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Chapter 9

The ecology of urban emissions

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Abstract

Vehicle emissions depend directly on urban driving patterns which are an integral part of a wider range of urban features including density of settlement, car ownership, status of public transport, etc. Thus the conditions vehicles experience and their consequent emissions are directly related to the urban fabric. A methodology of sampling an urban area is developed by defining homogeneous areas within the city in terms of their activity intensity, modal split and social/economic status. These homogeneous areas are used as a basis for sampling an urban area and defining the variation in driving patterns both spatially and temporally. This illustrates that changes in traffic conditions are based primarily on a decrease in intersection-based traffic events from central to outer areas, and secondarily on a general decrease in the number of vehicle-based traffic events. These progressively freer flowing driving patterns, are associated directly with a variety of wider land-use and transport features, which also vary systematically according to centrality. Thus urban structure is directly related to vehicle emissions with an increase in emission rate as a function of proximity to the central business district.

1 Introduction

Urban air pollution is directly related to the urban transport system and its interaction with the city, as motor vehicles produce different emissions when driven under different conditions of speed, acceleration and idle. Although cities are recognised as a complex collection of interacting factors, few attempts have been made to isolate key variables to describe the interaction between the city and its transport system. As such, most attempts to monitor mobile urban air pollution sources are based on intuitive sampling rather than a rational framework. This chapter attempts to lay such a framework by defining homogeneous areas within a city on the assumption that the conditions vehicles experience in driving on urban roads are influenced by a number of factors such as the density of the surrounding element, road type and availability, and public transport factors.

Thus, if homogeneous areas within a city can be defined using diverse urban characteristics which together significantly affect driving patterns, then routes within these areas may provide a rational framework for sampling driving patterns and consequently emissions. Collecting driving pattern data on the basis of these homogeneous areas is aimed at maximising the probability that all noteworthy variations in driving patterns and fuel efficiency across the city are identified and accounted for in the data collection.

Driving cycles have been used to provide a single speed-time trace that characterises driving conditions across an urban area (i.e. Stonex (1957); Kuhler and Karstens (1978); Gandhi *et al.* (1983)). However, few studies have collected sufficient data to be able to specify the intra city variability in driving patterns or relate this to the structure of the city. The definition of homogeneous areas within a city, enables us to define representative driving cycles for each region of the city and discuss variations in the individual driving cycles in relation to the structure of the city. Such considerations have direct application to urban transport planning in relating the structure of the city to fuel consumption and urban air pollution through driving pattern variations.

Thus, this chapter develops a methodology for sampling an urban system and applies it to Perth, Western Australia (Kenworthy *et al.* (1992)). Driving pattern data collected on the basis of the homogeneous areas are used to characterise morning, evening and off-peak driving and highlight the magnitude of congestion on a broad city wide scale. It then provides a morning, evening and off-peak driving cycle for each of the homogeneous areas in an attempt to link the extra detail afforded by

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these to the form and function of different areas of the city (Newman *et al.* (1992)). Such driving cycles lead directly to an evaluation of vehicle emissions as a function of urban structure (Lyons *et al.* (1990a); (1990b)).

2 Definition of homogeneous areas

Cities present a complex collection of interacting factors and processes that are difficult to understand without approaches and techniques which help to reveal underlying patterns or themes. Shevky and Williams (1949) and Shevky and Bell (1955) defined social areas within a city in terms of socio-economic status, family status and ethnic status. This enabled them to define areas containing persons having the same level of living, the same way of life and the same ethnic background. They hypothesized that the behaviour and attitudes of people in these areas would be systematically different from persons living in other areas. Subsequent studies, involving the application of factor analysis and multivariate statistical techniques (Knox (1982)), have tended to support this hypothesis, although the constructs sometimes overlap or are weakened by the peculiarities of a particular city. Stimson (1982) went a step further by considering the overall spatial patterns defined by certain variables and developing a typology of residential areas. That is, using cluster analysis, he derived a set of territorial spaces that are characterised by as high as possible a degree of within group homogeneity and between group heterogeneity with respect to overall social space characteristics.

Enormous scope exists for describing a city both in the variables that can be chosen and in the level at which observations are made. A basic problem is achieving some degree of compatibility between these, by choosing variables that are available at the desired observation level. Within Perth, a reasonable solution was achieved by defining the basic spatial unit in terms of postcode areas. The available parameters, classified under six headings of (i) social/economic factors, (ii) land-use intensity factors, (iii) road availability factors, (iv) congestion factors, (v) public transport availability factors and (vi) modal split factors, are shown in Table 1. Most of these were available at a postcode level, although parameters 16-21 often required amalgamations of up to three postcode areas. Thus the Perth urban region was divided into thirty-eight zones over which all of these parameters were available.

These basic parameters do not represent the only parameters that could describe the urban system but rather represent a compromise be-

Table 1: Basic parameters affecting travel and travel patterns (after Kenworthy *et al.* (1992))

Parameters	Source
Social/economic	
1. Population	1976 Census
2. Total vehicles on register	1976 Motor vehicle census
3. Total vehicles parked at residence	1976 Census
4. Household income	1976 Census
Land-use intensity	
5. Total area	WA Educ. Dept.
6. Urbanised area	WA Educ. Dept.
7. Straight line distance to CBD	Calculated
8. Number of dwellings	1976 Census
Road availability	
9. Total length arterial roads	Calculated
Congestion	
10. Vehicle kms on arterial roads	Main Roads Dept.
Public transport availability	
11. Length of routes	Measured
12. Service kms	Calculated
Modal split	
13. Journey to work by public transport	1976 Census
14. Journey to work by private transport	1976 Census
15. Journey to work by walking and biking	1976 Census
16. All other public transport trips	Director General Transport (DGT)
17. All other private transport trips	DGT
18. All other walking biking trips	DGT
19. Total public transport trips	DGT
20. Total private transport trips	DGT
21. Total walking biking trips	DGT

tween available data and the need to characterise the city. The effects on fuel consumption and emissions of modifying driving patterns in selected areas (for example, through new roads or traffic management) cannot be adequately gauged without considering such things as possible changes in the use of public and non-motorised transport. Thus public transport and walking/cycling data were included because these other forms of mobility affect and are affected by driving patterns. Other variables, such as workforce location, land-use diversity or average distance between intersections, would also provide useful measures of the urban system but were not readily available in sufficient detail.

