# URBAN TRIP DISTRIBUTION MODELS: ANALYSIS OF SPATIAL RESIDUAL ERRORS AND SOME IMPLICATIONS FOR TRANSPORTATION POLICY AND RESEARCH

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**Abstract:**

Researchers have clearly demonstrated the weaknesses in the gravity model specification. Yet the model remains today at the heart of the four-step modeling (for example, TransCAD) used in practice in the urban transportation planning process. There is an array of suitable statistical measures to test model goodness-of-fit against survey origin-destination (O-D) data that allow calibrated model specifications to be evaluated and the best model selected; but the implications of inaccuracies in trip distribution models are avoided by practitioners. The aggregated gravity model, one stratified by industry and occupation, and an intervening opportunities model are calibrated on journey-to-work Census data for Sydney. O-D residuals are assigned to the transport network to check for spatial bias using the TransCAD software to pinpoint where investment decisions may have been based on either over- or under-estimation of traffic flows. The implications of these findings for transportation policy and infrastructure investment are articulated. The conclusions point towards a need for research and development into improved spatial interaction models.

**Key Words:** Journey-to-work, spatial interaction, trip distribution, forecasting accuracy

## 1. INTRODUCTION

The gravity model of trip distribution forms the basis of modeling in urban transportation planning. Applied in the late 19th century by German railway engineers to estimate inter-city traffic for proposed lines it found its way into mainstream US practice in the mid-1950s. Interestingly, one of the first comprehensive land use and transportation studies of the 1950s (Chicago) applied the intervening opportunities model for trip distribution modeling and, despite comparative evaluations in the 1960s of both models that showed little difference in model accuracies, the gravity model appears to have been subsequently favored by practitioners on the grounds of computational ease (Easa, 1993). Alternative model specifications can be generated by the degree of stratification of the trips, constraints on trip-ends (unconstrained, production/attraction constrained, and fully constrained), different measures of transport impedance, and the functional form of the deterrence function (Black and Salter, 1975), although, in practice, rarely is such a systematic search undertaken to determine the best model. Researchers have pointed out weaknesses of the gravity model such as its dependence on travel distance or travel time, mismatches between model and survey O-D matrices, and constant socio-economic conditions (for example, see Smith and Hutchinson, 1981; Volet and Hutchinson, 1986) and yet the model remains as the cornerstone of current computer packages, such as TransCAD. International studies have demonstrated the importance of model stratification. Previous research (Black, *et al*., 2003) has convincingly demonstrated that when modeling the urban journey-to-work origin-destination (O-D) flows in Sydney, there are different spatial labor markets.

The aim of this research is to develop a model with stratification by employment group followed by re-aggregation of the stratified model outputs to give the total O-D flow pattern and to assign this traffic to a transport network to identify links with under- or over-estimated traffic. As a benchmark of conventional practice, we calibrate (based on the trip-length frequency distribution criteria) a fully-constrained gravity model using various deterrence functions to represent the intra- and inter-zonal (Statistical Local Areas) O-D flows of journey-to-work commuters in the Greater Sydney Metropolitan Region based on data from the 1996 Census of Population and Housing Journey-to-Work Tabulations. We use a Geographical Information System-Transportation (GIS-T) program, TransCAD, to plot the spatial residuals (differences between model estimates and survey data) and assign the residuals to the network.

We hypothesize that different industry groups have different spatial labor markets, and explore the trip-length characteristics of these groupings, presenting the results as descriptive statistics. The results confirm that there are indeed clear differences by groups, and therefore we build a family of stratified gravity models, calibrate them individually, and then re-aggregate the stratified model O-D matrices estimates to give an overall model pattern of O-D flows of journey-to-work commuters in Sydney. The spatial residuals obtained from this family of stratified models are compared with the benchmark model with all matrices being assigned to the road transport network by the minimum path (all-or-nothing) assignment algorithm. They differ from that obtained from the original aggregate model, yet there remain systematic spatial errors in the model desire lines and assignments when compared with survey O-D assignments. We then formulate a different trip distribution model based on the theory of intervening opportunities (Ruiter, 1969) and use, for an initial exploration, the calibration parameter of the aggregate journey-to-work flows that is the unweighted average of all zonal (local government area) preference functions, as calculated by Suthanaya (2002). Its statistical performance is superior to the stratified models despite the model mean trip length being considerably greater than the true mean trip length, which is resulted from the unweighted average.

The implications of these research findings are explored in the final section of this paper with particular reference to policy – both in terms of research and development by government agencies; and of implications for private-sector investors in urban toll roads. An agenda for further research into urban trip distribution model formulation and validation is proposed.

## 2. CONCEPTUAL FRAMEWORK

Figure 1 outlines the overall approach of the research methodology using data for Sydney as a case study. The stages that have been covered in a previous paper (Black, et al, 2003) are in bold. The input data allows us to evaluate two broad classes of urban trip distribution model – the gravity model and the intervening opportunities model, together with their variants – stratified by industry or occupation group. In this paper only the results for the stratified gravity model and the aggregate intervening opportunities model are presented. (Technical information on the alternative modeling approach can be found in: Black, *et al.* 1993; and Black, *et al*., 2002.) The evaluation is based on statistical comparisons of the model output, and on the GIS mapping of spatial residuals and their assignment to the road network.

