residential Exposure**	**Dynamic Exposure**
$PM_{2.5}$	34.8	79.6	82.7
Organics	9.7	18.8	19.4
Elemental Carbon	2.8	17.3	18.2
Sulfate	6.3	14.7	15.3
Metals & Other	2.6	11.4	12.0
Nitrate	4.2	5.2	5.3
Ammonium	2.5	6.1	6.3
Non-volatile background	4.3	4.2	4.3
Sea-Salt	2.3	1.9	1.9

For both gaseous and particle pollutants, it appears that the ratio of *dynamic* to *uniform* exposure estimates depends strongly on how closely the spatial pattern of emissions matches the pattern of population. This is partly a function of whether the pollutant is primary or secondary, but also a function of the location of pollutant sources. For example, the ratio for elemental carbon (strongly primary) is 6.4, whereas the ratio for nitrate (strongly secondary) is 1.3. For ozone, uniform exposure estimates are *larger* than dynamic estimates (ratio 0.74), reflecting the secondary nature of ozone, the influence of substantial background ozone concentrations, and the fact that ozone is rapidly lost to titration in the presence of fresh NO emissions from urban activity.

The above tables show that average dynamic exposures for zero threshold are marginally higher (+2 to +6%) than average residential exposures. A larger effect is found when higher thresholds are considered.

An example of this effect can be seen in Figure 4, which shows the total annual exposure to SO_2 over the study region, considering exposure above various threshold (T) values. As T increases, the result is dependent on a decreasing number of highly polluted days, and on such days, the exact position of the population becomes quite important, from an exposure point of view.

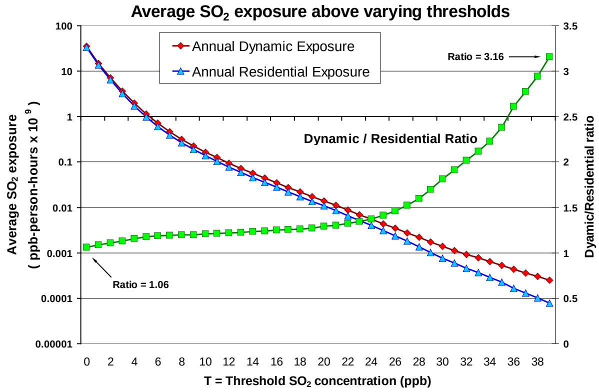

Figure 4. SO_2 exposure – varying thresholds

Another perspective may be gained by calculating spatial and temporal peak exposures (see equation 6). Such worse-case exposures, even at zero threshold, were found to be significantly different between dynamic and residential estimates.

To illustrate this effect, Figure 5 shows Carbon Monoxide exposures in a single 3km x 3km grid cell in the inner city area on a day of light winds in June. In this case the peak modelled CO concentration of 2.6 ppm occurred just before midday, when the dynamic population was also near its peak, with a large number of people working in the inner city at this time. Consequently, the use of residential (census) population gives substantially lower exposure estimates on this day.

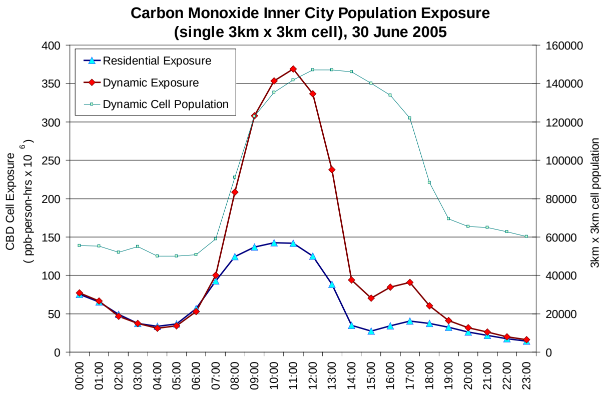

Figure 5. City CO exposure - light wind conditions

Looking over the whole year of simulations, and grouping the data by day of week and hour of day, we can see certain patterns in the peak exposure. Figure 6 shows the peak annual residential and dynamic CO exposures, for an average week day and an average weekend day. Clearly, the effect of using dynamic population data is much more important for weekdays than for weekends. There are two peaks in dynamic exposure corresponding to the overlap of peak traffic concentrations and peak inner city dynamic population.