These initial parameters were used to define the twenty-two standardised variables shown in Table 2. Standardisation accounted for the marked variation in area and population between the different zones and also ensured the elimination of dependent ratios between variables. The resulting zones and variables accounted for 90% of Perth's population and 75% of its urbanised area. The areas not covered are highly dispersed, low density suburbs with insufficient data available to incorporate them in this analysis.

Cattell *et al.* (1966) defined a class as a clustering of objects wherein every object in the class is more like every other member of the class than it is like any object placed outside the class. Using this definition, Carlson (1972) developed a clustering technique that arranges zones into various homogeneous classes depending upon the input variables and a percent error factor. This technique defines the input variables as a number between 1 and 5. Hence the variables listed in Table 2 were classified for each zone in terms of their percentile distribution across the metropolitan area and redefined in the range 1-5. The boundary between percentiles was chosen subjectively to eliminate placing disparate variables in the same category when there were large differences in variable values. Such a technique defined seven clusters comprising thirty-four zones (four zones did not cluster) with a 10% error factor.

Although these clusters appear to offer a reasonable framework, they were quantitatively evaluated through disciminant analysis (Finn (1977)). In this, the actual value of each variable was used and it showed that a significant difference existed overall among the clusters with three discriminant functions accounting for 88.1% of the between group variation. These functions could be classified as:

Function 1 - 43.1% of variation between clusters. This function appeared to relate chiefly to land-use intensity, all aspects of private vehicle usage, off-peak public transport usage and especially off-peak walking and cycling.

Table 2: Standardised variables (after Kenworthy *et al.* (1992))

	Social/economic factors
1.	Vehicles on register per person
2.	Vehicles parked at residence per person
3.	Household income
	Land-use intensity factors
4.	Straight line distance to CDB
5.	Urban density
6.	Dwelling density
	Main road availability
7.	Length of arterial road per vehicle on register
8.	Length of arterial road per hectare
	Congestion factors
9.	Vehicle kms per km per min
10.	Vehicle kms per hectare
	Public transport availabilty factors
11.	Length of public transport route per hectare
12.	Service kms per hectare
13.	Service kms per km
	Modal split factors
14.	% of journey to work trips by public transport
15.	% of journey to work trips by private vehicle
16.	% of journey to work trips by walking and biking
17.	% of other trips by public transport
18.	% of other trips by private vehicle
19.	% of other trips by walking and biking
20.	% of total trips by public transport
21.	% of total trips by private vehicle
22.	% of total trips by walking and biking

Function 2 - 28.1% of variation between clusters. The main contributors to this function were the degree of congestion, intensity of public transport routes and use of private vehicles for the journey-to-work.
Function 3 - 16.7% of variation between clusters. Modal split for off-peak travel, proximity to the city and concentration of public transport services clearly defined this function.

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To test if any clusters should be amalgamated the discriminant analysis was re-run using these functions as single variables. This provided cluster or cell means for each of these three composite variables and allowed systematic tests to see where significant differences existed between clusters. In particular, the Newman-Keuls method for testing differences between all pairs of ordered means gives

$$q_r = \frac{T_i - T_j}{\sqrt{\frac{\sigma}{N}}} \qquad (1)$$

where q_r is the test statistic to be compared to values in the distribution of the studentized range statistic (r being the number of steps the two means are apart on an ordered scale), T_i - T_j is the difference in the two means being compared, σ the mean square error, and N the harmonic mean of the number of observations in each of the means. Undertaking this test, in turn for each of the three discriminant functions, suggested that there was support for amalgamating two of the clusters to form a single group whereas the remaining clusters warranted inclusion as distinct groups.

3 Characteristics of homogeneous areas

The discrimant analysis provided cluster means and standard deviations for each of the twenty-two variables, whereas a factor analysis provided the grand means and standard deviations for each variable based on the original thirty-eight zones. Knox (1982) has shown that expressing the mean of each variable for a cluster in terms of standard deviations from the grand mean reveals patterns of differentiation between the clusters based on each variable. The patterns of differentiation in variables for the six groups have been summarised in Table 3, highlighting those variables which made a large contribution to the cluster's distinctiveness.

In this table land-use, congestion and public transport availability factors are listed as activity intensity because a high value for one of these factors is associated with comparably high values for the other two, relative to the average for Perth. Thus when urban density is high so are congestion and public transport availability. For modal split, there are consistently one or two variables which give each cluster a significantly different pattern of transport usage. As most journey to work trips are done during peak periods and most other trips during off peak times, Table 3 expresses modal split differences in these terms. Social/economic status is measured according to household income and vehicle onwership

Table 3: A summary description of the six driving pattern areas in terms of the major factors used to derive them (after Kenworthy *et al.* (1992)). Note all rankings of characteristics are made relative to Perth.

Characteristics	Social economic status of residents (household income and vehicle ownership)	Activity intensity of area, land-use intensity, congestion, public transport availability	Dominant modal split features of residents
Central core Area 1	Very low	Very high	*Peak periods* Low private vehicle usage, high public transport, walking, biking
Inner suburbs Area 2	Average to low	High	*All periods* Very high public transport
Middle Western suburbs Area 3	Average to high	Average to high	*Off peak* Very low public transport
Middle South, outer North and Eastern Suburbs Area 4	High	Low	*Peak periods* High private vehicle usage, low public transport, walking, biking
Outer South East and North East suburbs Area 5	Average	Very low	*Off peak* Very high private vehicle usage, very low walking, biking
Northern State housing suburbs Area 6	Low	Average to low	*Off peak* Very low private vehicle usage, very high walking, biking

variables. Total vehicles on register per person in an area tends to be a measure of the commercial/business nature of a zone as reflected in the enormous number of vehicles registered per person in the central core (Kenworthy (1986)), whereas people living in this area have very low vehicle ownership. Thus it is probably more a measure of congestion than social/economic status.

