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Statistical and spatial modelling of vehicle-kilometres of travel by car for the journey-to-work in Sydney, 1981 to 1996: implications for sustainable transport targets

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Abstract

In low density, car-dependent cities such as Sydney there have been two drivers of increased VKT: increasing use of the car for the journey-to-work; and increasing spatial separation of homes and workplaces. Descriptive analyses of data from the Census of Population and Housing, Journey-to-Work Tabulations by local government area (LGA), show how person-kilometres of travel by outer suburban residents (greater than 20km for the Sydney CBD) has mushroomed from 1961 to 1996, and how VKT by car has also exploded in the same suburbs (from 1981 when modal data were first reported).

The paper describes a modelling framework that allows future VKT by car for the journey to work from LGAs in Sydney to be estimated as a function of future urban form and socio-economic characteristics at the LGA level. Cross sectional and inter-census change statistical models of LGA travel behaviour and urban form (such as, accessibility to employment, density) are fitted. Spatial modelling (the intervening opportunity model) represents the third approach and the LGA preference function (for longer or shorter job destinations) is evaluated across LGAs and through time. A statistical model relates the slope of the preference function (and hence the LGA trip length frequency distribution) to urban form. Nine different scenarios of urban form have been formulated for the year 2011 to test a range of assumptions - existing trends and centralisation / decentralisation of homes and workplaces – and the practical application of the models are demonstrated to evaluate progress towards sustainable transport targets.

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Introduction

Car dependence is a fundamental problem in the sustainability of those cities with low-density suburban sprawl. Many cities are experiencing significant increases in vehicle kilometres of travel (VKT) - for example, in Sydney total VKT increased by 23.5 percent from 1991 to 1997. Environmental implications of growth in VKT – such as deteriorating air quality - are alarming because predicted growth is likely to outstrip measures to improve the energy efficiency and environmental performances of vehicles (NSW Department of Transport, 1999). Transport planners agree that sustainable transport indicators are needed to track progress in meeting targets (May, *et al*, 2001), and one appropriate indicator is VKT by car (Miller and Ibrahim, 1998).

Mathematical models are useful to determine the future VKT implications of land-use and transport policies, and any progress towards meeting targets. The report by the Ecologically Sustainable Development Transport Working Group of the Commonwealth Government advocated change to the transport sector to achieve sustainability, but when the 40 recommendations for urban transport are classified by the systems planning framework (Black, 1996), it is apparent they aim primarily to alter the value system, by specifying new goals and objectives, or prescribe policy solutions, such as higher density cities. Noticeably absent from the set of recommendations are appropriate "sustainability" indicators, and analytical tools suitable to examine urban sustainability issues. The Institution of Engineers Australia, New South Wales Transport Panel (see,http://www.civeng.unsw.edu.au/ieausttp/ Seminar2001/ Program.htm) convened a seminar that confirmed little progress had been made in Australia on analytical tools and performance indicators for sustainable transport (Black, Paez, and Suthanaya, 2001).

This paper proposes vehicle kilometres of travel (VKT) for the journey to work by car as one performance indicator of sustainable urban travel. For strategic metropolitan transport planning, the aggregate (local government area) models reported in this paper are sufficiently robust to examine urban form changes and their implications for journey-to-work VKT by car. (In 1999, commuting in Sydney accounted for 18 per cent of all trip purposes but about one third of journeys by distance.) Our aim is to develop analytical tools linking aggregate travel behaviour and explanatory variables for urban form and demographic/socio-economic factors as a basis to estimate the strategic travel implications of alternative urban development scenarios.

Results of journey-to-work VKT analysis from 1961 to 1996, and the more disaggregate modelling results of VKT by car from 1981 to 1996, are presented for the Sydney metropolitan region. Four approaches are used to estimate VKT – extrapolation; statistical cross-sectional models; statistical models representing inter-census change; and models based on commuting preference functions derived from the intervening opportunities model (Stouffer, 1940). Hypothetical land-use development scenarios for Sydney in 2011 are formulated, and the models are applied to estimate VKT by car in Sydney in

2011, to demonstrate the general feasibility of applying our modelling framework for policy analysis of future urban form and its travel consequences.

Study Area, Data and Variables

The study area is the Sydney Statistical Division defined by the Australian Bureau of Census, comprising 40 local government areas (LGA) in the County of Cumberland plus the four adjacent areas to Wollondilly, the Blue Mountains, Gosford and Wyong. Earlier Census of Population and Housing had divided the same study area into 38 LGAs. Figure A1 shows a diagrammatic map of Sydney region and Table A1 groups the 44 LGAs into three regional rings inner, middle and outer - consistent with those used in the Department of Urban Affairs and Planning studies (NSW Department of Urban Affairs and Planning, 1995). Results obtained for each LGA for vehicle (and personal) kilometres of travel for the journey to work are presented with reference to these three rings.

Primary data sources are the 1961, 1966, 1971, 1976, 1981, 1991, and 1996 Journey-to-Work data for Sydney Metropolitan Area. The Australian Bureau of Statistics (ABS) conducts the Census and the data are aggregated from census tracts for the Statistical Local Area (SLA) levels and cover 44 Local Government Areas. This research draws on tabulations provided by the NSW Department of Transport, Transport Data Centre (TDC) and any minor discrepancies between ABS and TDC data are a result of this process. Microsoft Access was used to compile relevant cross-tabulations and summaries from these data. Tabulations were then converted to Microsoft Excel spreadsheets to allow presentation and modification of format.