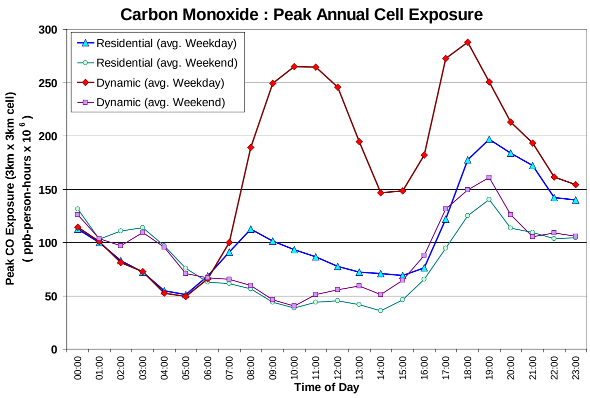

Figure 6. Weekday & weekend exposure profiles

When total annual exposures are calculated for the Central Business District (CBD) only, large differences can be seen between exposure estimates. Table 4 shows residential and dynamic estimates of annual NO_2 exposure on weekdays (M-F), broken down by hour of day, and age grouping, for a 6km x 6km CBD subregion (2 x 2 grid cells). It is interesting to note that the proportion of total exposure experienced by 0-14 year olds is quite different in the two estimates, reflecting the different daily travel patterns of this age group.

Table 4. Total annual weekday CBD exposure for NO_2 (ppb-person-hours x 10^6), threshold = 0

Age Group	CBD weekday Residential NO_2 Exposure	CBD weekday Dynamic NO_2 Exposure
0 - 14	107	129
15 - 64	1131	2357
65 +	63	104
All ages	**1302**	**2590**

6. Conclusions & Future Work

This study has found that the simple approach of averaging all concentrations and assuming a single population value can cause overestimates of exposure for ozone, and large underestimates for other pollutants. The spatial patterns of primary pollutants in general follow the emission sources, which are generally where people are, so a uniform population density assumption fails to account for the co-location of primary pollutants and people. In contrast, ozone is often higher away from sources, causing the opposite effect.

One implication of these results is that greater care may need to be taken in health studies to ensure that exposure estimates do not have a pollutant-specific bias. A commonly used method in epidemiology is to average all measured concentrations across a city (e.g. APHEA protocol, Katsouyanni *et al.* 1996). Because air monitoring stations are generally spread out over an urban area, but not beyond the urban area, this effectively performs a “partial weighting” by population. If these averages are multiplied by the total city population, exposure is likely to fall somewhere between the uniform estimates and the dynamic estimates. Consequently, some of the pollutant-specific bias seen in the uniform estimates may well exist in epidemiological estimates of exposure – this will be examined in more detail in a future study.

By introducing a survey-based approach to population, some new insights have been gained into population exposure to air pollutants in Melbourne. In general, exposure estimates based on dynamic (hourly) population were slightly larger than estimates based on a fixed (residential census) population. These differences were much more pronounced at higher concentration thresholds, when looking at annual worst-case exposures, and when looking at exposures in the Central Business District. In any study which seeks to examine the influence of highly polluted days on human health, it would seem beneficial to use population exposure calculations that account for the daily movements of people.

The next stage in this research will be to include results from time activity studies and personal exposure studies of indoor and in-vehicle air quality, especially those conducted in Melbourne (Ampt *et al*. 2009, EPHC 2005, Galbally *et al.* 2011, Physick *et al*. 2007a, Torre *et al.* 1998). This will allow a micro-environment approach to exposure to be combined with the existing spatial and temporal model of concentrations and population. The accuracy of exposure estimates may also be improved by employing the blending technique of Physick et al. (2007b), which adjusts modelled fields to match observations.

For simulations of future air quality, it may be possible to estimate dynamic exposure in the future by retaining the existing dynamic population patterns, but scaling according to total population projections, or if available, by regional (local government area) projections.

A final extension would be to attempt epidemiological analyses, using modelled population exposure estimates for each age group instead of simply concentrations. Given more refined estimates of the burden of air pollutants on the population, greater clarity may emerge about their associations with health effects.

Acknowledgments

The author would like to acknowledge the Victorian Department of Transport for permission to use and publish the VISTA 2007 population data.

References

Ampt, E., Ortuzar, J., and Richardson, A. 2009, 'Large-Scale Ongoing Mobility Surveys: the State of Practice', in *Transport Survey Methods: Keeping up with a changing world*, Emerald Group Publishing Limited (eds. Patrick Bonnel, Matin Lee-Gosselin, Johanna Zmud, Jean-Loup Madre).