The variables used to measure main road availability did not lead to a consistent picture across the urban area. For example, main road availability per vehicle on register in area 4 is higher than average, but per hectare it is lower than average. As well, in the central core where congestion is very high, main road availability is also high, but in the inner suburbs where congestion is still comparatively high, main road availability per vehicle is very low, but average on a per hectare basis. Overall main road availability does not appear to be a strong determinant of the clusters.

A factor analysis program employing a principal component solution and Varimax rotation was applied to the twenty-two cluster analysis variables (Kenworthy *et al.* (1992)). Combining the variables with high loadings suggests that the dimensions of the factors are
1 - *Private transport dominance*,
2 - *Biking and walking facilitation for non-work trips*,
3 - *Public transport facilitation*,
4 - *Public transport usage for non-work trips*, and
5 - *Main road availability*.
The spatial expression of these factors was found by defining a factor score as:

$$S = \sum_{i=1}^{22} \left(\frac{v_{i,j} - V_i}{\sigma_i} \right) f_i \qquad (2)$$

where $v_{i,j}$ is the individual value of the variable i (1-22) for zone j (1-38), V_i is the grand mean of variable i, σ_i is the standard deviation of variable i and f_i is the corresponding factor loading. Each range of factor scores was divided into five groups by taking the seven zones with the highest and lowest scores for each factor, plus three groups of eight zones each. The spatial distribution of these groups for Perth has been discussed by Kenworthy *et al.* (1989); (1992).

These distributions show that the six areas of the city which were identified using the cluster analysis, are partly reproduced by the first factor of private transport dominance, which incorporates parameters associated with car availability, public transport availability and congestion. The spatial expression of this factor shows a clear pattern of private transport dominance for residents in Perth's outer suburbs with comparatively less emphasis on private transport and more emphasis on public transport/biking/walking for residents nearer the CBD. On the other hand, factor 3, public transport facilitation (with its land-use parameters), is almost the inverse spatial pattern to that of private transport dominance. The inner areas are clearly dominant in characteristics that promote public transport usage, especially for the journey to work, while the outer areas are almost uniformly the poorest at facilitating public transport due to their low density and comparatively low intensity public transport service.

If factor 3 is considered along with factor 1, then the cluster analysis result is almost reproduced. Thus the more urban an area becomes (defined in terms of its activity intensity), the more the area becomes oriented to public transport, biking and walking, and the less private car oriented it becomes for residents. On the other hand, the more suburban an area becomes, the more the area becomes dominated by private vehicle usage and less public transport, biking or walking oriented. The other factors explain only a small amount of the variance and can be understood by reference to specific Perth suburbs (Kenworthy *et al.* (1989)).

4 Route selection

The usual approach to the collection of driving pattern data has been to choose a number of fixed routes throughout the city and to follow vehicles along these routes as many times as required to obtain a statistically meaningful sample (i.e. Watson (1978); Kent *et al.* (1978)). Isolating a relatively small part of a total road network in an urban area so that the observed driving patterns are representative of the total network is a difficult problem. However, given the definition of homogeneous areas within the city, it becomes more a question of finding routes within these areas that are representative of vehicle travel within that area. As such the fixed routes are not meant to represent actual trips that an individual driver would make but rather attempt to characterise the various factors peculiar to a given area to determine the type of driving pattern experienced.

Representative routes for this study were defined by utilizing (i) a detailed breakdown of daily vehicle kilometres of travel (VKT) according to road type and section of the city; (ii) average daily traffic flow data; and (iii) the Main Roads Department road classification system.

The VKT illustrated that any fixed routes need to include all road types to be representative. Thus fixed routes need to comprise road types in similar proportions to the amount of travel done on each road type in the area under consideration. It is also necessary to ensure road links of appropriate type and daily volume are incorporated into the fixed routes while maintaining the fixed routes within a given area.

Given these constraints, a series of thirteen routes were chosen within the six homogeneous areas. These routes are described in detail in Kenworthy (1986) and all contain a mix of road types and volumes representative of the specific area, with an overall mix of road types that approximate the proportions of daily driving done on different road types in Perth.

5 Vehicle data collection

Weekday driving patterns were characterised by collecting driving pattern data on each on the thirteen fixed routes which were driven in morning peak, evening peak and off-peak using the chase car technique. This consists of randomly selecting a target vehicle in the traffic stream and following it, keeping as near as possible to a constant distance during cruise conditions, and constant time during acceleration and deceleration, but allowing a time lag during the latter conditions. Such a technique has been evaluated (Scott Research Laboratories (1971); Johnson *et al.* (1975)) and found to accurately represent the target vehicle's driving patterns. Where target vehicles turned off the fixed route, the nearest vehicle in front of the research vehicle was selected as the new target.

The research vehicle was a 1980 General Motors Holden 3.3 litre, four speed manual, VC Commodore sedan equipped with a speed transducer capable of providing speed data at one second intervals resolved to 0.1 km h^{-1}, a fuel meter and associated data logging equipment. Vehicle speed was measured through revolutions of the tailshaft and regular calibrations showed it to be accurate to within 0.5%. Full details of the instrumentation is presented elsewhere (Kenworthy (1986)).

A minimum of five runs along each route in each period were logged. Morning peak sampling was carried out between 0700 and 0900 and evening peak between 1600 and 1800, with each route being driven in the one direction. This resulted in some 3000 kms of driving data spread across the urban area.