There are two distinct data sets aggregated at the LGA level. The first is for the longer period – 1961 to 1996 – but is only journey-to-work behaviour for all modes of travel. The second data for 1981, 1991, and 1996 set allows journey-to-work travel to be stratified by transport mode (although our macro analysis considers only the main modes of drive by car, bus and train). Journey-to-work travel by LGA is the dependent variable – specifically defined in various ways: person (or vehicle) kilometres of travel, trip lengths (by transport mode) and mode share. Table A2 lists the urban form, socio-economic and demographic variables that have been identified as possible explanatory variables of travel behaviour.

Trends in Person Kilometres of Journey-to-Work Travel

The total load on a multi-modal transport system is the amount of travel, measured in person kilometres. We are interested in the total load for journey-to-work travel, especially that made by car. The total amount of travel for an LGA is the summation for each LGA in the study area of the total amount of travel generated by that LGA, for destinations both within that LGA and to all other LGAs in the study area. Similarly, vehicle kilometres of travel (VKT) by car for an LGA is obtained by considering all journeys to work by car produced by residents of that LGA multiplied by the road distances these journeys take. These definitions of the amount of travel by an LGA should not be confused, for example, with the VKT taking place within that LGA – a figure that might include traffic from other destinations and traffic passing through an LGA.

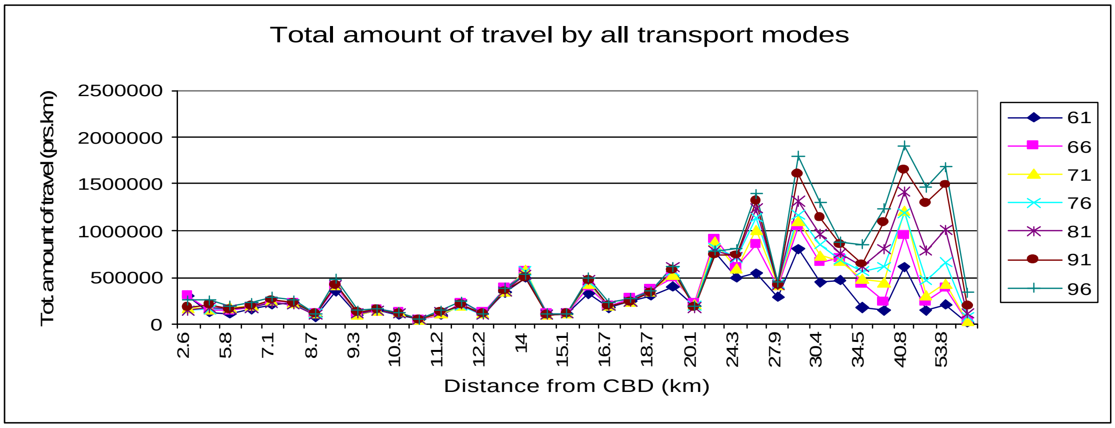
Previous research (Black, 1979; Black and Katakos, 1987) allows the following plausible observations to be made about cities such as Sydney aggregate journey-to-work travel:

(a) The person kilometres of travel by LGA is a function of the number of residential workers (commuters) and the distances they travel;
(b) For a centralised pattern of employment (Sydney at the 1951 Census of Population and Housing, for example) trip lengths increase the further away the LGA is located from the CBD;
(c) As population and jobs increase over time so too does the total amount of travel because, historically, there has been no evidence of declining overall mean trip lengths;
(d) The post-war period has seen a massive addition of population and resident workers in the outer ring of suburbs and a suburbanisation of jobs;
(e) We might anticipate the following results from 1961 to 1996: a stable pattern of travel for the inner ring with declining residential populations but longer average journeys to work as jobs move outwards, relatively stable development patterns in the middle ring (more jobs), substantially more travel in the outer ring.

Figure 1 shows the total amount of travel (person kilometres) by all transport modes for 38 LGAs in Sydney over 35-year period from 1961 to 1996 and confirms intuition. In 1961, the total amount of travel for LGAs located in the inner and middle ring was not much different than that in the outer ring (where the numbers were relatively small but the distances travelled great)). However, a dramatic increase in person kilometres of travel over time has been experienced by those LGAs located in the outer ring, beyond 20 km from the CBD. The superimposition of all seven Census results confirms that person kilometres of travel for the journey to work have remained relatively stable in the inner and middle rings, but exploded in the outer suburbs, suggesting a consumer preference for low density outer urban living fuelled by land availability a cheaper land costs.

Based on the1996 census, the total amount of journey-to-work travel in the inner ring averaged 221,249 person kilometres generated by each LGA. This average had increased from 170,160 person kilometres in 1961 to 188,528 person kilometres in 1966 and then decreased consistently to 174,201 person kilometres in 1981 followed by an increasing trend that reached 221,249 person kilometres in 1996. The LGA average amount of travel has increased by about 1,460 person kilometres per year between 1961 and 1996. In the middle ring, the total amount of travel has been relatively stable over time with a slight increase from 1961 to1966 and again from 1991 to 1996. The average amount of travel by middle LGA has increased from 288,376 person kilometres in 1961 to 351,871 person kilometres in 1996 with a rate of increase similar to the inner ring of about 1,810 person kilometres per year.