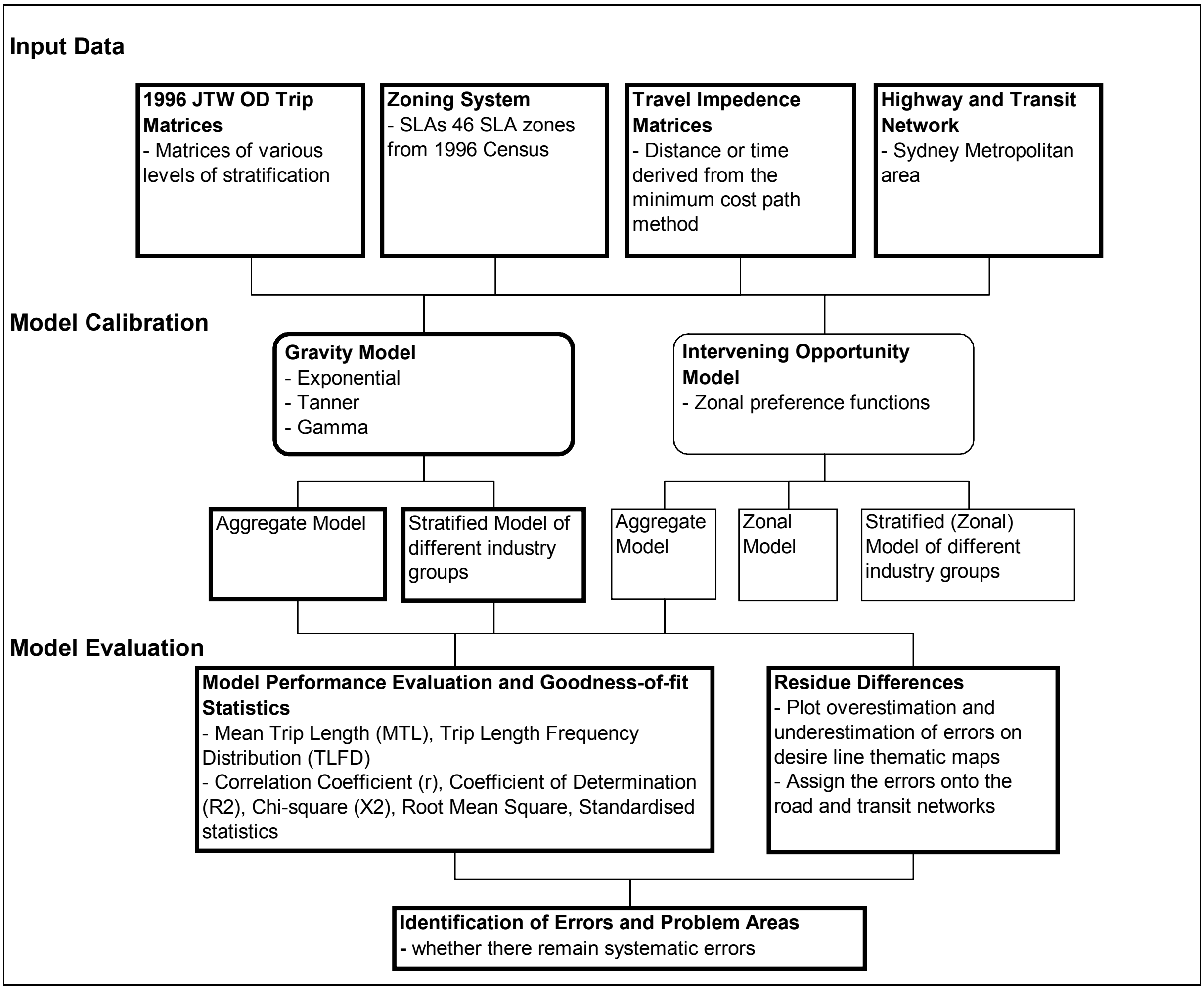


Figure 1. Overall Structure of Spatial Interaction Model Development and Validation Process

As a benchmark of conventional practice, doubly-constrained gravity models with various types of deterrence functions are used in the calibration process and their goodness-of-fit to the data are established. Origin-destination matrices of groups of industry and occupation categories of similar trip-length characteristics are calibrated separately based on the trip-length frequency distribution criteria. The rationale for the four categories is based on industry groups with similar trip length frequency distributions (Figure 2).

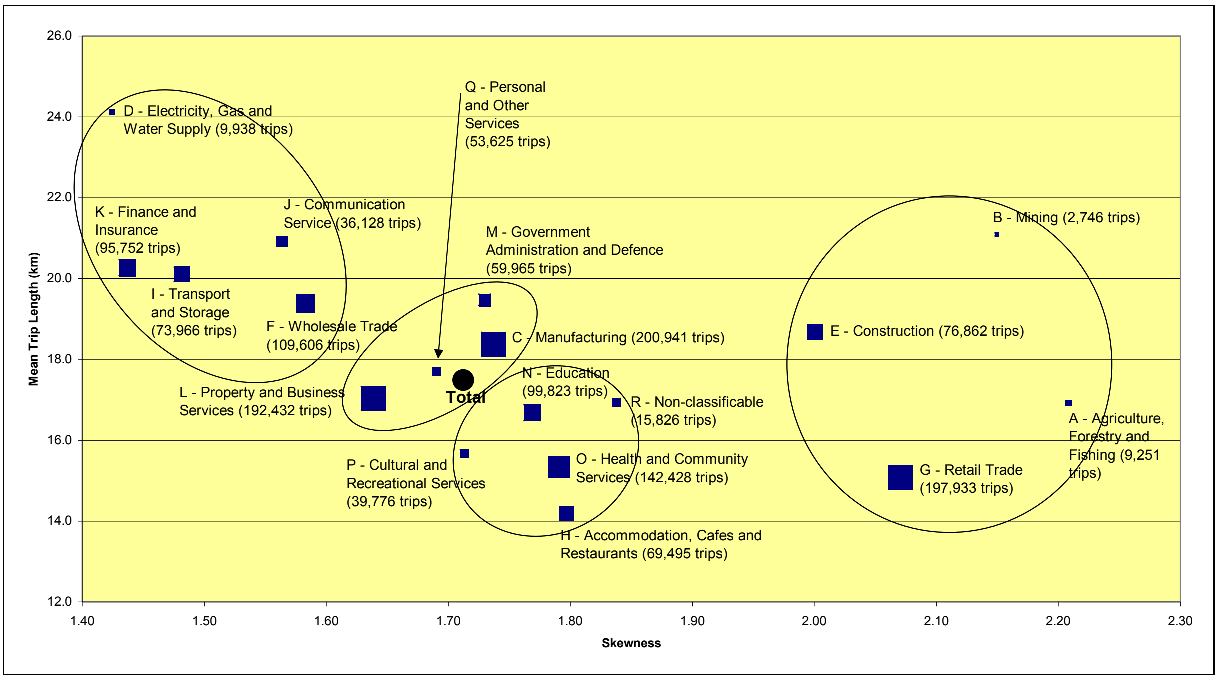


Figure 2. Industrial Groups with Similar Statistical Characteristics

The stratified gravity modeled O-D matrices estimates are then re-aggregated to give an overall model pattern of O-D flows of journey-to-work commuters in the Greater Sydney Metropolitan Region. An array of suitable goodness-of-fit statistical measures, including the coefficient of determination ($R^2$); chi-square; root mean square; and others, are used to evaluate the accuracy of parameter estimates and the ability of the model to replicate O-D commuting flow patterns compared with the survey data. General representations of the performance of the model are given by a trip-length frequency comparison and mean trip length measures.