6 Peak and off-peak driving cycles

Although statistically representative driving cycles can be generated from such data, they suffer a considerable loss in speed resolution (Lyons *et al.* (1986)), and emission estimates from modal synthetic cycles are affected by the loss of transient accelerations (Bulach (1977)). Hence, Newman *et al.* (1992) obtained representative driving cycles for each region by matching summary characteristics of individual speed/time traces with averaged summary characteristics based on all data collected in each of the six areas and over each of the three time periods. This is consistent with the methodology of Kuhler and Karstens (1978), who adopted 10 summary variables to characterise urban driving. These were average speed, average running speed (i.e. excluding idle periods), average acceleration of all acceleration phases, average deceleration of all deceleration phases, mean duration of a driving period from start to stop, average number of acceleration-deceleration changes within one driving period, proportion of time spent idling, proportion of time decelerating as well as the relative distribution of speeds and accelerations. Of these assessment criteria, Kuhler and Karstens (1978) considered it most important to match average speed, followed by average accelerations and decelerations. Time proportions in the four operating modes were allowed less strict tolerances, whereas the other criteria were allowed large tolerances. Similar assessment criteria have been used in other studies (i.e. Watson *et al.* (1982); Lyons *et al.* (1986)).

Overall statistics from the entire driving data defined target statistics, and the representative runs chosen for each time period to match these weighted target values are summarised in Table 4. In matching runs with the target values, the run which best matched average speed, stops per km, PKE and RMS acceleration was chosen. Although speed intervals were generally treated as a lower priority to the other parameters, runs were not considered that, for example, had extremely different percentage idle times from the target. Evans and Herman (1978) showed average speed is the primary determinant of fuel consumption in a range of urban driving and Kuhler and Karstens (1978) also treated average speed as the primary variable.

These cycles illustrate that Perth is comparatively free of congestion. Differences in average speed between peak and off-peak driving according to the weighted target values is only 4 to 5 km hr^{-1} and the average speed for any period does not drop below 40 km hr^{-1}. The proportion of time spent idling in Perth in the off-peak is close to 10% while in peak periods it is 15%.

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Table 4: Characteristics of target and actual driving cycles for Perth for each time period (after Newman *et al.* (1992))

	MP		OP		EP	
	Target	Run	Target	Run	Target	Run
Distance (kms)		15.8		15.8		18.4
Duration (s)		1448		1276		1626
Average speed (km/h)	40.3	39.5	45.3	44.5	41.3	40.7
Stops per km	1.04	1.01	0.73	0.76	0.95	0.98
PKE (m/s/s)	0.42	0.41	0.41	0.43	0.43	0.42
RMS accel. (m/s/s)	0.77	0.78	0.79	0.85	0.79	0.78
% Idle time	14.8	17.8	9.7	11.0	14.5	13.5
% Time within speed ranges						
0.1 - 7.0 km/h	4.6	4.0	3.6	4.0	4.5	4.7
7.1 - 17.0 km/h	6.2	5.1	4.2	4.3	5.9	5.2
17.1 - 27.0 km/h	7.5	8.0	7.0	6.9	7.1	5.6
27.1 - 37.0 km/h	8.1	6.2	7.6	6.3	7.5	7.0
37.1 - 47.0 km/h	9.9	11.4	10.3	8.7	9.2	10.3
47.1 - 57.0 km/h	16.1	18.2	17.1	16.0	14.8	17.2
57.1 - 67.0 km/h	21.9	13.1	25.3	27.5	23.0	29.4
67.1 - 77.0 km/h	9.0	7.0	12.5	12.8	10.7	7.1
77.1 - 87.0 km/h	1.7	8.5	2.4	2.6	2.7	0.0
87.1 - 97.0 km/h	0.1	0.8	0.4	0.0	0.1	0.0

The summary data for each of the six areas and three time periods form the target characteristics for each driving cycle. Selected individual driving traces that approximate these targets are summarised in Table 5.

These driving cycles change from central core to outer suburbs in a visual pattern not unlike an expanding concertina, i.e. the traffic events are increasingly wider in their spacing (Lyons *et al.* (1986); Newman *et al.* (1992)). This is expected as the number of intersections, and hence stops, decreases from central to outer areas, leaving longer periods at higher speeds. Despite the difference in time spent at higher speeds, the major impression for all areas is a fairly uniform range of cruising speed towards which traffic returns after each stop or near stop.

Previously driving cycles have been used in motor vehicle engineering, fuel consumption modelling, emissions testing and traffic management but they also contain an imprint of the city through urban ecology. Newman *et al.* (1992) suggested that driving cycles are an expression of

Table 5: Characteristics of representative driving cycles for each area and time period, where MP is morning peak, OP off peak and EP evening peak (after Newman *et al.* (1992)).

Area	Dist from CBD (km)	Average Speed ($km\ h^{-1}$)	RMS Accel. ($m\ s^{-2}$)	Stops per km. (km^{-1})	Idle Time (%)	Cruise Time (%)	Distance d_k (km)
1	2						
MP		30.0	0.89	1.60	20.6	13.8	11.9
OP		35.1	0.86	1.43	15.6	13.7	11.9
EP		30.6	0.87	1.60	18.4	12.5	11.9
2	5						
MP		36.4	0.80	1.39	17.9	27.5	14.5
OP		43.1	0.82	0.84	9.6	38.3	14.2
EP		38.8	0.85	0.95	17.9	30.3	16.8
3	9						
MP		40.6	0.78	0.79	11.4	30.8	17.7
OP		46.7	0.70	0.45	5.3	35.5	17.8
EP		45.3	0.71	0.56	8.2	38.5	17.7
4	13						
MP		37.6	0.77	1.08	14.3	30.6	19.4
OP		46.8	0.80	0.67	10.1	46.7	19.4
EP		41.1	0.76	0.82	18.3	33.7	19.4
5	19						
MP		52.9	0.69	0.33	3.4	59.4	18.4
OP		52.0	0.70	0.27	3.6	55.2	18.3
EP		50.0	0.78	0.30	4.6	54.9	19.8
6	11						
MP		42.4	0.74	0.72	13.3	36.7	19.4
OP		47.4	0.76	0.54	11.3	44.7	20.3
EP		45.2	0.76	0.64	14.4	49.5	20.3

