URBAN FORM AND JOURNEY-TO-WORK TRAVEL BEHAVIOR USING CENSUS DATA FROM 1961 TO 1996

Putu SUTHANAYA
Postgraduate Research Student
School of Civil and Environmental Engineering
UNSW
Sydney, NSW 2052
Australia
Email: putu@civeng.unsw.edu.au

John BLACK
Professor
UNSW
Sydney, NSW 2052
Australia
Fax: +61 2 9385 6139
Email: j.black@unsw.edu.au

Abstract: This paper presents an empirical investigation into the relationship between journey-to-work travel behavior, automobile usage (and implicitly energy use) and the spatial form of the Sydney Metropolitan area using Census data for seven segments of time from 1961 to 1996. Aggregate relationships between travel behavior variables and urban form variables are reviewed indicating a vast literature and conflicting, contentious findings for policy formulation. Time-series data over 35 years provides the opportunities of testing the long-term stability of statistical models. Univariate and multivariate analyses are presented. Test of statistical significance confirm that neither gross residential nor employment densities are suitable explanatory variables of aggregate travel behavior at the spatial resolution of the local government area (LGA). Accessibility to jobs is an important predictor of travel behavior. Multivariate equations used to forecast future scenarios must be applied cautiously as widely differing urban form variables can enter the model depending on the data set used.

Key Words: Sustainability, Commuting, Urban Form, Statistical Model

1. INTRODUCTION

Evidence in Australia suggests that urban form is a significant factor in automobile dependence. Automobile dependence is a fundamental problem in the sustainability of cities with low-density suburban sprawl. Obvious (although sometimes simplistic) policy prescriptions are to increase urban densities (Newman and Kenworthy, 1999). Policy guidance provided by such aggregate, cross-city, analyzes is not always clear. Should higher densities be encouraged everywhere? Are certain areas, or combination of factors, more conducive to achieving less travel and energy-efficiency improvements through density increase than others? Transportation and land use patterns evolve together over long periods of time in any community, each influenced by multiple complex forces. There is an extensive literature on urban form and travel but academic controversy as to what is useful to policy makers.

This paper examines one aspect of the transportation and density sustainability debate by evaluating the changes to urban form and travel behavior from 1961 to 1996 and then the urban form and disaggregate travel pattern implications at a regional level based on 1981, 1991, and 1996 Journey-to-Work Census data for the greater Sydney metropolitan area. The analysis of the journey-to-work data at the regional level allows broad conclusions to be drawn in order to get an initial insight of the travel pattern implications of the urban form changes before conducting a more detailed level of analysis. The study poses three major questions: (a) How urban form changes over these periods? (b) How travel patterns change over these periods? (c) Is there any consistent relationship between urban form and travel behavior over long periods of time? Journey-to-work time-series data allows us to explore empirically the cross-sectional relationship between the physical dimensions of urban form and travel behavior, especially automobile travel (as a surrogate of energy use) within a large urban area (the greater Sydney Metropolitan area), with particular emphasis on identifying within-area variations in VKT as a function of within-area variations in the urban form attributes. Not only is automobile energy use highly correlated with the total number of vehicle kilometers traveled (Stead, 1999) but VKT is a convenient summary measure that reduces the highly dimensional nature of travel demand (number of trips, the spatial distribution of these trips, the modes, and routes) to a single variable (Miller and Ibrahim, 1998). Furthermore, VKT is widely used as an environmental indicator and the New South Wales Department of Transport, *Action for Transport 2010*, aims to improve air quality in Sydney by halting the growth in per capita VKT by 2011.

In order to achieve the desired understanding of the interaction of housing, employment and the journey to work, the research study is divided into a number of more manageable tasks. The first was to conduct a meta-analysis and review what had been written about the subject internationally (and in Australia) to provide background information on competing theories and interpretations that would suggest hypotheses that should be tested with the data collected for this study (Section 2). Section 3 describes the methodology, data used, and a brief description of the Sydney study area. The fourth section presents the analysis of aggregate changes from 1961 to 1996 at the metropolitan level – drawing briefly on the extensive preliminary work entailing descriptive statistics with LGAs grouped into similar distance bands from the central business district (CBD). The fifth section describes the results from linear regression analysis using a single explanatory variable and conducted at the sub-regional level of LGAs for the seven Census periods. Section 6 extends this using multivariate statistical analysis. Section 7 summarizes the findings and presents our observations on the urban transportation sustainability debate with particulate reference to Sydney.

2. LITERATURE REVIEW

A vast literature exists, as reviewed by Suthanaya (in preparation), but this is well beyond the scope of this paper to include. Publications may be conveniently grouped into three categories of methodology:

- Simulation studies
- Aggregate analysis
- Disaggregate analysis.

Simulation studies differ from the other methodological types as they assume certain relationships between urban form and travel behavior and then use these assumed relationships to predict the implications for travel for alternative forms of development. They do not empirically test the relationship between urban form and travel behavior. In most cases, hypothetical cities or neighborhoods, or hypothetical changes in real cities or neighborhoods, are tested using a traditional transportation planning models. In contrast to aggregate analysis, disaggregate analyses use individual and household socio-economic and travel characteristics, rather than zonal averages. Analysis-of-variance or regression models are estimated to test the strength of the relationship between socio-economic, urban form and travel characteristics, but in this case, for the individual or the household, rather than for zonal averages, thus accounting for within zone variations. Some of these studies also incorporate disaggregate measures of urban form into the analysis; although many aspects of urban form are most appropriately measured at an aggregate level.