The use of different goodness-of-fit statistical measures may lead to different conclusions being reached on the model performance. Although a combination of two or three statistical measures can be used to determine the best model, these measures only provide indications on the overall global performance of the accuracy of interactions. They are not assessing the actual prediction of spatial interaction, providing no spatial information. The implications of these findings for transportation policy development and infrastructure investment are articulated and hence there is a need to investigate over- and under-estimation of O-D commuting flow patterns. The spatial residuals (derived from a cell-by-cell comparison of the survey matrix and the model matrix), obtained from the family of stratified models, are compared with the benchmark (aggregate) model. Using the TransCAD program, desire-line patterns of spatial residuals are plotted to represent the bias of inter-zonal (based on Statistical Local Areas) O-D flows of journey-to-work commuters. Furthermore, the spatial residual errors are assigned to the Sydney metropolitan road network to give representations of areas where over-estimation and under-estimation of commuting flows are found, which pinpoint where recent infrastructure investment decisions may have been based on either over- or under-estimation of traffic flows from the conventional modeling approach.

## 3. APPLICATION TO THE SYDNEY ENVIRONMENT

This research focuses on the development and validation of appropriate stratified gravity and intervening opportunities trip distribution models to improve the accuracy in forecasting journey-to-work commuting patterns in the Greater Sydney Metropolitan Region. Using the 1996 Census of Population and Housing Journey-to-Work (JTW) tabulations obtained from the NSW Department of Transport – Transport Data Centre (TDC), O-D trip matrices, based on Statistical Local Areas, of different industry and occupation groups are collated and analyzed to give representations of their trip-length characteristics.

### 3.1. 1996 JTW Zoning System

The 1996 JTW dataset and its tabulations for the Greater Sydney Metropolitan Region are the most recent sources of data for the preparation of origin-destination trip matrices. The 1996 JTW data is derived by the Australian Bureau of Statistics (ABS) from its 1996 Census of Population and Housing, using information supplied by the TDC to code the employment location of employed people to a Statistical Local Area (SLA) or a TDC Travel Zone (TZ). For the purpose of this research, only those 46 SLAs located within the Sydney Statistical Division (SD) are used.

The JTW data set provides information on the trip to work on Census day undertaken by all employed people aged 15 years and over who were enumerated in the JTW Study Area on Census night. In addition to providing information on modes of travel and key demographic data, the JTW also provides origin and destination data coded to the SLA level. The Study Area includes 57 SLAs. A SLA is a general-purpose spatial unit. According to the Australian Standard Geographical Classification (ASGC) 1999, SLAs are based on the boundaries of incorporated bodies of local government where these exist, and are more widely known as Local Government Areas (LGAs).

### 3.2. 1996 JTW Origin-Destination Trip Matrices

Table 14 of the JTW data set provides the number of trips from an origin SLA to a destination SLA, stratified by industry, occupation and gender (Table 1). There are 19 industry classifications and 11 occupation classifications (both with a "not stated" category. Matrices of dimension 46 rows and 46 columns are derived for each industry and occupation categories.

Table 1. Format of Table 14 of 1996 JTW Data Set

| Variable Name | Format | Description |
|---|---|---|
| SLA96_O | Integer | *Origin 1996 SLA* |
| SLA96_D | Integer | *Destination 1996 SLA* |
| INDUST19 | Character (1) | *Industry (1 digit ANZSIC code)* |
| OCCPN11 | Character (1) | *Occupation (1 digit ASCO code)* |
| SEX | Integer | *Sex* |
| FREQ | Long Integer | *Number of employed persons* |

### 3.3.Sydney Integrated Road and Public Transport Network

The inter-SLA transport and road networks are essential in the modeling process to give measures of distance, time and cost of travel between pairs of zones. For the purpose of this research, the 2002 Sydney Integrated Road and Public Transport Network was obtained from a private transport consultant (Computing in Transportation) who has advised the NSW Government on multi-modal transport network modeling. The whole network includes all arterial roads, bus, heavy rail, ferry, light rail, monorail, walking, transfer links and centroid connectors.

A travel impedance matrix records the average travel impedance, usually in the form of distance, time or cost, between each pair of origins and destinations. For the purpose of this analysis, either distance or time is used as a measure of travel impedance. In transport modeling exercises, the average travel distance or time between two different zones is usually measured by their shortest separation (minimum impedance) over the road or transport network. This is called the inter-zonal travel distance or time. Intra-zonal travel impedance is used when the journey-to-work travel occurs within a zone (i.e. the origin is the same as the destination).

The zone (SLA) centroids and the transport and road networks are required as input data for the calculation of the inter- and intra-zonal travel impedance. The SLA centroids are identified by using a geographical and demographic approach, which takes not only the geographical center, but also the demographic distribution of the population of a zone into consideration. The inter-zonal distance or time of a pair of origin and destination is taken as the shortest distance or time between the two centroids over the network. This is found by using the built-in program of the TransCAD modeling package. The package also performs calculations for the intra-zonal travel impedance. The intra-zonal travel impedance, representing local travel beginning and ending in the same zone, is determined according to the nearest neighbor zone theory. Adjusting the intra-zonal travel impedance to represent Sydney's condition, the closest 3 neighboring zones and a factor of 0.7 is applied in the TransCAD simulation process.

## 4. INDUSTRY STRATIFICATION – GRAVITY MODEL

Three different functional forms of the deterrence function – exponential, Tanner and gamma - are tested in the calibration of a fully-constrained gravity model:

$$\mathbf{T_{ij} = k_i k'_j P_i A_j f(d_{ij})} \qquad (1)$$

Where,

$\mathbf{k_i = \{1/\Sigma\, k'_j A_j f(d_{ij})\}}$ and $\mathbf{k'_j = \{1/\Sigma\, k_i P_i f(d_{ij})\}}$

$\mathbf{T_{ij}}$ = estimate of journey to work trips from zone i to zone j;

$\mathbf{P_i}$ = total number of residential workers produced by zone i;

$\mathbf{A_j}$ = total number of jobs in zone j; and

$\mathbf{d_{ij}}$ = over-the-road distance from zone i to zone j.

Their specifications are as follows;

Exponential Function: $\mathbf{f(d_{ij}) = exp(-\beta\, d_{ij})}$ (2)

Tanner Function: $\mathbf{f(d_{ij}) = d_{ij}\alpha exp(-\beta d_{ij})}$ (3)

Gamma Function: $\mathbf{f(d_{ij}) = \gamma d_{ij}\alpha exp(-\beta d_{ij})}$ (4)

Calibrations of an aggregate gravity model, a model stratified by manufacturing and non-manufacturing employment, and a four-grouping industrial stratified model were undertaken. The parameter results (for the two extreme ends: exponential and gamma functions) are shown in Table 2.