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7	19.4
4	18.4
2	18.3
9	19.8
7	19.4
7	20.3
5	20.3

traffic events made up of (i) *intersection-related traffic events* which are the primary physical obstacles to free movement, and (ii) *vehicle-related traffic events* which are those restrictions to free movement caused by the number of vehicles on the road. In developing this conceptual model, Newman *et al.* (1992) defined these events directly in terms of the individual speed/time histories giving the results shown in Table 6.

Intersections are the dominant feature in the traffic system. These determine around 75% of the traffic events for most of the driving cycles. The exceptions are areas 5,6 in which intersections are responsible for 97% and 82% respectively. Area 5 has virtually negligible vehicle-based traffic events consistent with its outer suburban character, whereas area 6 has a relatively high proportion of uncontrolled intersections. In most areas the off-peak traffic events are fewer than the peak periods. There is a consistent decline in traffic events from central core to outer suburbs, which is mainly due to a decline in the number of intersections per km.

7 Specification of emission factors

Motor vehicles are the source of oxides of nitrogen (NO_x), brake lining dust, hydrocarbons (HC), carbon monoxide (CO), smoke, aldehydes, lead salts and particles, rubber, gaseous petrol and carbon particles (Lay (1984)). All of the CO and NO_x are emitted from the exhaust pipe whereas approximately 50% of the HCs from an uncontrolled vehicle are emitted via the exhaust, with the remainder coming from the crankcase, carburettor and fuel tank vents (SPCC (1980)).

Evaporative emissions result from the fuel system leaking HCs to the atmosphere at a rate determined by the temperature of the system (diurnal emissions) and hot soak emissions occurring after the vehicle has been driven some distance, through heating of the carburettor and fuel lines (Nelson (1981)). Hamilton *et al.* (1982) estimated evaporative emissions from typical early 1970s vehicles as 0.8 g km^{-1} and noted that these are generally constant throughout the life of the vehicle. Subsequent to 1975, Australian emission standards (Table 7) have resulted in improved pollution control, as evidenced by Nelson (1981). He confirmed diurnal evaporative emission factors of 22.1 g vehicle^{-1} day^{-1} for uncontrolled (pre 1975), and 5.1 g vehicle^{-1} day^{-1} for controlled vehicles, respectively; with hot soak emissions of 12.5 g vehicle^{-1} for uncontrolled, and 4.2 g vehicle^{-1} for controlled vehicles. Consequently, evaporative emissions are a function of the age of the fleet whereas exhaust emissions are also dependent on vehicle driving characteristics. Hence the spatial

Table 6: Traffic events for each representative driving cycle in each area and time period (after Newman *et al.* (1992)).

	Total traffic events per km	Intersection based traffic events per km	Vehicle based traffic events per km	Intersection based events as a proportion of total %
Area 1				
MP	2.77	2.27	0.50	82
OP	2.69	1.85	0.74	69
EP	2.61	2.10	0.51	80
Average	2.69	2.07	0.62	77
Area 2				
MP	2.21	1.52	0.69	69
OP	1.62	1.34	0.28	83
EP	2.14	1.55	0.59	72
Average	2.00	1.47	0.53	74
Area 3				
MP	1.92	1.47	0.45	77
OP	1.35	0.96	0.39	71
EP	1.41	0.96	0.45	68
Average	1.56	1.13	0.43	72
Area 6				
MP	1.34	0.98	0.36	73
OP	1.08	0.94	0.14	87
EP	1.23	1.08	0.15	88
Average	1.22	1.00	0.22	82
Area 4				
MP	1.70	1.29	0.41	76
OP	1.39	1.08	0.31	78
EP	1.44	1.08	0.36	75
Average	1.51	1.15	0.36	76
Area 5				
MP	0.92	0.92	0.00	100
OP	0.93	0.87	0.06	94
EP	1.11	1.06	0.05	95
Average	0.99	0.96	0.03	97

and temporal variation of emission source

Table 7: Australian emission standards, g km^{-1} (after SPCC (1980)).

	Date of manufacture	
	After 1 July 1976	After 1 January 1981
CO	24.2	18.6
HC	2.1	1.75
NO_x	1.9	1.9

Table 8: General emission factors (g km^{-1}) for heavy duty diesel powered vehicles (after [1] Stern (1976); [2] USEPA (1977)) and those used in this study assuming an average speed of 42.3 km h^{-1} (after [3] Luria *et al.* (1984)).

Pollutant	Emission Factor (g km^{-1})	
	(1,2)	(3)
Particulates	0.8	
CO	17.8	9.5
HC	2.9	1.5
NO_x	13.0	10.2
Aldehydes	0.2	
Organic acids	0.2	
SO_x	1.7	

strength is dependant on driving characteristics across the urban area as well as the age mix of the vehicle fleet.

Vehicle emissions in Sydney were estimated by Stewart *et al.* (1982) from the product of VKT, emissions per kilometre for each model year and travel fraction done by each model year. Although this gives a bulk estimate across the airshed it does not allow for the spatial resolution of the sources nor does it account for variations in driving conditions.