The literature of most relevance to the aggregate approach has been reviewed so as to identify those urban form variables most likely to explain travel behavior (Cervero and Gorham, 1995; Frank and Pivo, 1994; Friedman, *et. al.*, 1994; Holtzclaw, 1990, 1994). Many of these studies have shown significant relationships between population or employment density and trip frequency, average trip lengths, mode split or total automobile travel. At the most aggregate scale, and in a widely quoted study, Newman and Kenworthy (1989) found an exponential increase in gasoline use as population density falls, especially to levels below 30 persons/ha. They found significant negative correlations between density and energy use. However, their research has been criticized on a number of methodological points (Gomez-Ibanez, 1991; Gordon and Richardson, 1989; Handy, 1996). Brunton and Brindle (1999) using 1994,1995 and 1996 Melbourne travel data sets are also critical of Newman and Kenworthy, finding that accessibility to activities (employment, shopping, etc) is a more powerful explanatory variable for travel choice than is density.

Our methodology is similar to that of Miller and Ibrahim (1998) who investigated the statistical relationship between urban form and work trip commuting efficiency based on analysis of 1986 work trip commuting pattern in the greater Toronto area. The work trip commuting efficiency is measured with respect to the average number of vehicle kilometers traveled (VKT) per worker in a given zone. They found that the VKT per worker increases moving away from both the central core of the city and from other high-density employment centers within the region. Job-housing balance was found to have a little impact on commuting VKT and population density did not explain variations on commuting VKT once other urban structure variables have been taken into account.

3. METHODOLOGY

The method used to analyse the urban form and travel pattern changes at the aggregate regional level for the Sydney Metropolitan area was driven by two goals. The first goal was to keep the analysis as simple and straightforward as possible. In this way, the effectiveness of a simple approach was tested before more time and resources were expended – perhaps unnecessarily – for a more complicated approach. The second goal, related to the first, was to make use of extensive time-series Census data collected for the journey-to-work in Australian cities. A combination of descriptive statistics, univariate analyzes and multivariate statistics are employed to probe the relationship between travel behavior variables and urban form variables. This phase of the research has provided guidance for detailed case studies at the micro-zonal level that will be conducted later.

3.1 Data

The primary data source is the 1961,1966,1971,1981, 1991, and 1996 Journey-to-Work data for Sydney Metropolitan Area conducted by the Australian Bureau of Statistics (ABS). Household data are aggregated for travel zones, for the Statistical Local Area (SLA) levels and cover 44 Local Government Areas in Sydney. The 1996 data is the most recent currently available. The data source is the NSW Department of Transport, Transport Data Centre (TDC). The Transport Data Centre has refined and validated the data, and any minor discrepancies between ABS and TDC data are a result of this process.

3.2 The Variables

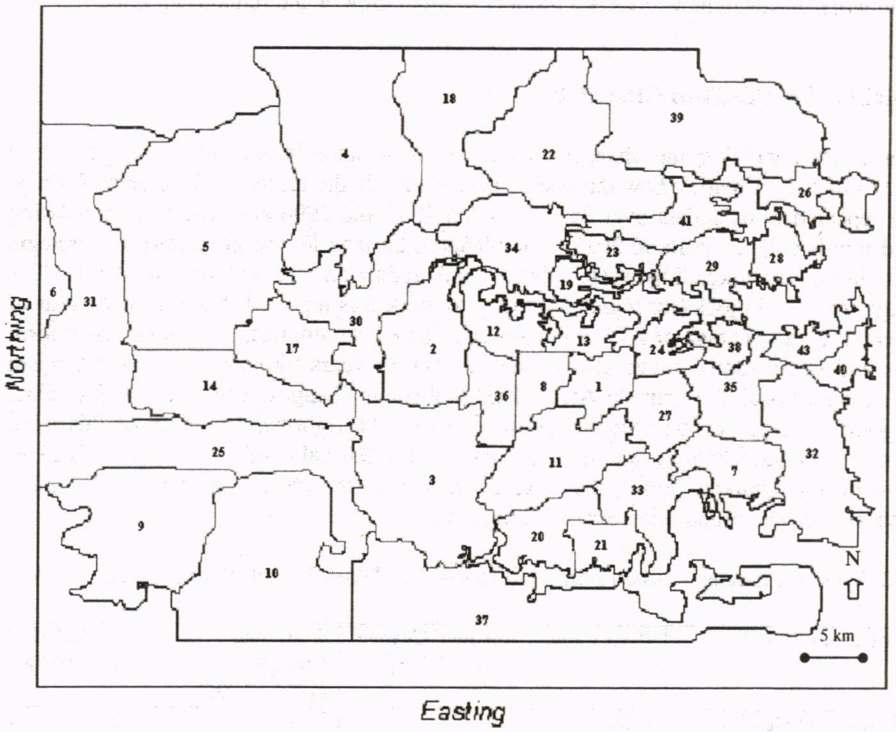
There are two time-series data sets used in our statistical analysis. The first is for the longer period – 1961 to 1996 – were only aggregate journey-to-work behavior could be analyzed because questions were not asked until 1981 about mode of travel. The second data set allows journey-to-work travel to be stratified by transportation mode, but only for 1981, 1991 and 1996. Dependent variables describing LGA zonal travel behavior when stratified by mode were of three kinds: the proportion of journey-to-work travel on the three major modes (automobile, bus and train); the total amount of travel, also stratified by mode; and the mean trip length, again also stratified by mode. The independent variables investigated also include socio-economic characteristics of each LGA. Table 1 lists dependent and independent variables.