Table 2. Results of Model Calibration Parameters for Gravity Models

| Degree of Stratification | | Exp. | Gamma | | |
|---|---|---|---|---|---|
| | | beta | gamma | alpha | beta |
| 1 Group | Total | 0.1225 | 13931.4 | 1.2720 | 0.0722 |
| 2 Groups | Manufacturing | 0.1106 | 4205.0 | 0.9852 | 0.0718 |
| | Non-manufacturing | 0.1241 | 16531.1 | 1.2994 | 0.0732 |
| 4 Groups | Group 1<br>Finance and Insurance, Transport and Storage, Communication Services, Wholesale Trade | 0.1070 | 4044.6 | 0.7293 | 0.0887 |
| | Group 2<br>Manufacturing, Property and Business Services, Government Administration and Defence, Personal and Other Services | 0.1192 | 9582.4 | 1.0681 | 0.0799 |
| | Group 3<br>Accommodation, Cafes and Restaurants, Education, Health and Community Services, Cultural and Recreational Services, Non-classifiable Economic Units | 0.1343 | 23104.4 | 1.4525 | 0.0683 |
| | Group 4<br>Electricity, Gas and Water Supply, Construction, Retail Trade, Mining, Agriculture, Forestry and Fishing | 0.1356 | 27478.8 | 1.5975 | 0.0613 |

The values of the calibration parameters in Table 2 confirm that there are differences in travel patterns experienced by the different employment groups. Considering the calibration parameter (beta) of the exponential function, it can be seen that the parameter for the aggregate model is 0.123. By stratifying the trips into two groups, the manufacturing sector has a parameter of 0.111, much less than the parameter value in the aggregate model, and indicates that employment in the manufacturing sector generally has a longer trip length. On the other hand, the parameter value of 0.124 for the non-manufacturing sector has a shorter trip length characteristic. Further stratification into four groups of JTW trips provides a more detailed understanding of the general trip length patterns of the various employment categories and their role in the calibration process.

The aggregate intervening opportunity model is also tested with the calibration of the preference function which is a curve of the relationship between the proportion of travelers from a designated origin zone who reach their workplace destination zone, given that they have passed a certain proportion of total metropolitan jobs. Proportions of zonal totals and metropolitan totals are used for standardization purposes, rather than absolute numbers, to facilitate comparison of the shape of preference functions across origin zones within a city, across different cities, and within the same city over time. As defined here, the raw preference function is the inverse of Stouffer's intervening opportunities model (the l-factor). Only a provisional estimate for the 38 LGAs in the Sydney area was made drawing, for convenience, on the results already provided by Suthanaya (2002, Chapter 5, pp.231-282). The Suthanaya's research also examined the preference functions for different transportation modes over time based on some earlier census data. The formula for the calibrated preference function, based on the 46 SLAs, is recalculated as:

$$\mathbf{Y = -0.1984[-ln(X)] + 1.0176} \quad (5)$$

where
Y = cumulative proportion of total metropolitan jobs taken from an origin zone;
X = cumulative proportion of zonal jobs reached from each origin zone; and
the slope (-0.1984) and the intercept (1.0176) are the unweighted mean values of the 46 SLAs.

Using the above equation, the modeled total trips are 1,514,053 whereas the observed trips from the Census are 1,487,867, meaning that the modeled total number of trips is not constrained. Therefore, there is a model over-estimation. This may be resolved by using a weighted preference function for each zone, or by applying the zonal preference function for each of the 46 SLAs. This will be the next stage of the research, together with a further investigation of a stratified industry group intervening opportunities model.

## 5. MODEL EVALUATION

There are an array of suitable statistical measures to test model goodness-of-fit against survey O-D data that allow calibrated model specifications to be evaluated and the best model selected. For the purpose of this paper, a comparison of the trip length frequency distribution curves, mean trip length and the coefficient of determination ($R^2$) are used initially to test the model goodness-of-fit.

All models replicate the frequency distribution reasonably well for the median and longer trip lengths (30 plus km), but under-estimate the frequency of very short trips (0-10km) and over-estimate the frequency of short to median length trips (10-25km). In most cases, the stratified model of 4 employment groups tends to replicate the curve slightly better than the other models except for the 10-20 km trip length category. Mean trip length and coefficient of determination ($R^2$) statistics are shown in Table 3 for the various degree of trip stratification of the gravity model and for the aggregate intervening opportunities model. The table shows that there are marginal improvements in the model's predication power by using a stratified approach of JTW O-D trips.

Mean trip length and $R^2$ statistics are shown in Table 3 for the various degree of trip stratification. The table shows that there are marginal improvements in the gravity model's estimation power by using a stratified approach of JTW O-D trips.

Nevertheless, by examining the goodness-of-fit statistics alone, the inaccuracies of the various models are not revealed. By presenting a spatial interpretation of O-D trip patterns over the Sydney major road network using GIS, greater insights can be obtained. Analysis of residuals – the difference in a cell-by-cell comparison of the modeled and survey trip matrix – is performed and the residuals are assigned to the Sydney road network using an all-or-nothing assignment approach with the aid of the TransCAD software.

Table 3. Comparison of Census Data and Trip Distribution Models
- Mean Trip Length and $R^2$ Statistics

| Data and Model | Mean Trip Length (km) | $R^2$ |
|---|---|---|
| Census data | 17.49 | |
| 1 Group - aggregate GM | 18.29 | 0.86 |
| 2 Groups - GM stratification | 18.15 | 0.86 |
| 4 Groups - GM stratification | 17.51 | 0.89 |
| 1 Group - aggregate IOM | 20.60* | 0.91 |

Note: GM – gravity model; IOM – intervening opportunity model
*Based on an un-weighted preference function model

The spatial residuals errors obtained from the stratified gravity model (4 groups) and the aggregate gravity model are compared (Figures 3a – 3f). As shown in the figures, there are systematic errors remained in the process of trip distribution modeling using the gravity model. Under-estimations are found on many regional road networks within the Sydney Metropolitan Area. These networks include the Pacific Highway, Epping Road and M4/Parramatta Road/Victoria Road corridor. Over-estimations are found on the M5 corridor, and for some short trips in the Warringah region - north of the Sydney CBD. Over estimation also occurs around outlying centers, for example Gosford and Wyong at the northern edge of the Metropolitan area of Sydney, Blue Mountains and Penrith on the western edge, Liverpool and Campbelltown at the south-western edge, the Sutherland, Kogarah and Hurstville triangle to the south of the Sydney CBD.