From a preliminary dynamometer test of 28 vehicles, Kent and Mudford (1979) found that typical emissions under Australian urban driving conditions, at that time, could be expressed as:

$$[CO] = 465s^{-0.97} \qquad (3)$$

$$[HC] = 21.5s^{-0.73} \tag{4}$$

$$[NO_x] = 2.2 + 0.008s \tag{5}$$

where $[CO]$ is the carbon monoxide emission (g km^{-1}),$[HC]$ hydrocarbon emission (g km^{-1}),$[NO_x]$ oxides of nitrogen emission (g km^{-1}) and s the average vehicle speed (km h^{-1}). These are of a similar form to the estimates used by Iverach *et al.* (1976), based on US experience, and equivalent to the values employed by Taylor and Anderson (1982).

Such an estimation assumes emissions can be represented in terms of average speed alone. It neglects the influence of variations in driving conditions, particularly changes in acceleration, on emissions. For example, Kent and Mudford (1979) found that a three-dimensional plot of emission rates against speed and acceleration led to parabolic surfaces for CO and HCs, while NO_x showed a general increase in emission rates with speed and acceleration. In particular, they found that both CO and NO_x show marked increases in emission rate with positive acceleration. This cannot be accounted for from an average speed model and highlights the need to incorporate a wide range of accelerations and speeds to produce reasonably representative emission inventories.

The spatial resolution of these emissions requires an integration of data concerning traffic flow characteristics with data on vehicle numbers, vehicle types and VKT. Previous work in this area has emphasised the latter data on vehicles and has lacked any detailed input about how those vehicles are being driven (SATS (1974); Visalli (1981)). A very basic approach to incorporate driving patterns has been attempted for Melbourne but uses only the standard Los Angeles driving cycle for its traffic characteristics (Neylon and Collins (1982)).

The driving patterns for Perth (Table 5) illustrate a graduation from the CBD with higher speeds, longer cruise periods and shorter stops as you move further out. Average speed increases with distance from the CBD and is around 5 km h^{-1} higher in off peak driving except in the outer suburbs where driving is consistently free flowing. Stops km^{-1} and root mean square acceleration are consistent with this and exhibit a general decreasing trend with distance from the CBD. Thus, driving characteristics are determined by location within the urban area and it is reasonable to expect that vehicle emissions will also be dependant on location.

The characteristic speed time traces for each region were converted into speed acceleration probability matrices, where each matrix cell, of size 5 km h^{-1} by 1 km h^{-1} s^{-1}, contains the total number of one-second observations in the respective range from the representative driving cycle. Thus each matrix element represents the total time during the representative driving cycle that the vehicle was at that speed and acceleration.

Post *et al.* (1985) extended the analysis of Kent and Mudford (1979) to 177 Australian light duty vehicles in use, and obtained fleet averaged emission rates as a function of vehicle velocity and acceleration. Their results are presented at the same resolution as the speed acceleration probability matrices. Since cell averaged emission rates are independent of the velocity profile followed by the vehicle (Post *et al.* (1981a); (1981b)), these can be used to estimate emissions for any driving pattern, assuming that the vehicles used by Post *et al.* (1985) are representative of the typical Australian urban fleet. Hence the total emissions over a representative driving cycle can be expressed as (Lyons *et al.* (1990b))

$$[P] = \sum_{i=1}^{i=n} \sum_{j=1}^{j=n} e_{i,j} t_{i,j} \tag{6}$$

where $[P]$ is the emission (g) of pollutant species P, $e_{i,j}$ is the emission rate (g s^{-1}) of pollutant species P for the matrix element defined by velocity i and acceleration j (Post *et al.* (1985)), $t_{i,j}$ total time (s) vehicle spent at that velocity and acceleration during the driving cycle, and the summation is over all possible speed acceleration cells. $[P]$ is the total emission over the period of the driving cycle. Hence the characteristic emission factor (g km^{-1}) for that driving cycle can be represented as

$$[P]_k = \frac{[P]}{d_k} \tag{7}$$

where d_k is the distance covered during the representative driving cycle (see Table 5).

Within Australia, exhaust emission rates for CO and NO_x for heavy duty diesel powered vehicles remain uncontrolled and no locally validated data was readily available. Emission rates based on US experience and assumed independent of vehicle speed are listed in Table 8 (Stern (1976); USEPA (1977)). These represent uncontrolled emissions averaged over a number of vehicles operating under a variety of conditions, and are consistent with the heavy duty emission rates used by Jakeman *et al.* (1984) for Australian conditions. Luria *et al.* (1984) obtained similar values for buses and expressed the emission factors for NO_x, HC and CO as a function of speed. They showed a marked decrease in CO and HC emissions with speed and an increase in NO_x emissions up to a speed of 40 km h^{-1}. In the absence of alternate emission factors these were used.

Trucks within the Perth metropolitan area are mostly able to maintain easy cruise conditions and appear to avoid built up areas and peak conditions (Lyons *et al.* (1987)). Unlike automobiles, their driving cycle shows no dependence on location or time period. Consequently, as the heavy duty diesel emission factors are only expressed as a function of speed, the average speed from the Perth truck driving cycle of 43.2 km h^{-1} (Lyons *et al.* (1987)) was assumed for all truck emissions, leading to the emission factors shown in Table 8.

The total emission in any period and any area of the city can be expressed as

$$E = \sum_{m=1}^{m=n} [P]_{k,m} VKT_{k,m} \tag{8}$$

where $[P]_{k,m}$ and $VKT_{k,m}$ are the emission factor and total VKT, respectively, for that time period and area and the summation is over vehicle type.

Combining the characteristic driving patterns (Newman *et al.* (1992)) and the fleet emissions (Post *et al.* (1985)) leads to the automobile emission factors shown in Table 9 for each of the representative areas. As these factors are based on the same fleet data, the differences are directly attributable to the style of driving in each of the areas. This emphasises the contribution of variations in speed and acceleration patterns across a metropolitan area in determining the spatial variation of emissions. Emission factors show the same decline as a function of distance from the CBD as traffic events. Since traffic events are directly related to the urban fabric this also illustrates the linkage between the physical structure of the city and motor vehicle emissions.