Table 1. Dependent and Independent Variables, Journey to Work and Urban Form

Dependent Variables	Independent Variables	
	Urban Form	Socio-economic
Proportion using car (%)	Proportion residential worker (%)	Proportion labourer (%)
Proportion using bus (%)	Proportion job (%)	Proportion clerical (%)
Proportion using train (%)	Worker density (prs/km^2)	Proportion professional (%)
Total amount of travel by car (prs.kms)	Job density (prs/km^2)	No-car household (%)
Total amount of travel by bus (prs.kms)	Ratio of residential worker to job	One-car household (%)
Total amount of travel by train (prs.kms)	Proportion employed in CBD (%)	Two- or more car household (%)
Total amount of travel by all mode (prs.kms)	Proportion employed locally (%)	Low income (%)
Trip length by car (km)	Average job distance (km)	Medium income (%)
Trip length by bus (km)	Job accessibility by all mode	High income (%)
Trip length by train (km)	Job accessibility by car	Age 15-29 (%)
Trip length by all mode (km)	Job accessibility by bus	Age 30-49 (%)
	Job accessibility by train	Age 50-64 (%)
	Separate dwelling (%)	Age 65+ (%)
	Semi-detached dwelling (%)	
	Flat 1-3 storey (%)	
	Flat 4+ storey (%)	
	Road length per 1000 workers (km/1000workers)	

3.3 The Analytical Regions

Although there are more than 50 statistical local areas (SLAs) in the study area, only 44 SLAs are considered in this study area that includes the central coast but excludes Newcastle and Wollongong. These 44 SLAs are further grouped into three regional rings - i.e Inner ring which comprises 13 SLAs; the Middle ring with15 SLAs; and the Outer ring with 16 SLAs (Figure 1). The Central Coast is included in the Outer ring, as it forms part of the ABS Sydney statistical division. These rings are consistent with those used in studies by the NSW Department of Urban Affairs and Planning (1995).



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

Figure 1. Diagrammatic Map of Local Government Area (LGA) Boundaries and Zone Numbers for Sydney Study Area

3.4 Study Area: The Greater Sydney Metropolitan Area

In 200 years Sydney has grown from a small penal colony of 1000 people into a great international city, a vast metropolis of 3.5 million people housed in suburbs that sprawl over an area of 1500 square kilometers. The early Sydney was a walking or pedestrian city where the activities were clustered in the central business district (CBD) close to the docks of Circular Quay and Darling Harbour. The building of Sydney's first railway line to Parramatta (zone 30) in the 1850s reinforced the westward growth of Sydney. The period since the end of World War II has seen Sydney's greatest suburban expansion, and rapid industrialization. The built up area increased almost fourfold from 400 square kilometers to over 1500 square kilometers. Widespread automobile ownership facilitated rapid, low-density suburban growth on the urban fringe (especially, zones 4,5, 9, 10,14, 17,and 37) where cheap land was readily available beyond those areas served by public transportation.

The automobile changed the shape of Sydney more than any other factor because it changed Sydney from a single centered city focused on the CBD (zone 38) into a multi-centered city. The CBD however, still remains the most important center for finance, government and corporate offices (NSW Department of Urban Affairs and Planning, 1995). Government policies aim to reduce the rate of outward spread by increasing residential densities within established urban areas and getting the right activities in the right place (NSW Department of

Urban Affairs and Planning, In Press). The long-standing imbalance between the location of home and work places in new areas is a product of rapid growth and remains an issue.

4. AGGREGATE SYSTEM CHANGE

One reason for analyzing the changes that have taken place in the past is to provide a plausible basis for estimating how the system may evolve in the future. In the case of Sydney, we have repeated Census data over 35 years from 1961 and 1996 and will be extrapolating historical trends over 15 years to 2011 – the planning horizon for the government's strategic transport initiatives including sustainability and reductions in automobile VKT. The percentage increase in jobs (for which a journey to work was reported) from the base year of 1961 was 62 % - an average of 1.77 % per annum. Table 2 summarizes how other urban form variables and travel indices have also increased over 35 years by showing the 1996 mean value for the 38 Local Government Areas (LGA), absolute changes in the mean LGA value, and long-term average annual percentage increments. The right-hand column of this table uses these percentage changes to extrapolate the mean LGA value of each index to 2011 to provide some benchmark, noting the obvious caveat of the dangers and methodological weaknesses of trend extrapolation over the long term.