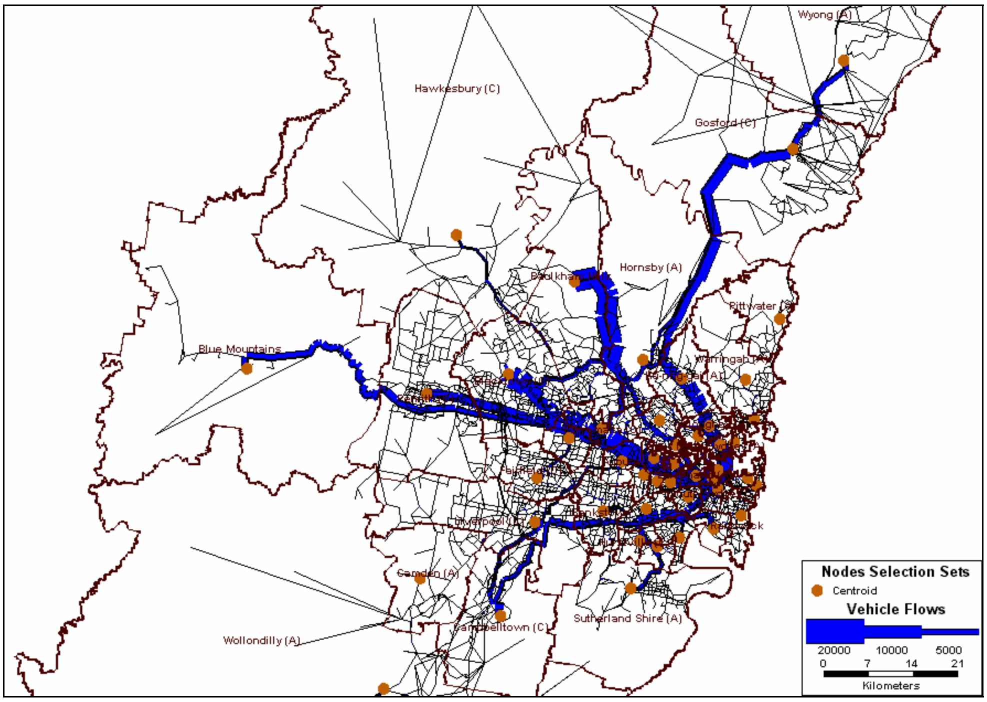


Figure 3a. Spatial Residual Errors – Aggregate Gravity Model - Underestimation

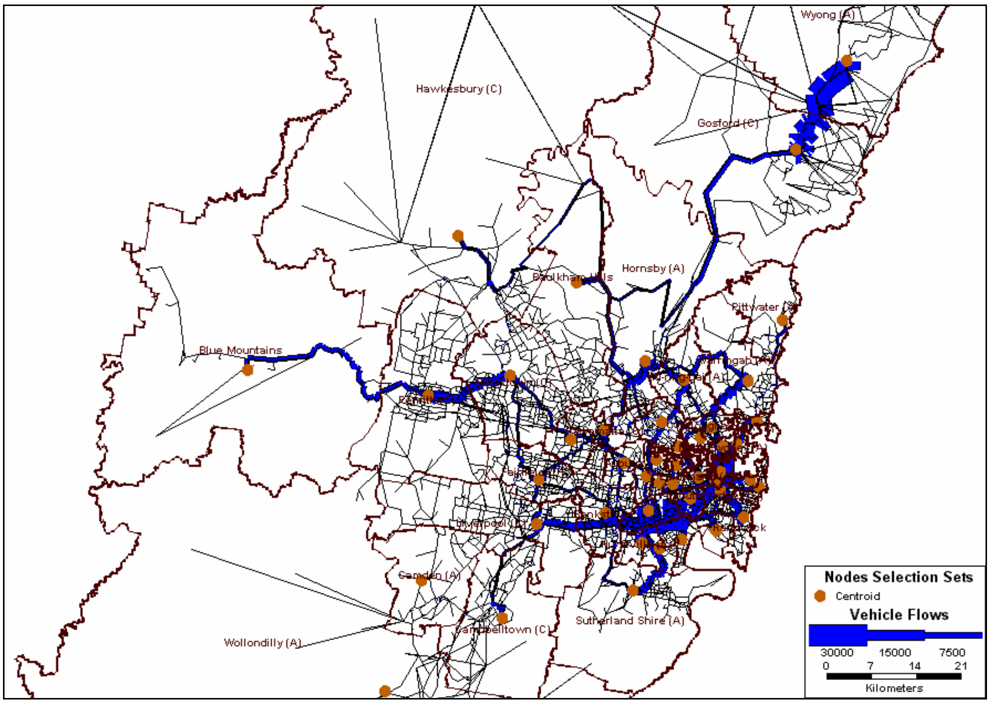


Figure 3b. Spatial Residual Errors – Aggregate Gravity Model – Overestimation

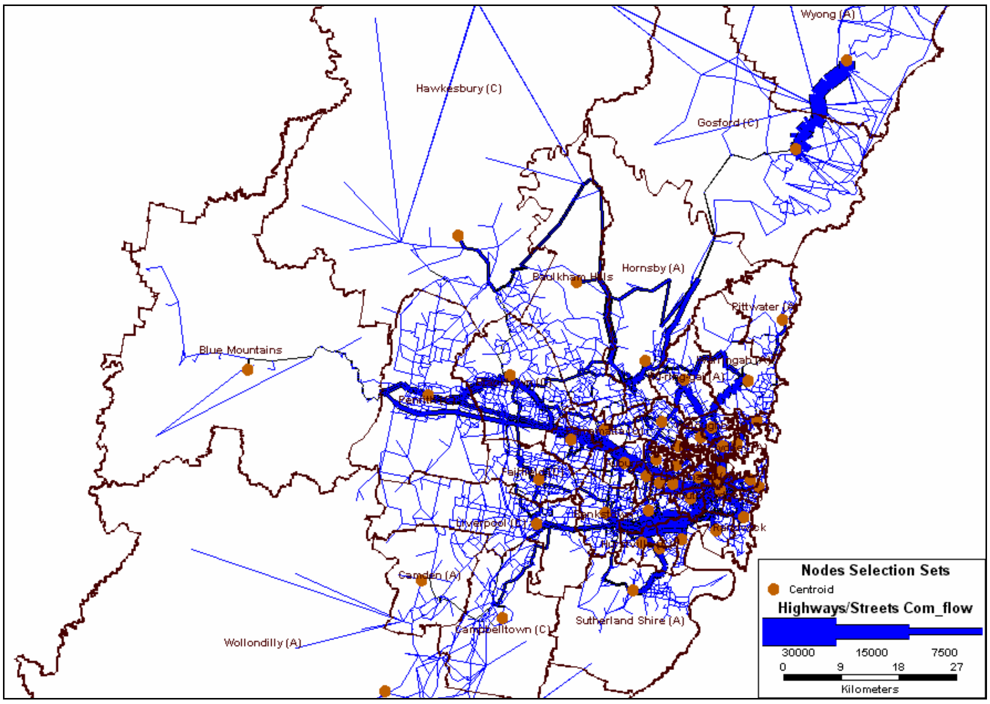


Figure 3c. Spatial Residual Errors – Aggregate Gravity Model – Combined Error

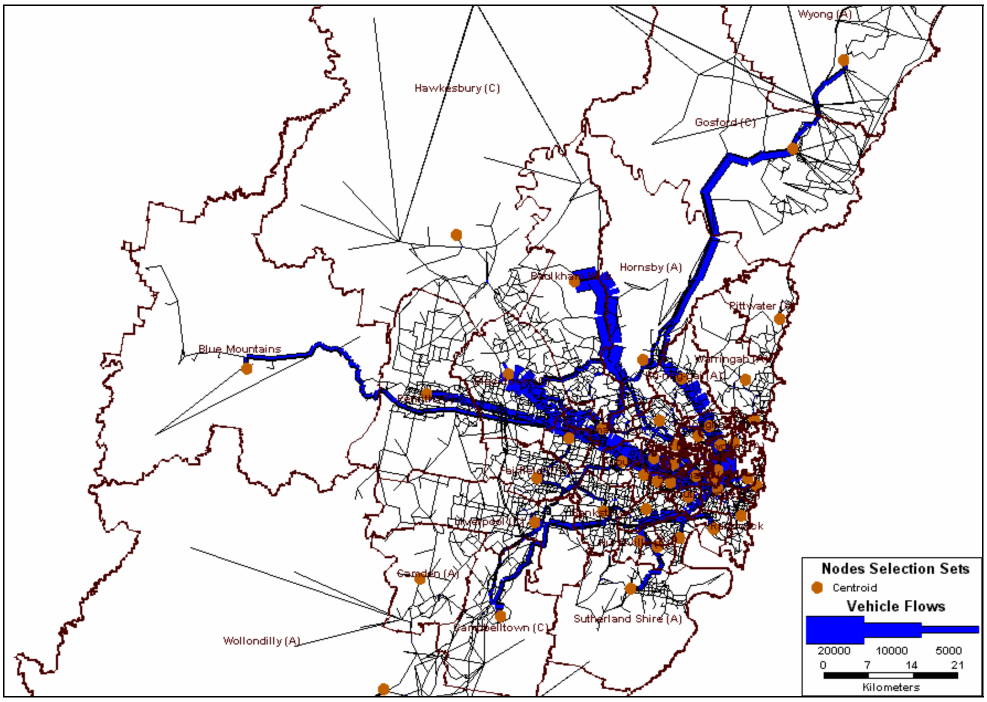


Figure 3d. Spatial Residual Errors – Stratified Gravity Model – Underestimation

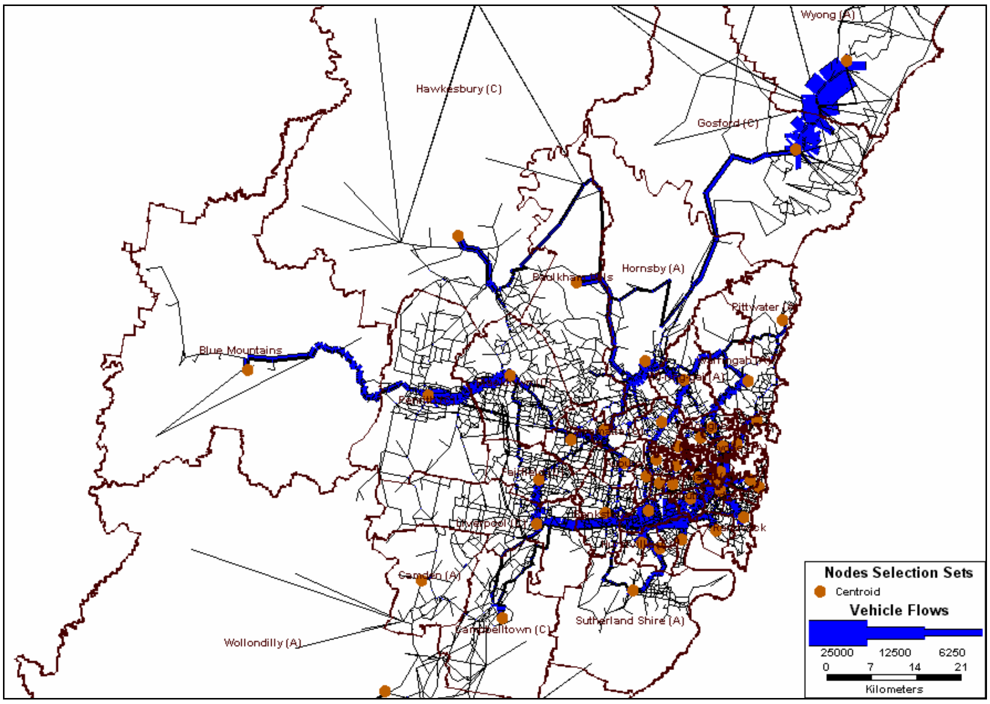


Figure 3e. Spatial Residual Errors – Stratified Gravity Model - Overestimation

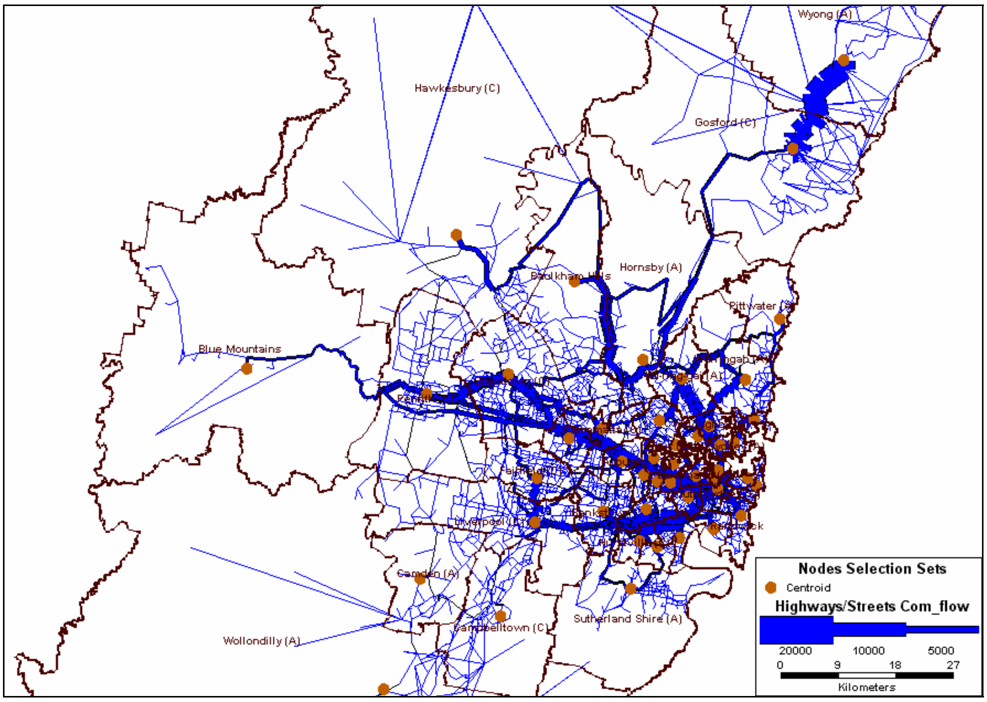


Figure 3f. Spatial Residual Errors – Stratified Gravity Model – Combined Error