The corresponding automobile emission factors based solely on average speed in each of the regions (Table 5) are shown in Table 10. With the exception of the NO_x emission factors, the average speed factors are lower, as would be expected, since the incorporation of acceleration leads to greater variability in the driving patterns and hence higher emissions. The NO_x emissions are higher because the average speed equation implies a speed independent emission of 2.2 g km^{-1} (Kent and Mudford (1979)) compared to the idle emission of 0.039 g min^{-1} of Post *et al.* (1985). Their results also suggest that emissions of the order of 2.2 g km^{-1} are only observed under high acceleration which is not maintained for any length of time in representative urban driving cycles (Lyons *et*

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Table 9: Emission factors g km^{-1} for exhaust emissions for each time period and region based on the speed acceleration matrix (after Lyons *et al.* (1990b)).

Area	1	2	3	6	4	5
NO_x						
MP	1.9	1.8	1.8	1.7	1.9	1.7
OP	1.9	1.9	1.7	1.8	2.0	1.7
EP	1.8	1.8	1.8	1.9	1.9	1.8
CO						
MP	21.8	18.4	18.1	16.9	19.2	14.8
OP	19.2	17.4	15.7	15.9	16.8	15.2
EP	21.3	18.5	16.7	16.9	17.5	16.0
HC						
MP	2.2	1.9	1.9	1.8	2.0	1.8
OP	2.0	1.8	1.7	1.8	1.8	1.7
EP	2.2	1.9	1.8	1.9	1.8	1.7

Table 10: Emission factors (g km^{-1}) for exhaust emissions for each time period and region based on average vehicle speed (after Lyons *et al.* (1990b)).

Area	1	2	3	6	4	5
NO_x						
MP	2.4	2.5	2.5	2.5	2.5	2.6
OP	2.5	2.5	2.6	2.6	2.6	2.6
EP	2.4	2.5	2.6	2.6	2.5	2.6
CO						
MP	17.2	14.2	12.8	12.3	13.8	9.9
OP	14.7	12.1	11.2	11.0	11.2	10.1
EP	16.8	13.4	11.5	11.5	12.7	10.5
HC						
MP	1.8	1.6	1.4	1.4	1.5	1.2
OP	1.6	1.4	1.3	1.3	1.3	1.2
EP	1.8	1.5	1.3	1.3	1.4	1.2

al. (1986)).

Within Perth, areas 1 and 5 illustrate the greatest differences in activity intensity ranging from the congested CBD, with its greater reliance on public transport, to the private vehicle dominated outer suburbs. Emission factors, based on the speed/acceleration distribution, show a decrease in emission factors between the CBD and the outer suburbs for NO_x corresponding to decreased accelerations characterised by high average speeds and maintained cruise conditions. Alternatively, emission factors based solely on average speed illustrate an increase as you move away from the congested CBD. Thus, a simple average speed model suggests higher emissions away from the congested CBD by not accounting for the marked acceleration changes induced by the congested stop start driving of the CBD.

Although the rate of emission is a function of distance from the CBD, the total source emission is the product of these emission factors with the total VKT in each region. Thus, the Perth metropolitan region was divided into grid squares of 1 km by 1 km and estimated daily VKT for each of these was obtained from traffic count information collected by the Main Roads Department (MRD (1986)). Automatic traffic counts, of 1 - 3 days duration, are carried out on all major roads in the region, as well as points on these at which a change in volume might be expected. They are expressed as annual average weekday traffic flow and represent the 24 hour traffic volume passing through a site on a typical weekday (MRD (1986)).

These individual grid values were summed to provided an overall measure of the recorded total daily VKT for Perth. Any shortfall between this figure and the estimated total VKT, listed in Table 11, can be attributed to subarterial roads. This was allocated across the region on the basis of the recorded traffic volumes.

The total truck VKT, given in Table 11, was allocated to high truck usage routes in the metropolitan area (Lyons *et al.* (1987)) on the basis of the total grid VKT and subtracted from the individual grid totals. As the truck driving cycle is independent of peak periods, the truck VKT was divided by 24 to represent an average hourly truck VKT.

Twenty-four hour VKT weightings for Perth are 16.5% morning peak (0700 - 0900), 18.5% evening peak (1600 - 1800) and 65% for all off-peak times (Kenworthy *et al.* (1983)). Consequently, the daily VKT for each grid square was corrected by these factors and divided by the length of the period to provide an hourly estimate of non-truck VKT.

The truck and non-truck VKT were then multiplied by the appropriate emission factors (Tables 9, 8), to provide an estimate of the total

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Table 11: Estimated total VKT (Vehicle Kilometres Travelled) for Perth 1985. Note weekend VKT is estimated at 1.5 average weekday VKT (after ABS (1985)).

Vehicle Class	Total Annual VKT (10^9 km)	Equivalent average daily VKT (10^7 km)
Automobiles	6.996	2.064
Utilities/Panel vans	1.168	0.345
Total motor vehicles	8.164	2.409
Trucks	0.445	0.131
Motor cycles	0.138	0.041
Total	8.747	2.581

Table 12: Variation of CO/NO_x ratio across the Perth airshed resulting from temporal and spatial variations in driving patterns, where MP is morning peak, EP evening peak and OP off peak (after Lyons *et al.* (1990b)).

Region	CO/NO_x Ratio		
	MP (0700-0900)	EP (1600-1800)	OP
1. Central Core	9.44	9.84	6.65
2. Inner suburbs	8.84	9.01	6.72
3. Middle western suburbs	9.06	8.45	7.17
4. Middle south, outer north and eastern suburbs	8.88	8.12	6.38
5. Outer south east and north east suburbs	8.07	8.34	7.47
6. Northern state housing suburbs	8.43	8.05	6.26

vehicle exhaust emission across the metropolitan area. Additional evaporative emissions are accounted for from the distribution of registered vehicles and added to the total for HC. Such calculations yield the spatial variation of emissions (Lyons *et al.* (1990b)).