Table 2. System Changes - Urban Form and Journey-to-Work Travel, Sydney 1961 – 1996

Index (Mean for 38 LGAs)	1996 Value	Absolute Change (1961 - 1996)	% Annual Change (1961 - 1996)	Extrapolated Value (2011)
Gross Residential Density (persons per km^2)	1 060	113	0.34	1 114
Gross Job Density (persons per km^2)	1 291	292	0.83	1 452
Mean Job Distance (km)	25.22	3.24	0.42	26.81
Trip Length (km)	13.78	0.84	0.19	14.17
Person – Km of Travel per LGA	559 021	289 854	3.08	817 289

These percentage changes, averaged as the annual absolute percentage change for the entire period, highlight that growth and redistribution within an urban system over the long-term is modest (less than 0.8 % p.a.). However, there is a relative explosion at 3.1 per cent per annum in the average LGA value of the amount of person-kilometers of journey-to-work travel. This travel growth is fueled by more workers, longer mean trip lengths of individual workers, and, most importantly, the fact that those workers are locating in the peripheral suburbs where the LGA trip lengths are the highest. Should these trends recorded in the past continue unabated until 2011 we would expect the total amount of person travel in the journey to and from work to reach 62 million kilometers *each* working day of the week – possibly 90 per cent of this by automobile. This is clearly of concern to policy makers.

Time-series data for seven Census of Population and Housing has allowed us to apply descriptive statistics to show how the aggregate LGA mean values outlined above, and other urban form and travel variables, have changed from 1961 to 1996 at the spatial resolution of each Local Government Area in the Sydney metropolitan region. The LGAs were grouped into inner, middle and outer suburbs. Changes in indices were plotted over time to help understand the aggregate trends identified in Table 2. Whilst this preliminary analysis in the study of urban form and travel is an essential part of any statistical methodology it is not reported here. However, given the importance of person-kilometers of travel both in our analysis and to a more sustainable city we include Figure 2 to reinforce the point that it is in those suburbs beyond 20 km of the Sydney CBD where the greatest increases in person-kilometers of travel have occurred. Whilst the original illustration is in color to allow each of the seven Census periods to be distinguished the value of this black-and-white figure is that it clearly shows the highly consistent amount of person-kilometers of travel in the journey to work in those LGAs located within about 20 km of the CBD (the lines are superimposed on each other). Beyond this distance, where the lines separate, there is an increasing amount of travel at each successive Census.

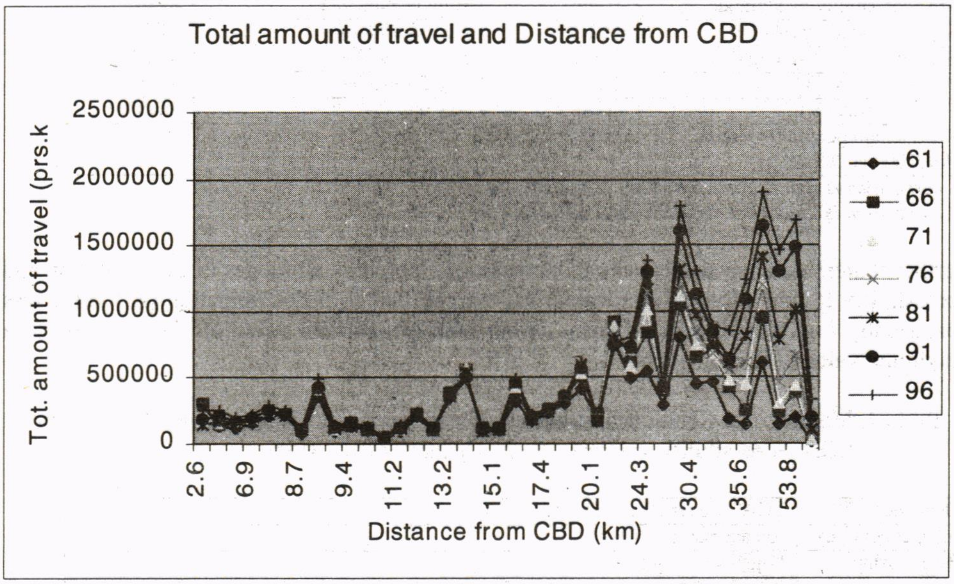


Figure 2. Total Amount of Person Journey-to-Work Travel by All Modes of Transportation at Increasing Distance from CBD in Sydney (1961-1996)

5. REGRESSION ANALYSIS – SINGLE VARIABLE CASE

Interpretation of the descriptive statistics involved in changes to travel behavior and urban form in Sydney allowed us to move more confidently into the quantitative phase and apply regression analysis. Several of the hypothesized explanatory variables were found to be statistically significant in explaining the macro-zonal relationship between travel behavior and urban form but the independent variable that over time had the highest correlation coefficient was accessibility to jobs. For example, Table 3 shows the result of correlation analysis for 1996 data using trip length by all transportation mode as the dependent variable.