Figure 1 Total Amount of LGA Journey from Home to Work Travel by All Transport Modes, Sydney (1961-1996)



The total amount of journey-to-work travel has increased dramatically over time in the outer ring: from a LGA average of 350,976 person kilometres in 1961 to 1,209,975 person kilometres in 1996 - an annual increase at about 24,540 person kilometres per LGA per year). This annual increment in travel load is thirteen and a half times higher than that recorded for the middle ring and nearly eighteen times recorded for the inner ring.

Person Kilometres of JTW Travel by Transport Mode 1996

In the post-war period in Sydney incomes and car ownership has risen to the extent that private transport is the dominant mode of getting to work. This is especially true of outer suburban commuters. Table 1 shows the total amount of journey-to-work travel by main transport modes (car, bus and train) in Sydney at the 1996 Census. As the proportion of workers using the car is higher than other transport modes and the distance travelled is relatively long, the total amount of travel by car is much higher than that of train and bus. As we would expect, the total amount of travel by car in the outer ring of LGAs is considerably higher than that for the inner and middle rings - about three times higher than that of the middle ring and six times higher than that of the inner ring. Sutherland generates the highest amount of VKT by car of all of the outer suburban LGAs and Bankstown generates the highest amount of VKT by car of all of the middle ring of LGAs.

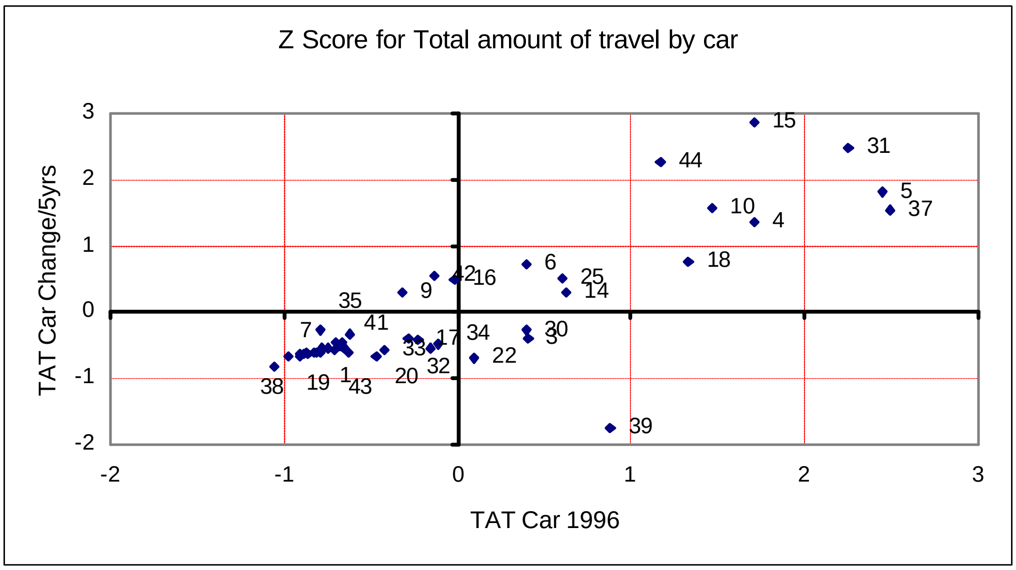
Whilst intuitively we know that the problems of car dependency are greater in low density sprawling suburbs it is helpful in public policy formulation to identify not only those local government areas generating the greatest journey-to-work VKT by car but also those with the greatest growth rates in VKT. Similarly, it is equally helpful to identify, and then explain, why some LGAs have total amounts of travel by car below the mean and with relatively

Table 1 LGA Person Kilometres of Travel from Home to Work by Main Transport Modes by Ring, Sydney, 1996

Ring	Mode	LGA Minimum		LGA Maximum		LGA Mean and Change	
		Location	Min Value	Location	Max Value	Average (1996)	Change per 5 years
Inner	Car	Sydney	12 254	Randwick	241 110	103 639	9 318
	Bus	Sydney	3 375	Randwick	92 987	26 233	-1 584
	Train	Mosman	5 258	Marrickville	76 356	30 843	2 716
Middle	Car	Hunters Hill	34 390	Bankstown	449 259	193 876	7 313
	Bus	Auburn	1 154	Ryde	55 780	13 161	-944
	Train	Hunters Hill	1 036	Parramatta	180 795	76 259	-1 696
Outer	Car	Camden	231 703	Sutherland	1 073 159	633 325	82 652
	Bus	Camden	1 544	Warringah	130 611	19 466	-35
	Train	Warringah	31 565	Gosford	552 167	222 125	16 660

low growth rates. One way of doing this is to calculate the Z-score for each LGA and a produce a scatter-plot of the results. The horizontal axis of Figure 2 is the total amount of journey-to-work travel of travel (VKT) by car by each LGA in 1996 whilst the vertical axis represents the average change in the total amount of journey-to-work travel (VKT) by car per 5-year interval by each LGA. The total amount of VKT by car is found to be positively linearly associated with the average change in VKT per 5 years. This indicates that the LGAs with a high VKT by car in 1996 also tend to have high increases in their VKT by car over time.