Figures 4a and b illustrate the assignment of trip residual errors for the intervening opportunities model based on a global un-weighted preference function. The traffic assignments shown in Figure 4 are very different from the ones obtained using the gravity model – aggregate or stratified. The under-estimation of trips is found along the regional motorways/routes. The over-estimation of trips is found along other regional connections.

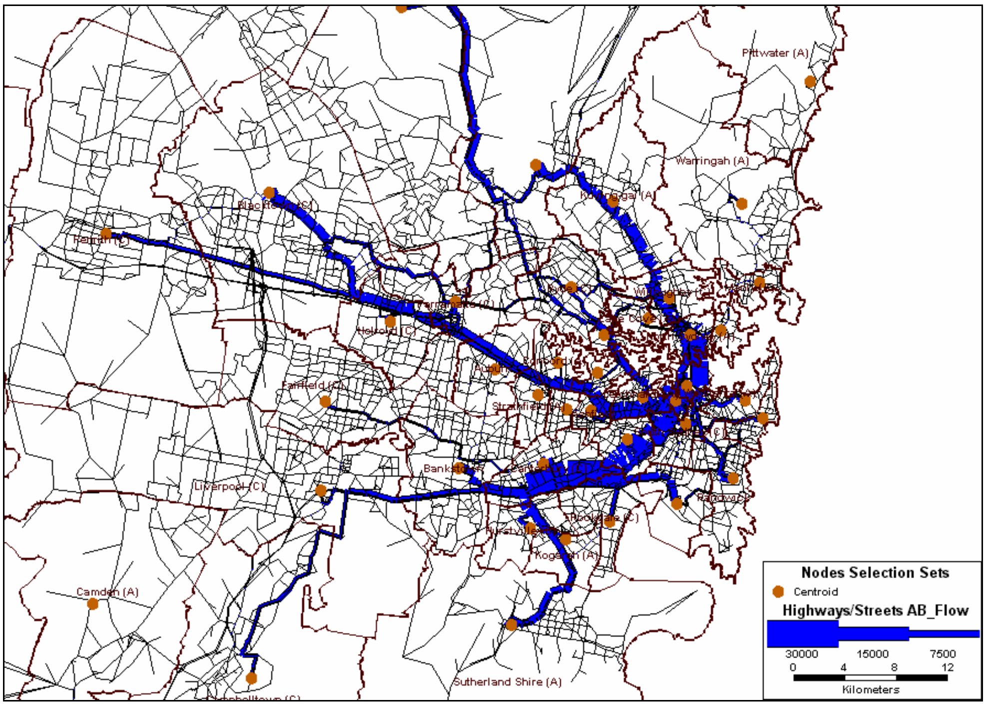


Figure 4a. Spatial Residual Errors – Intervening Opportunities Model - Underestimation

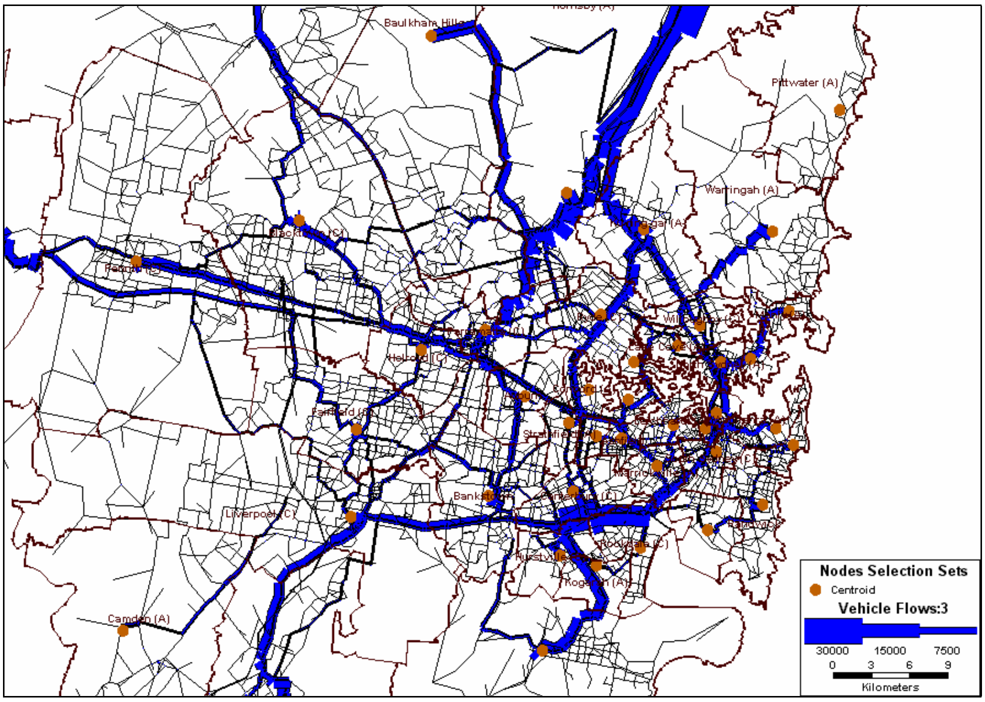


Figure 4b. Spatial Residual Errors – Intervening Opportunities Model - Overestimation

## 6. IMPLICATIONS FOR POLICY

A research and development program by government transport agencies in Sydney into suitable trip distribution models for strategic land-use and transportation planning is needed. The gravity model is part of the modeling suite developed by the NSW Department of Transport (now Transport Coordination Agency within the Department of Planning) and used by government transport agencies and their consultants for strategic planning. The current version stratifies the journey-to-work by manufacturing and non-manufacturing employment, and only incorporates the commuter and non-commuter trips. The NSW government is currently implementing the Stage 2 of the Sydney Strategic Transport Model. This version will incorporate additional trip purposes. Stage 2 will split the non-commuter component but does not address the commuting component despite the dominance of peak-hour analyses in many transport studies. The rolling Household Travel Survey will provide data for this part of the model.