These emission totals are not directly verifiable as they are based on average traffic conditions across the metropolitan area, which are not necessarily observed on any one day. However, they do indicate the spatial variation in source strength and provide an indication of the relative magnitude of pollutant sources in different regions which is essential for appropriate air quality modelling. An alternative statistic can be obtained from Table 9 by computing the predicted CO/NO_x ratio on the basis of both time period and location (Table 12).

The greater congestion and higher accelerations as you approach the CBD leads to an increase in the CO/NO_x ratio of pollutants emitted from the exhaust pipe. As both smog-chamber and computed results suggest that added CO accelerates the depletion of NO and the generation of NO_2 as well as enhanced generation of O_3 through NO_2 photolysis (Demerjian *et al.* (1974); Drake *et al.* (1979)), the change in driving patterns brought about by increased congestion enhances smog formation, through increased CO generation per kilometre of travel. Given the increased concentration of vehicles using the CBD this becomes significant. If evaporative emissions are also included, the greater number of vehicles in the CBD would lead to a corresponding increase in HC emissions (Lyons *et al.* (1990a)).

8 Conclusions

Since driving patterns are an integral part of the urban fabric, they cannot be sampled in isolation from an holistic concept of the city. Thus the city transport infrastructure is defined in terms of social/economic, land-use and transportation factors to define homogeneous areas within the Perth metropolitan region. Clustering techniques combined with factor analysis illustrate that homogeneous areas can be defined directly in terms of their activity intensity, modal split and social/economic status. This illustrates that the more urban an area becomes the greater its reliance on public transport whereas, conversely, the more suburban, the greater the reliance on private vehicle usage.

The analysis of actual speed-time traces of representative driving in different areas and time periods, illustrates how traffic conditions change in a relatively ordered way from central to outer areas. These changes are based primarily on a decrease in intersection-based traffic events from central to outer areas, and secondarily on a general decrease in the number of vehicle-based traffic events. These results also illustate a number of important traffic parameters vary systematically with distance from the CBD.

This pattern of traffic events has a broader land-use base. In the central areas of comparatively high congestion, land-use intensity is also high; in the outer areas the reverse is true. There is greater walking, bicycling and public transport in central areas and higher car dependence in outer areas. The progressively freer flowing driving patterns from central to outer areas, are thus associated directly with a variety of wider land-use and transport features, which also vary systematically according to centrality.

The motor vehicle emission inventory integrates data on traffic conditions with emission factors that incorporate the effects of both speed and acceleration. This highlights the impact of varying driving conditions on the spatial and temporal resolution of vehicle emissions, and illustrates that traffic congestion enhances pollutant production through increased variations in vehicle accelerations.

In particular, the greater congestion and corresponding variations in acceleration within the CBD, increases the production of pollutants and the potential for photochemical smog through enhanced CO production. As the central core facilitates air quality emission stress through its greater congestion, this suggests that urban planning can influence air pollution through planning for reduced congestion and more free flowing traffic. Such a conclusion assumes a linear relationship between traffic flow and emissions which Lyons *et al.* (1990a) and Newman *et al.* (1992) dispute in arguing that the extra road building required to reduce congestion would only further extend urban sprawl and create greater vehicle usage. It is a prescription for increasing total emissions whereas increased intensity of urban activity can be used to reduce automobile dependence leading not necessarily to a reduction in congestion but a reduction in overall emissions (Newman *et al.* (1988); (1992); Kenworthy *et al.* (1989)).

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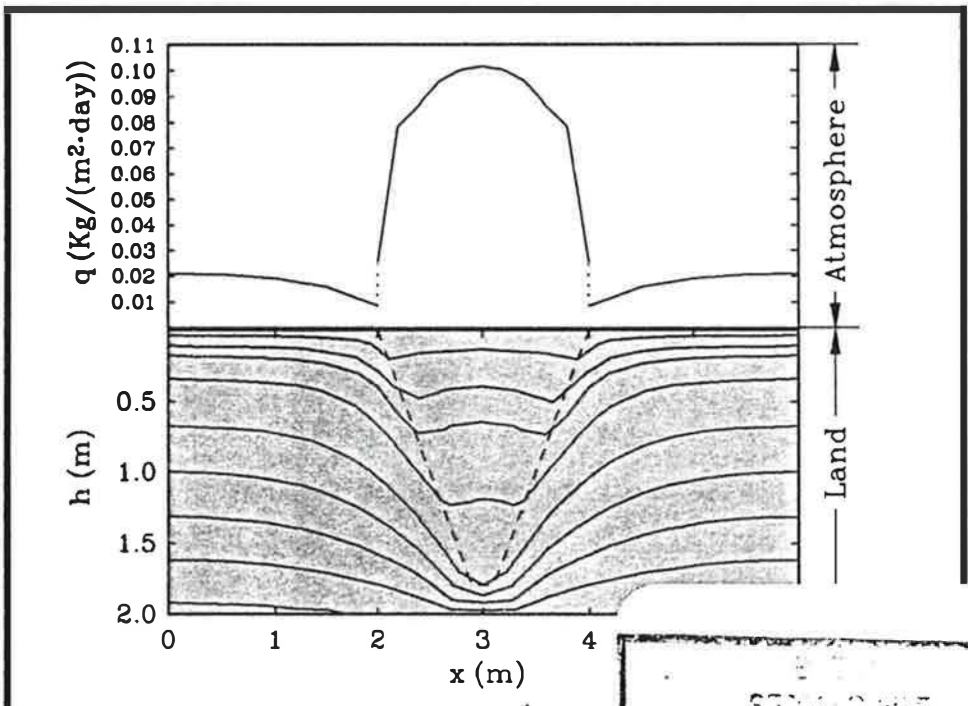

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