Figure 2 Scatter-plot of Z-score for Total Amount of VKT and 5-Year Change in VKT by Car in Sydney, 1996



Observations on the horizontal axis of Figure 2 indicate that Sutherland (37), Blacktown (5) and Penrith (31) have values over two positive standard deviations higher than the mean VKT by car. Observations on the vertical axis indicate that Gosford (15), Penrith (31) and Wyong (44) experience a relatively high increase in the change in the total amount of VKT travel by car of more than two positive standard deviations from the mean for all LGAs. Note the outlier of Warringah, zone 39, which shows the necessity of further research at the sub-regional level to determine the explanations for this unusually low growth figure.

Modelling Future VKT by Car at the LGA Level

Modelling Aims

The common practical method to estimate the future amount of urban travel (including VKT by car for the journey to work) is the application of the four-step transport-planning model with exogenous inputs for future land use at the spatial resolution of traffic zones. One problem with this approach is the fundamental difficulty of estimating accurately the future values of the land-use input variables for the very fine spatial resolution of the traffic zone. Another problem is that the mean trip length estimated by the gravity model (and hence VKT) is insensitive to radically different distributions of land-use activity (homes and workplaces) – a weakness long recognised (Black and Katakos, 1981).

We provide a modelling framework that is aimed at the strategic forecasting and assessment of metropolitan-wide VKT by car whilst at the same time producing LGA estimates based on readily available projections of urban form, socio-economic trends and demography at the LGA level (Suthanaya, 2002). The specific purposes of the models developed are to provide plausible future estimates of VKT by car that are sensitive to changes in urban form, demographic and socio-economic factors. For this reason we have developed models where aggregate travel behaviour is a direct function of urban form (distributions of activity and density of activity) and where the necessary input data to these models is deliberately restricted to the LGA level of aggregation for ease of forecasting future values for 44 areas rather than for the multitude of zones in, say, the Sydney strategic model.

Hypothesis Testing

The literature on urban form and travel has informed us on the most likely variables to consider, and their working definitions (Suthanaya and Black, 2001). Evidence suggests that urban form is a significant factor in car dependence and VKT by car (Newman and Kenworthy, 1999). Many cross-sectional analyses at the macro (census tract) and micro (neighbourhood, household or individual) level have been conducted, but the influence of density is mixed. Brunton and Brindle (1999) found that, in Melbourne, density variables (population and activity density) are not a suitable predictor for average car distance travelled when other urban form variables (such as accessibility to activities, socio-economic factors or a welfare index) are included. Miller and

Ibrahim (1998) argued that population density was an insignificant predictor for VKT in Toronto when other urban form variables (such as zone distances from the CBD) are considered.

Initially, urban form and travel behaviour trends were analysed descriptively at the LGA level using seven census data sets over 35-years from 1961 to 1996. Graphical plots were used to show the trends visually, at the metropolitan, the ring and the local government area level (Suthanaya and Black, 2001). This careful application of descriptive statistics has provided the springboard for later hypothesis testing and developing a suite of statistical models. These techniques are described fully in Black, Paez and Suthanaya (2002). They include: descriptive statistics – exploratory and graphical methods; correlation analysis; spatial mapping; spatial statistics, especially to identify geographical patterns and to identify outliers in the data; univariate and multivariate analyses; and travel preference functions based on Stouffer's intervening opportunity model.

Two statistical models are used to estimate future VKT by car for the journey to work in each LGA in the Sydney region. Both cross-sectional (1996 Census data) and change over time (1981, 1991 and 1996) between urban form and VKT by car have been investigated at the LGA level of spatial resolution using multiple regression analysis (stepwise approach) that includes socio-economic and demographic factors. The working hypothesis is that the aggregate amount of VKT travel by car in an LGA is explained by urban form and socio-economic variables. The screening procedure of the stepwise regression in the SPSS-software package was used to identify the best set of the explanatory variables. As different explanatory variables entered in the model for different census years it was also hypothesised that the amount of change in LGA VKT travel was a function of the change in urban form and socio-economic variables. Analysis of variance was applied to compare the travel behaviour among inner, middle and outer area residents. The input variables to the models are future urban form and socio-economic factors.

Cross-sectional Analysis

The main conclusions from cross-sectional analyses of journey-to-work census data are summarised as follows:

(a) No consistent model with the same explanatory variables could be found for the total amount of travel by car over time.
(b) Urban form variables were more important predictors for the total amount of travel by car than the demographic or socio-economic characteristics of the residents.
(c) The total number of workers (or the proportion of metropolitan workers) living in a LGA was consistently found to be the main determinant of the total amount of travel by private car.
(d) Other key urban form variables that consistently entered the model were: accessibility to jobs; the ratio of residential workers to jobs; and the proportion of residential workers employed locally. These variables

entered the regression model consistently over time. Therefore, these urban form variables might be selected for estimation purpose.

(e) Non-urban form variables that entered the regression model - the proportion of low-income workers; the proportion of labourers; and proportion of workers aged between 30 to 49 years – but only in some census years.