Attention must be also given to changes in urban labor markets, as recognized in the more recent studies undertaken by the Greater Western Sydney Economic Development Broad (2003) and Greater Western Sydney Regional Planning Futures Project (2003). As Sydney's employment structure has been undergoing a significant change for the last two decades, evidenced by an 88 percent increase in financial, property and business services between 1981 and 1996; and an 30 percent reduction in manufacturing in the same period; as well as recognized increase in part-time and casual jobs and the number of women in the workforce, the traditional stratification approach (manufacturing and non-manufacturing) in trip distribution modeling is doubt to produce accurate modeling outputs for policy appraisal and decision making.

Whilst system analysis emphasizes the importance of testing the validity of models, in practice, this task has been performed somewhat superficially, at least in Sydney. As noted by Lewandowski (1982, p. 2):

> *"It is commonly agreed ... that model validation is one of the most important stages in the model building process", yet, "the number of papers dealing with methods of model validation is also rather limited".*

Advances in the speed of computing processing and the availability of Geographical Information System (GIS) software - together with the availability of data in electronic format for different years (in the case of Census data for sometimes over decades) - allow a rigorous analysis of the quality of transportation models and their predictions to be examined in a way not previously feasible. Furthermore, the ability to manipulate and disaggregate large databases, such as the Census of Population and Housing JTW tabulations, on the modern personal computer (PC), allows researchers to re-examine the structure models to develop alternative and more accurate model structures for prediction purposes.

Intuitively, the gravity approach appeals for smaller cities with a "simple" transport infrastructure. It is possible that in large cities – both in terms of population and geographical area – with "complex" transport infrastructure, research should be directed to developing the mathematical models for multiple "centers of economic gravity". For example in Sydney, the second CBD is given as the Parramatta CBD (30km west of Sydney CBD). Some local planners think that Liverpool (45km south-west of Sydney CBD) will become the third CBD. However, Hurstville (25km south of Sydney CBD), Strathfield (20km west of Sydney CBD) and Chatswood (15km north of Sydney CBD) are already large centers of economic activity. They might be modeled on a sub-regional basis.

However, there are practical resource constraints that limit the adoption of innovations by government agencies. As computer technology improves its performance, the models are becoming more complex. Tests using Stage 2 of the model by the NSW Department of Transport indicate that a model run takes 32 hours. Stratification followed by re-aggregation would lengthen the computational effort. There is a list of improvements already agreed to by the transport agencies on further developments of the model and budgets allocated. It will obviously be some time before the type of research work reported in this paper can be incorporated into an operational model for Sydney.

In practice, the under/over estimation can be of concern. In Sydney, much of the modeling is done for the 2-hour AM peak. The reason behind this practical consideration is that for the public transport travel component, many commuting trips would not be completed if a 1-hour model is used. The "sanity check" generally applied to most modeling work in Sydney is that if the assigned flows are close enough to the traffic counts, the trip matrix must have been correctly specified. The fact that there is compensation of errors (from the under-estimated short trips and over-estimated short-to-medium trips) is of little importance to the validation process. However, the implication for toll road modeling is more serious – it is the short trips that are likely to avoid the toll road, and this research has shown that in certain corridors, these trips are under-estimated.

The greatest practical implications of our findings of systematic bias in the trip distribution model outputs relate to the investors of private-sector transport infrastructure. Risk analysis is a routine part of assessing the commercial viability of a proposal and most bankers would agree that traffic risk is the most important of all risk categories when formulating a venture. Accurate traffic predictions are essential in the calculation of toll tariffs and in the revenue expected from the tolls. When the private sector issues prospectus to attract investors, a financial rate of return is quoted that is underpinned by traffic levels and toll structures. This opens up the possibility of litigation, especially from sections of the community opposed to toll way development. Our research highlights the worrying finding that the gravity model, in one of the corridors in the Sydney metropolitan region – the M5 in the southwest of the city – consistently over-estimates traffic flow where a toll-way has recently opened for business and the toll revenue has been initially below the expectations implicit in the demand forecasts.

## 7. CONCLUSIONS

Whereas the limited computing hardware and software technologies of the 1960s and 1970s may have provided an excuse for the limited testing of alternative model structures and their levels of accuracy by practitioners, advances have removed many constraints. Urban transportation practice, at least in Australia, continues to use conventional four-step models albeit with a GIS mapping capability for network visualizations and environmental impacts. There is an array of suitable statistical measures, for example, to test the gravity model goodness-of-fit against survey O-D data that allow calibrated model specifications to be evaluated. The best model is usually selected based on the goodness-of-fit statistics. Alternative model specifications can be generated by the degree of stratification of the trips; constraints on trip-ends (unconstrained, production or attraction constrained, and fully constrained); different measures of transport impedance (distance; time and generalized cost); and the functional form of the deterrence function (power, exponential, tanner and gamma).

The research framework presented in this paper aims to compare and contrast different spatial interaction models and their levels in accuracy for forecasting VKT – an important performance indicator for sustainable urban transportation. From the assessment of the trip distribution models for journey-to-work travel in the Sydney metropolitan region – both of the gravity model and the intervening opportunity type – it is clear that systematic spatial (and network) bias occurs (see, Figures 3 and 4) and that new predictive models are required for use by practitioners. The lack of the degree of stratification in employment categories for the preparation of trip O-D matrices can be seen from the operation of the current Sydney Land-use Model (SLM) and the Sydney Strategic Travel Model (STM).

Our stratified model for the Greater Sydney Metropolitan Region, with groups of industry and occupation categories of similar trip-length characteristics calibrated separately and then re-aggregated, reduces to a small degree systematic bias but does not eliminate it. The intervening opportunity model in its aggregate form provides a slightly better output than stratified gravity models despite limitations with the un-weighted global preference function. Spatial modeling with zone-specific preference functions should eliminate this and it will be interesting to see whether the systematic bias is removed. Further research is planned by our research team to calibrate new model structures on the 1996 data – especially an intervening opportunities model with zonal preference functions and one with stratification by industry or occupation groups – that we believe will result in more accurate model forecasts. All models calibrated on 1996 data will be validated as forecasting models using the 2001 Journey to Work Census data released to the public in early 2003. Similar work is planned using Census data for other Australian cities, and a new research project has recently commenced that aims to formulate spatially-partitioned gravity models for different regions of the metropolitan area.

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