Table 3. Correlation Coefficients for Trip Length by All Transportation Modes as Dependent Variables

Independent Variables			
Urban Form	**Correlation**	**Socio-economic**	**Correlation**
Proportion residential worker (%)	0.556**	Proportion labourer (%)	0.233
Proportion job (%)	-0.125	Proportion clerical (%)	0.536**
Worker density (prs/km^2)	-0.908**	Proportion professional (%)	-0.472**
Job density (prs/km^2)	-0.922**	No-car household (%)	-0.733**
Ratio of residential worker to job	0.490**	One-car household (%)	-0.676**
Proportion employed in CBD (%)	-0.905**	Two- or more car household (%)	0.700**
Proportion employed locally (%)	0.359*	Low income (%)	0.369*
Average job distance (km)	0.908**	Medium income (%)	-0.291
Job accessibility by all mode	-0.966**	High income (%)	-0.387*
Separate dwelling (%)	0.621**	Age 15-29 (%)	0.032
Semi-detached dwelling (%)	-0.582**	Age 30-49 (%)	0.217
Flat 1-3 storey (%)	-0.824**	Age 50-64 (%)	-0.038
Flat 4+ storey (%)	-0.782**	Age 65+ (%)	-0.453**
Road length per 1000 workers (km/1000workers)	0.673**		

* *correlation is significant at 0.05 level (2-tailed)*
** *correlation is significant at 0.01 level (2-tailed)*

Further regression analysis between LGA mean trip length by all modes of transportation and accessibility to jobs (Table 4) indicated that the coefficient of determination (R^2) value was consistently high for all seven Census years, with a minimum value of 0.90 in 1961 to a maximum value of 0.96 in 1966.

Table 4. Macro-zonal Relationship Between Mean Journey-to-Work Travel Distance and LGA Accessibility to Employment, Sydney, 1961 - 1996

Dependent (Y)	LGA Trip length by all modes (km)						
Independent (X)	Job accessibility (Acc)						
Relationship	Log Y = a Log (X) + b						
Year	Intercept (b)		Coefficient (a)		R^2	F	Sig.F
1961	4.769		-0.785		0.90	314.9	2.2E-19
	t- stat	22.85548	t-stat	17.7465			
	p-value	5.05E-23	p-value	2.2E-19			
1966	5.407		-0.903		0.96	974.3	1.2E-27
	t- stat	38.96952	t-stat	31.2133			
	p-value	4.9E-31	p-value	1.15E-27			
1971	5.257		-0.872		0.94	617.3	2.9E-24
	t- stat	31.20798	t-stat	24.8463			
	p-value	1.16E-27	p-value	2.97E-24			
1976	5.236		-0.868		0.92	422.9	1.7E-21
	t- stat	25.84039	t-stat	-20.5654			
	p-value	7.79E-25	p-value	1.74E-21			
1981	5.311		-0.879		0.92	418.3	2E-21
	t- stat	25.6698	t-stat	-20.4534			
	p-value	9.77E-25	p-value	2.08E-21			
1991	5.405		-0.891		0.93	445.1	7.4E-22
	t- stat	26.45637	t-stat	21.0981			
	p-value	3.48E-25	p-value	7.4E-22			
1996	5.427		-0.885		0.93	497.7	1.1E-22
	t- stat	28.02331	t-stat	22.3094			
	p-value	4.81E-26	p-value	1.14E-22			

Note the long-term consistency of the fitted parameter values (Figure 3). Let us examine the temporal stability in the parameters of this model over a period of 15 years, as we will be interested in making estimates for 2011. In 1981, the parameters were: a = -0.879 and b = 5.311; in 1996, they were a = -0.885 and b = 5.427. If we treat the 1996 parameters as the true values then the 1981 model is inaccurate by a = 0.006 and b = 0.116. We can use the trends in the parameter values over the last 15 years in Figure 3 to extrapolate their values in 2011. If the zonal (LGA) distribution of accessibility to jobs is known, it is possible to estimate zonal trip lengths for the year 2011. This will allow a perspective on the VKT of travel by region and an identification of the magnitude of the task in meeting VKT targets for journey-to-work travel. The sustainability of future urban transportation systems requires a substitution of public for private means of travel, and a reduction in automobile travel is required in Sydney if VKT targets are to be met by 2011. For this reason, a stratified model of the relationship between travel behavior in the journey-to-work and urban form is desirable (see Section 6). Further analysis on trip length by automobile as dependent variables for 1996 data indicated that accessibility to jobs by automobile has the highest correlation (r=-0.96) followed by accessibility to jobs by train and by bus with the same correlation coefficient (r) values of –0.95.