In the light of the above findings, caution should be exercised when applying a cross-sectional regression model for estimation purposes. For our purposes of estimating LGA journey-to-work travel under different land use scenarios, the model fitted to 1996 census data has been selected for estimation purposes. The constant and all explanatory variables are statistically significant. No collinearity is identified as indicated by the tolerance value (>0.1) and variance inflation factors (VIF<10) obtained. The model is as follows:

$$Y = 4\,770\,475 + 11.9\,X_1 - 376\,244\,\mathrm{Ln}(X_2) - 112\,048\,\mathrm{Ln}(X_3) - 193\,868\,\mathrm{Ln}(X_4) \quad (r^2=0.95)$$

Where,

Y = estimate of total amount of LGA journey-to-work travel (VKT) by car;
X_1 = total number of residential workers in a LGA;
X_2 = LGA accessibility to jobs (Hansen index using road distance as the denominator);
X_3 = ratio of residential workers to jobs in a LGA; and
X_4 = proportion of residential workers in a LGA employed locally.

The Hansen index for the accessibility of an origin LGA zone is obtained by summing the quotient of the number of jobs located in each LGA in turn divided by the road distances from the origin zone to those destination zones (the number of jobs in the origin zone divided by an average intra-zonal distance is included in these calculations).

Analysis of Inter-Census Change

Although analysis of inter-census change involves a reduction in the number of models that could be specified to predict change requires information from two census periods, we speculated that dependent and independent variables defined as a five-year change might provide a more stable forecasting model. The average changes in urban form and socio-economic variables per 5 years from 1981 to 1996 in Sydney were used as independent variables. The dependent variable was specified as the average change in the total amount of travel by private car (VKT) per 5 years during the same period of time. The hypothesis is that change in the amount of VKT by car by each LGA is a function of change in urban form and change in socio-economic factors. Urban form variables are better predictors travel patterns than socio-economic and demographic factors, and only the proportion of household with zero-cars entered the model. The model is:

$$Y = 63\,769 + 10.3\,X_1 - 12.5\,X_2 - 37\,140\,X_3 - 3\,845\,X_4 \qquad (r^2=0.94)$$

Where,

- Y = average change in the total amount of travel by car of a LGA per 5 years;
- X_1 = average change in the total number of residential workers in a LGA per 5 years;
- X_2 = average change in the accessibility to jobs (Hansen index using road distance as the denominator) of a LGA per 5 years;
- X_3 = average change in mean distance to jobs from a LGA per 5 years; and
- X_4 = average change in the proportion of households with no car in a LGA per 5 years.

Intervening Opportunities Model Based on Preference Functions

Mindful of the treacherous nature of regression models when applied to long-term forecasts we have formulated a very different approach structured within the framework of spatial interaction models, but one that remains sensitive to urban form changes. Its novelty is that overcomes the weakness of the gravity model with a fixed calibration parameter that demonstrably is inaccurate in estimating future mean trip lengths (Masuya, Shitamura, Saito and Black, 2002). Unlike the conventional intervening opportunity model, with its calibration against all inter-zonal trips (Ruiter, 1967) we have fitted mathematical functions to each zonal (LGA) origin – destination trip pattern. These LGA “preference functions” for longer or for shorter destinations (analogous to the l-factor in the intervening opportunity model) are used to investigate the spatial (across LGAs) and temporal (inter-census) commuting behaviour when the spatial distribution of job opportunities are normalised as the percentage of metropolitan jobs at increasing distance from each origin LGA.

A preference function is thus an aggregate of the individual travel behavioural responses for an LGA, given a particular opportunity surface distribution of jobs surrounding those commuters in that LGA across the whole of the study area. Empirically, non-linear shaped preference functions are obtained for the proportion of trips from an LGA stopping plotted against the proportion of total metropolitan jobs reached by increasing distance by road from that LGA. Mathematical transformations are used to produce linearity and the gradient of the slope of the preference function gives information on whether the LGA exhibits an aggregate “maximising” travel or “minimising” travel behaviour (Black, Cheng, Ton and Masuya, 1993). Steep slopes imply a propensity to take up the nearer opportunities; shallow gradients imply nearer opportunities are by-passed and there is a propensity to travel longer distances. Similar gradients across all LGA would imply a common travel behavioural response to the normalised opportunity surface.

Our research using journey-to-work data sets from 1981 to 1996 in Sydney has found that variation in urban form across LGAs is associated with variation in the slope of the commuting preference function by car. In this analysis, we have stratified the LGA by LGA journey-to-work trip matrix by mode (car travellers) and estimated the (negative) slope of the transformed function. For 1981, the minimum slope was - 0.274 and the maximum – 0.033 (mean = - 0.195); for 1996, the mean had increased to – 0.208, with a range from – 0.303 to – 0.076.

Variations in the slopes of the LGA commuting preference functions by car were found to be associated with the variation in the LGA mean trip length by car.