Cope, M., Lee., S.,. Physick, B., Abbs, D., Nguyen, K.C., and McGregor, J. 2008, 'A Methodology for Determining the Impact of Climate Change on Ozone Levels in an Urban Area', final report to the Department of Environment, Water, Heritage and the Arts, Canberra, ACT.

Cope, M., Lee., S.,. Walsh, S., Bannister, M., Delaney, W. and Marshall, A. (in press), 'Verification of a Dynamical Downscaling System for undertaking Air Quality Projections in Melbourne, Australia', *Proceedings of the 20th International Clean Air and Environment Conference*, Auckland, 31 Jul – 2 Aug 2011,, Clean Air Society of Australia & New Zealand, Eastwood, NSW, Australia.

Delaney, W. and Marshall, A. 2011 (in press), 'Victorian Air Emissions Inventory for 2006', *Proceedings of the 20th International Clean Air and Environment Conference*, Auckland, 31 Jul – 2 Aug 2011, Clean Air Society of Australia & New Zealand, Eastwood, NSW, Australia.

Department of Transport. 'Victorian Integrated Survey of Travel And Activity 2007 (VISTA 07): Summary statistics', Victorian Government, 2009.

EPHC 2005, 'Time Activity Study: Summary of Findings', report to the Environment Protection and Heritage Council, Centre for Population Studies in Epidemiology, South Australian Department of Human Services.

Jerrett M., Burnett, R., Ma, R., Pope, C.A. III *et al*. 2005, 'Spatial analysis of air pollution and mortality in Los Angeles', *Epidemiology,* 2005:**16** (6):727-736.

Galbally, I., Keywood, M., Powell, J., Lawson, S., Cheng, M., Dunne, E., Gillett, R., Molloy, S., Selleck, P., Ward, J. and Reisen, F. 2011, 'An overview of the CSIRO 2008-2009 indoor air quality study', *Air Quality and Climate Change*, **45**:27-35.

Katsouyanni, K., Schwartz, J., Spix, C., Touloumi et al. 1996, 'Short term effects of air pollution on health: a European approach using epidemiologic time series data: The APHEA protocol', *Journal of Epidemiology and Community Health*, **50** (Supplement 1):S12-S18.

Kousa, A., Kukkonen, J., Karppinen, A., Aarnio, P. and Koskentalo, T. 2002, 'A model for evaluating the population exposure to ambient air pollution in an urban area', *Atmospheric Environment*, 36:2109-2119.

Marquez, L., Smith, N., Trinidad, G. And Guo, J. 2001, 'Activity Patterns and Pollution Exposure: A Case Study of Melbourne', *European Journal of Transport and Infrastructure Research*, **1**(4):371-390.

Ott W. 1982, 'Concepts of Human Exposure to Air Pollution', *Environment International*, **7**:179-196.

Physick. W., Powell, J., Cope, M., Lee, S., Boast, K., Gillett, R. and Edgar, G. 2007a, 'Approaches for Estimating Personal Exposure to NO2 across Melbourne', *Proceedings of the 14th IUAPPA World Congress*, Brisbane, 9-13 September 2007, Clean Air Society of Australia & New Zealand, Eastwood, NSW, Australia.

Physick. W., Cope, M., Lee, S., Hurley, P. 2007b, 'Estimation of Exposure to Ambient Concentrations', *Proceedings of the 14th IUAPPA World Congress*, Brisbane, 9-13 September 2007, Clean Air Society of Australia & New Zealand, Eastwood, NSW, Australia.

Roddis, S.M. and Richardson, A.J. 'The Construction of Daytime Activity Profiles from Household Travel Survey Data', *77th Annual meeting of the Transportation Research Board*, Washington, D.C., January 11-15, 1998.

Torre, P., Bardsley, T.B., Whillans, F.D. and Hughes, J. 1998, 'Measuring Volatile Organic Compounds during Four Modes of Commuting in Melbourne', *Proceedings of the 14th International Clean Air and Environment Conference*, Melbourne, 18-22 October 1998, Clean Air Society of Australia & New Zealand, Eastwood, NSW, Australia.

Zartarian, V., Bahadori, T. and McKone, T. 2005, 'Adoption of an official ISEA glossary', *Journal of Exposure Analysis and Environmental Epidemiology*, **15**:1-5.