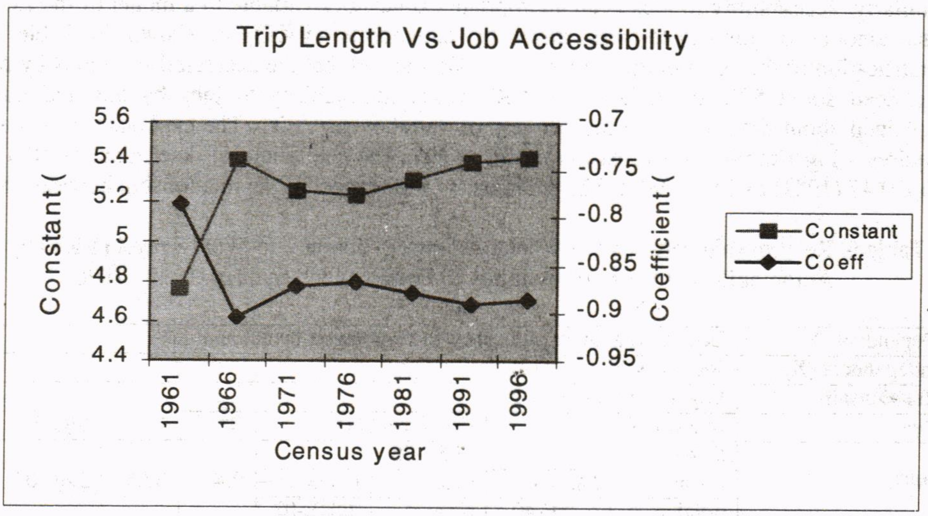


Figure 3. The Trends of the Fitted Parameter Values for Trip Length by All Transportation Mode (1961-1996)

Table 5 summarizes the statistical results for the best model for the macro-zonal relationship between LGA percentage of journey-to-work trips by automobile and LGA accessibility to employment for the years 1981, 1991 and 1996. Job accessibility (as measured by the Hansen accessibility index) is also found to be the best predictor of the LGA percentage of automobile trips for the journey-to-work, although the strength of the linear relationship is weaker than the aggregate results presented before. The coefficient of determination (R^2) is from 0.71 (1991) to 0.76 (1981). The coefficient (a) and the regression constant (b) have similar values in each of the three years analysed. Further stratification of accessibility to jobs by mode for 1996 data indicated that the accessibility to jobs by car explained about 65% of variation in the proportion using automobile while accessibility to jobs by bus and train explained about 71% and 72%, respectively.

Table 5. Macro-zonal Relationship Between LGA Percentage of Journey-to-work Trips by Automobile and LGA Accessibility to Employment, Sydney, 1981 - 1996

Dependent (Y)	LGA % automobile trips for journey-to-work						
Independent (X)	Job Accessibility (Acc)						
Relationship	Y = a X + b						
Year	Intercept (b)		Coefficient (a)		R^2	F	Sig.F
1981	88.857		-0.00031		0.76	130.6	1.8E-14
	t- stat	43.340	t-stat	11.426			
	p-value	1.7E-36	p-value	1.81E-14			
1991	91.630		-0.00028		0.71	104.7	5.7E-13
	t- stat	41.961	t-stat	10.230			
	p-value	6.4E-36	p-value	5.66E-13			
1996	93.078		-0.00027		0.73	113.7	1.6E-13
	t- stat	43.235	t-stat	10.662			
	p-value	1.87E-36	p-value	1.6E-13			

Similarly, accessibility to jobs is an appropriate explanatory variable in a model of the LGA total amount of journey-to-work travel by automobile (VKT), as shown in Table 6. Stratification of the accessibility to jobs by mode showed that the accessibility to jobs by car explained about 57% of variation in VKT while accessibility to jobs by bus and train explained about 58% and 59% respectively of variation in VKT. The explanatory variable requires a logarithmic transformation in this model. The coefficient of determination (R^2) is from 0.47 (1981) to 0.62 (1996). The parameters of the model of the relationship between the

Table 6. Relationship between LGA Total Amount of Journey-to-Work Travel (VKT) by Automobile and LGA Accessibility to Employment, Sydney, 1981 - 1996

Dependent (Y)	LGA total amount of journey-to-work travel by automobile						
Independent (X)	Job accessibility (Acc)						
Relationship	Log Y = a Log (X) + b						
Year	Intercept (b)		Coefficient (a)		R^2	F	Sig. F
1981	5.742		-8.5E-06		0.47	37.3	2.8E-07
	t- stat	54.576	t-stat	6.103			
	p-value	1.25E-40	p-value	2.83E-07			
1991	6.0660		-1.1E-05		0.60	64.3	5.3E-10
	t- stat	53.971	t-stat	8.018			
	p-value	1.98E-40	p-value	5.28E-10			
1996	6.1043		-1E-05		0.62	69.2	2E-10
	t- stat	58.812	t-stat	8.319			
	p-value	5.63E-42	p-value	2.02E-10			

LGA total amount of journey-to-work travel by automobile measured in VKT and LGA accessibility to employment from 1981 to 1996 are not very stable over time. The issue of the stability over time of the regression constant and regression coefficient warrants further examination and would be a subject of further statistical investigation (see, Hackl, 1980). Any model of travel behavior with demonstrably unstable parameters would need to be applied with caution for any forecasting purposes.