The slope of the preference function is explained by urban form variables in a regression model. Urban form variables better predict commuting preference functions by car than do socio-economic factors. The average job distance was found to be the most important predictor for the absolute slope of commuting preferences by car based on multiple regression analysis that was repeated for data from three census years - 1981, 1991 and 1996. Although the average job distance variable entered into the model for these three census years no consistent set of explanatory variables could be identified, as was the case with the multivariate statistical analyses. Therefore, the 1991 model was selected because it had the strongest explanatory power amongst the three data sets with the model explaining 93 percent of variation in the commuting preferences by car:

$$Y = 0.297 – 0.0026 X_1 + 0.021 X_2 – 0.003 X_3 + 0.0017 X_4 – 0.000002 X_5$$

Where,

Y = slope commuting preferences by car;
X_1 = average job distance (kilometres);
X_2 = proportion of metropolitan jobs in the LGA;
X_3 = proportion of residential workers employed locally;
X_4 = LGA distance in kilometres from the CBD; and
X_5 = job density (gross).

Future values for these explanatory variables (see below) allow future estimates of the LGA preference function to be made. For any future land-use scenario the total amount of travel by car (VKT) for an LGA can be estimated from the predicted LGA mean trip length by multiplying the mean trip length by car of a LGA by the total number of residential workers living in that LGA.

Development of Scenarios

No attempt has been made to adopt government estimates of future geographical patterns of homes and workplaces. The authors developed three extreme scenarios for the distribution of jobs by LGA in the Sydney study area in the year 2011: existing trends; centralisation; and decentralisation. For each scenario, the distribution of residential workers for each LGA followed existing trends, was centralised or was decentralised, as shown summarised by ring (Table A3). Hypothetical distributions have been defined to bring out the differences between urban consolidation and suburban sprawl. These future land-use values provided input data to calculate the future explanatory variables required by the three models described above.

Estimation of Journey-to-Work VKT by Car, 2011

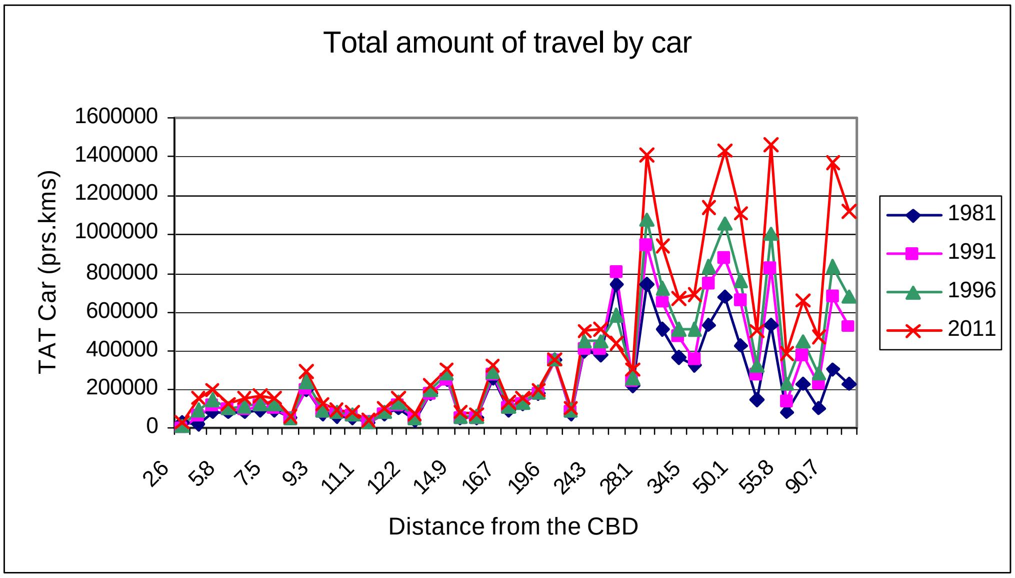
The daily total amount of journey from home to work VKT by car for all of the 44 LGAs in 1981 (the first year that transport mode questions were asked at the Census) was 9.7 million. It increased by a half to 14.4 million VKT in 1996 and it is predicted to reach 19 million VKT in 2011. By 2011 this VKT extrapolation will be about 96 percent higher than its 1981 value, or 33 per cent higher than the 1996 value (Table 2).

Table 2 Daily VKT by Car in the Journey from Home to Work, Sydney Metropolitan Area, 1981 to 1996 and Extrapolated Value to 2011

Census Year	Vehicle Kilometres of Travel by Car	Index (1981 = 100)
1981	9 728 796	100
1991	12 564 640	129
(1996)	14 388 616	148
2011	19 085 836	196

When this extrapolation is disaggregated at the LGA level (Figure 4) a dramatic increase in VKT for 2011 is seen for the outer ring of LGAs beyond 20 km from the CBD. On the assumption of trend extrapolation, the average total amount of VKT travel by car for the inner ring of LGAs will increase by 29 percent from its 1996 value. The average total amount of VKT travel by car in the middle and outer rings will increase by 11 and 40 percent, respectively, from their 1996 values.

Figure 4 Total Amount of LGA Journey-to-Work VKT Travel by Car in Sydney, 1981 – 1996, and Trend Extrapolation by LGA to 2011



As the total amount of VKT travel by car in the outer suburbs of the study area is expected to increase dramatically if trends continue we now concentrate on those 16 LGAs in the outer ring of Sydney (see Table A1).

By applying the three models described above with input data from radically different land-use scenarios for 2011 (Table A3) we assess the contribution to VKT that different patterns of urban form might make. The results from the three models are summarised in Table 3 by the 9 land-use scenarios (column 1).

Because of the inherent uncertainty in the forecasting accuracy of each method, an average of the three are taken (column 5), and this is expressed as the total VKT estimated for the outer LGAs in 2011 (column 6) and the increase from 1996 represented as a base of 100.

Table 3 VKT by Car for the Outer Ring LGAs in Sydney Based on Three Different Prediction Models by 2011 Land-use Scenario (see Table A4)

Scenario Table A4	Urban form 1 (cross section)	Urban form 2 (longitudinal)	Slope Preference	Mean of the Three (VKT-car/LGA)	Total for Outer ring	Index 1996 =100
S1a	746 123	890 482	1 483 256	1 039 954	16 639 259	164
S1b	401 173	591 330	803 168	598 557	9 576 912	95
S1c	1 027 027	1 134 093	1 993 901	1 385 007	22 160 112	219
S2a	683 660	945 637	1 234 704	954 667	15 274 672	151
S2b	409 308	646 484	670 933	575 575	9 209 200	91
S2c	628 350	1 189 247	1 650 662	1 156 086	18 497 381	183
S3a	674 023	812 909	1 819 077	1 102 003	17 632 048	174
S3b	515 980	513 757	981 834	670 524	10 728 379	106
S3c	1 035 067	1 056 519	2 457 654	1 516 413	24 262 613	239

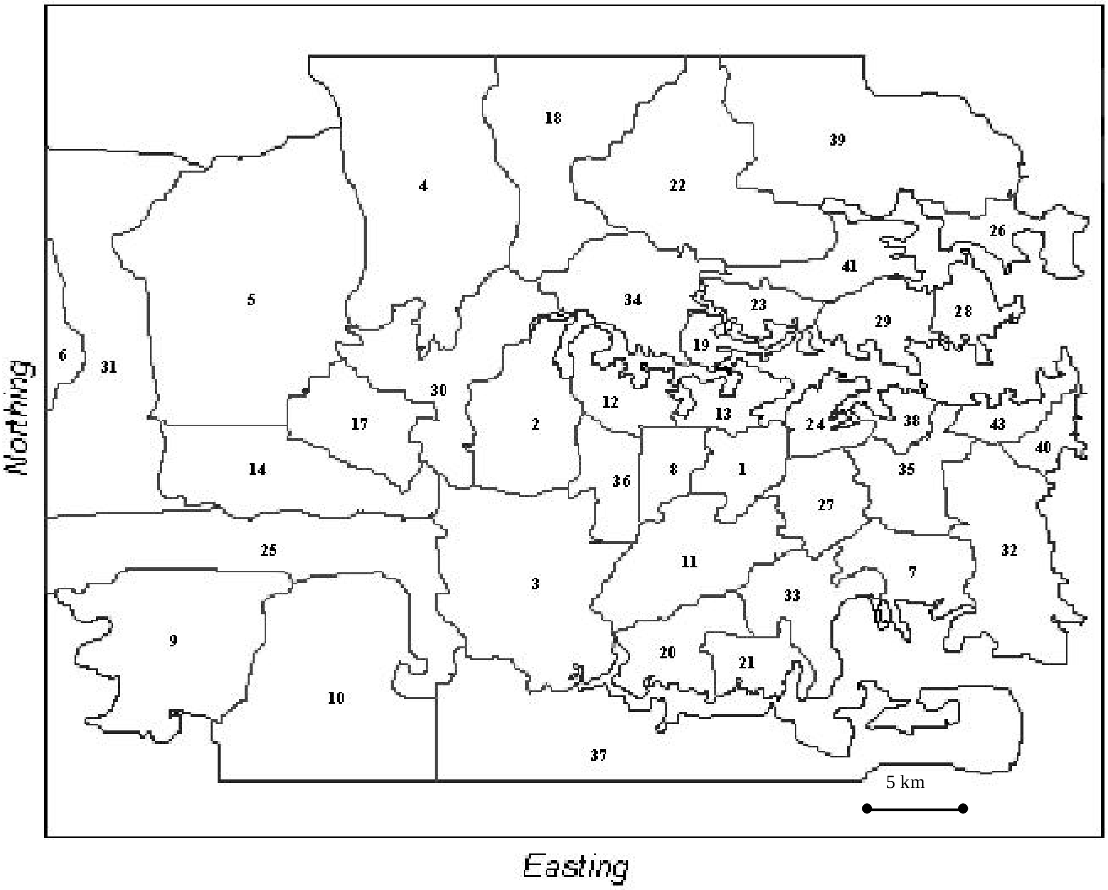
Irrespective of the future distribution of jobs in 2011, centralisation of residential workers (Scenarios S1b and S2b) - such that 70 per cent of the homes of workers are located in the middle and inner rings of Sydney - is expected to slightly reduce VKT of journey-to-work travel total amount of travel by car, or in the case of Scenario S3b, increase it slightly by 6 percent. These totally impractical land-use scenarios (consumer resistance to high density and urban consolidation, the impossibility of reversing development trends in fifteen years, lack of suitable sites for redevelopment, and so on) only highlight the futility of the government pretending that the equivalent VKT target currently set of a 15 per cent increase (for all journey purposes) over the 1996 base by 2011 in *Action for Transport 2010* is achievable.