6. MULTIVARIATE ANALYSIS

Multivariate analyzes provide additional insights into the relationship between travel behavior and urban form. In the case of the LGA mean trip length by all modes of transportation in the seven Census years, from 1961 – 1996, a combination of 7 different urban form explanatory variables are found to best explain travel behavior in various years. Four variables required logarithmic transformations – accessibility to jobs, job density, the proportion of all metropolitan jobs in the LGA, and residential worker density. Furthermore, the order that they enter the model differs over time based on step-wise multiple linear regression. The number of statistically significant variables range from two (1961) to four (1981 and 1991). The coefficient of multiple determination (R^2) ranges from 0.89 (1961) to 0.98 (1966 and 1996). Therefore, no consistent model could be recommended for forecasting mean trip length by all transportation modes. However, if accessibility to jobs is the main explanatory variable to be considered, a combination of accessibility to jobs with gross job density and proportion of jobs is recommended as the best combination of urban form variables to explain the variation in mean trip length by all transportation modes over 35 years.

When stratifying travel behavior by transportation mode the interpretations are hindered by the time-series data covering only three Census periods, although it appears that the patterns identified for aggregate travel and urban form variables hold. Table 7 shows the total amount of travel by car (VKT) as the dependent variable and that a combination of proportion of residential worker and accessibility to jobs are the best combination of urban form variables in explaining the variation in total amount of travel by car (VKT). Collinearity tests showed that there was no problem of multicollinearity as the tolerance value was higher than 0.1 and the Variance Inflation Factor (VIF) value was less than 10.

Table 7 Multiple Regression Analysis for Total Amount of Travel by Automobile (VKT) as Dependent Variable and Urban Form as Explanatory Variables

Year		Model	Unstandardized coefficient		Standardized coefficient	t	Significant
			B	Std Error	Beta		
1981	$R^2 = 0.90$	Constant	2511778	534530.1	-	4.699	0.000
	Adj.$R^2 = 0.89$	PropWrk	106349.6	7627.040	0.766	13.944	0.000
	(F=120.3,	LnAccess	-221105	44216.480	-0.654	-5.001	0.000
	Sig.=0.000)	JobDist	-3229.393	1383.515	-0.303	-2.334	0.025
1991	$R^2 = 0.93$	Constant	2134046	243760	-	8.755	0.000
	Adj.$R^2 = 0.93$	PropWrk	136935.8	8026.2	0.755	17.061	0.000
	(F=264.6,	LnAccess	-195192	21421.8	-0.403	-9.112	0.000
	Sig.=0.000)						
1996	$R^2 = 0.93$	Constant	2624058	274407	-	9.563	0.000
	Adj.$R^2 = 0.93$	PropWrk	155063.2	9150.703	0.728	16.945	0.000
	(F=289.7,	LnAccess	-237684	23868.735	-0.428	-9.958	0.000
	Sig.=0.000)						

The proportions using the automobile for the journey-to-work are best explained in 1981 and 1996 by accessibility to jobs and gross residential worker density (R^2 = 0.78 and 0.88, respectively). For 1991, four variables enter the model (R^2 = 0.80) in the order of accessibility to jobs, logarithm of job distance, logarithm of job density and residential worker density. All signs are intuitively plausible. The mean trip length of LGA automobile travel is best explained in 1991 and in 1996 (R^2 both 0.97) by six variables, entering step-wise in the same order: accessibility to jobs; gross residential worker density; proportion of residential workers employed in the CBD; distance to the CBD; average job distance in km from the LGA; and the ratio of residential workers to jobs in the LGA (local home-work balance).

7. DISCUSSION

Multivariate statistical analysis has shown that the LGA mean trip length of automobile travel is best explained in 1991 and in 1996 by the same variables, entering step-wise in the same order: accessibility to jobs; gross residential worker density; proportion of residential workers employed in the CBD; distance to the CBD; average job distance in km from the LGA; and the ratio of residential workers to jobs in the LGA (local home-work balance). Clearly, the total amount of employment and residential worker activity, its location and density will influence VKT in 2011. Our analysis confirms that urban form variables change at a very low annual percentage rate (Table 2) so the pattern of urban development in 2011 is unlikely to be radically different to that of today. Accessibility to employment is a dominant factor in explaining variations in journey-to-work travel behavior amongst LGAs and this has been consistently the case since 1961 in Sydney.

The analytical tools used to assess the travel implications of different urban forms normally use travel demand parameters that are assumed to be uniform across the area. According to Ghaeli and Hutchinson (1998), this has yielded misleading estimates of travel demands. Household characteristics and travel behavior are quite similar for both established and redeveloping zones in the older, stable, suburbs but there are significant differences in travel characteristics between the older, established zones and the growing zones in the developing suburbs. We have found this to be the case also in Sydney (see Figure 2) and recommend there should be a spatial dimension to VKT targets. Urban consolidation in the inner areas does relatively little in reducing VKT because the total amount of person travel has changed very little from 1961 to 1996 in the middle and inner suburbs. The differing patterns of journey-to-work travel behavior in the outer suburbs (beyond 20 km of the Sydney CBD) should be understood and priorities developed for those sub-regions in terms of employment location policies, densities of that development, residential densities all supported by integrated public transportation infrastructure, such as extensions to the suburban rail network, light rail transit or bus-ways.

Policies related solely to the location of homes and workplaces (density) are unlikely to achieve a reduction in VKT in Sydney as envisaged by the New South Wales Government by 2011 and beyond unless there is a substantial switch for automobiles to public transit and train. Therefore, a greater understanding of the factors explaining public transportation behavior in the journey to work is required. Multivariate statistical analysis at the LGA level shows that the proportion using the bus is explained by distance from the CBD and employment density but the explanatory power of the model is weak. There are no variables that are statistically significant in explaining the proportion using the train for the journey to work. The trip length by train is explained entirely by distance from the CBD and the average job distance in kilometers from the LGA; trip length by bus is explained by no consistent model except for the common variable of accessibility to jobs that enters a model for 1981, 1991 and 1996. The aggregate approach adopted in this paper is clearly unsuitable to modeling travel behavior and future research will focus on smaller zones and contrast behavior of commuters living close to and further away from railway stations.

Peak journey-to-work volumes have largely determined the supply of transportation infrastructure capacity. The journey to work remains significant as it impacts directly on individuals and families, and it is a major area of Government expenditure in transportation. Hence, Government policy about housing the population needs to relate in some way to policies about the locations of jobs and the connections between employment and housing. Decisions about the provision of public transportation services need to incorporate information about the location of jobs and households; incorrect decisions will naturally lead to under utilization and waste of resources. The journey-to work remains a key challenge for city management (Gipps, *et.al.*, 1996).

The relationship between travel behavior for non-work travel and urban form is beyond the scope of this paper. The NSW Department of Transport (1999) identified that social/recreation trips accounted for 14% on the average weekday trips while work trips accounted for 10.1% of trips in 1991 rising to 10.6% in 1997. From 1991 to 1997 there was a small decrease in the share of trips for shopping while social/recreation trips has increased at a slightly faster rate than work trips. Some studies found the increasing significance of leisure trips (D'Este, 1997; Downing and Gollner, 1997). This indicates that further study to identify the link between urban form and non-work trips is required.

By the year 2021 Sydney is expected to have a population of 4.5 million and a larger, more diverse economy (NSW Department of Transport, 1995). Dealing with this growth and change, and maintaining the city's high environmental quality, economic vitality and social equity, are major challenges facing Sydney. An important part of meeting the challenges of tomorrow is the development of a quality transportation system for the region. In the *Cities for the 21st Century* the NSW Department of Planning (1995), introduced a strategy that seeks to create compact cities in three ways: by increasing opportunities to build housing close to where jobs are now located; by promoting further employment growth where jobs are now concentrated; and by planning for new urban areas with a mix of land uses, increased residential densities and early provision of public transportation.

Integration of land-use and transportation planning is a key to meeting the challenge. The close links between housing choice, job location, environmental protection and travel, and the costs of all this to individuals and the community at large, need to be clearly understood and reshaped through a comprehensive program of consultation, policy making and action. Reductions in VKT are one of the policy goals and the analytical approach adopted by our research can inform the policy-making process.

8. CONCLUSIONS

The relationship between urban form and transportation energy-efficiency is a matter of considerable concern amongst planners and policy makers dealing with issue of sustainable urban development. This paper has presented an empirical investigation into the relationship between journey-to-work travel behavior – an important, but not the only, component of urban travel - automobile usage and the spatial form of the Sydney Metropolitan area using Census data for seven segments of time from 1961 to 1996. Urban form changes slowly at the LGA level but VKT has increased relatively rapidly. An important question posed in this paper is: can we establish any consistent relationship between urban form and travel behavior over long periods of time as represented by data from periodic Census of Population and Housing ?

The originality of this paper is that we have attempted to answer this question using time-series Census journey-to-work data over 35 years, both in the formulating of statistical models and in testing the long-term stability of these statistical models. Results of regression analysis are presented. Tests of statistical significance confirm that neither gross residential nor employment densities are suitable explanatory variables of aggregate travel behavior at the spatial resolution of the local government area (LGA). Accessibility to jobs is an important predictor of travel behavior and was found to have a consistently high correlation over 7 Census periods with relative consistent parameter values from 1966 onwards. On the other hand, multivariate models of journey-to-work travel behavior disaggregated by transportation mode and urban form variables used to forecast future scenarios must be applied cautiously as widely differing urban form variables can enter the model in any one year (Table 7 and the last paragraph of Section 6).

Drawing on previous aggregate analyses of this kind, some authors have prescribed higher densities as a suitable policy instrument for more sustainable cities. Should higher densities be encouraged everywhere? Are certain geographical areas, or combination of factors, more conducive to achieving VKT reductions and transportation energy-efficiency improvements through density increase than other areas? Our descriptive statistics as to how the Sydney metropolitan region has evolved since 1961 show that the greatest increases in VKT are in the outer suburbs beyond 20 km of the CBD. Therefore, urban consolidation in the inner areas is unlikely to contribute much in reducing VKT. The differing patterns of journey-to-work travel behavior (trip lengths and transportation mode) in the outer suburbs should be understood more, especially models explaining public transportation behavior. Priorities need to be developed for those outer sub-regions in terms of employment location policies, densities of development, that are all supported by integrated public transportation infrastructure and services if there is to be a substantial shift from private to public transportation. Only in this way are large metropolitan areas such as Sydney likely to become more sustainable from a transportation perspective.

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