Conclusions

The growth in person kilometres of travel in outer suburbs is a problem of concern in making cities more sustainable. A new modelling framework to address these kinds of policy questions has been described. Three models of the relationship between LGA journey-to-work travel by car and urban form and socio-economic variables by using successive census data from 1981 to 1996 have been formulated. These have been compared and contrasted with trend extrapolation from 1981 to 1996, and then to 2011 based on hypothetical distributions of homes and workplaces (scenarios), that demonstrates their applicability in sustainable urban transport analysis. For the whole of the metropolitan area, extrapolation suggests an increase of VKT of 33 per cent above the 1996 level; the worst-case land-use development scenario suggests a doubling of VKT. The models are sufficiently robust to allow strategic land-use policy scenarios for Sydney to be evaluated.

Appendices

Figure A 1 Sydney Local Government Area (LGA) Boundaries and Zone Numbering System



Note: Zones 15 (Gosford), 16 (Hawkesbury), 42 (Wollondilly) and 44 (Wyong) are located outside of the boundaries to this map

Table A 1 Local Government Areas by Ring in Sydney and Zone Number

Inner Ring				Middle Ring				Outer Ring			
Region	**SLA**	**Zone Number**	**SLA Code (ABS)**	**Region**	**SLA**	**Zone Number**	**SLA Code (ABS)**	**Region**	**SLA**	**Zone Number**	**SLA Code (ABS)**
Central Core	South Sydney	35	7070	Middle South	Hurstville	20	4150	Outer South	Sutherland	37	7150
	Sydney (inner)	38	7201		Kogarah	21	4450	Outer South-	Fairfield	14	2850
	Sydney (remainder)	38	7202		Rockdale	33	6650	West	Camden	9	1450
Inner East	Botany	7	1100	Middle South-	Canterbury	11	1550		Campbelltown	10	1500
	Randwick	32	6550	West	Bankstown	3	350		Wollondilly	42	8400
	Woollahra	43	8500	Middle West	Auburn	2	200		Liverpool	25	4900
	Waverley	40	8050		Parramatta	30	6250	Outer West	Blacktown	5	750
Inner West	Leichardt	24	4800		Concord	12	1900		Blue Mountains	6	900
	Marrickville	27	5200		Burwood	8	1300		Penrith	31	6350
	Ashfield	1	150		Strathfield	36	7100		Holroyd	17	3950
	Drummoyne	13	2550	Middle North	Ryde	34	6700		Hawkesbury	16	3800
Inner North	Lane Cove	23	4700		Ku-ring-gai	22	4500	Outer North	Warringah	39	8000
	Mosman	28	5350		Manly	26	5150		Baulkham Hills	4	500
	North Sydney	29	5950		Willoughby	41	8250		Hornsby	18	4000
					Hunters Hill	19	4100	Central Coast	Wyong	44	8550
									Gosford	15	3100

Table A 2 Urban Form, Socio-Economic and Demographic Variables

No	Urban Form	Socio-Economic	Demographic
1	Distance from CBD (DisCBD) in km	%Clerical	Total number of female worker (Female)
2	Job density (JobDen) in persons/km2	%Labour	Total number of male worker (Male)
3	Total number of jobs (Jobs) in persons	%Professional	%Female
4	Ratio of workers to jobs (RatioWJ)	%High personal income (PIH)	%Male
5	Total number of residential workers (Wrk) in persons	%Low personal income (PIL)	Ratio male to female (RatioM/F)
6	Proportion of workers employed in the CBD (WrkCBD) in percent	%Medium personal income (PIM)	%Family household (Family)
7	Residential worker density (WrkDen) in persons/km2	%Household with no car (No-Car)	%Non family/single household (Non-Family)
8	Average job distance (km)	%Household with one car (One-Car)	Ratio family to non-family household (RatioF/NF)
9	Job accessibility by all modes (Hansen Index)	%Household with two or more cars (Two+Car)	%Age(15-29)
10	Job accessibility by car		%Age(30-49)
11	Job accessibility by bus		%Age(50-64)
12	Job accessibility by train		%Age(65+)
13	Separate dwelling (%)		
14	Semi-detached dwelling (%)		
15	Flat 1-3 storey (%)		
16	Flat 4+ storey (%)		
17	Road length per 1000 workers (km/1000workers)		

Table A3 Workers and Jobs Distributed by Ring, Sydney, 2011

Variables	Scenario	Inner ring (%)	Middle ring (%)	Outer ring (%)
Residential workers	1996 data	20.7	27.5	51.8
	Existing trend 2011	20	24	56
	Centralisation 2011	30	40	30
	Decentralisation 2011	10	12	78
Jobs	1996 data	36.7	28.9	34.4
	Existing trend 2011	33	28	39
	Centralisation 2011	45	35	20
	Decentralisation 2011	20	15	65

Table A4 Summary of Scenarios for the Distribution of Jobs and Workers for the Year 2011

Scenario	Jobs Distribution	Residential Workers Distribution
1	Existing Trends	a. Existing trends
		b. Centralisation
		c. Decentralisation
2	Centralisation	a. Existing trends
		b. Centralisation
		c. Decentralisation
3	Decentralisation	a. Existing trends
		b. Centralisation
		c. Decentralisation

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