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*Urban Stud* 2002; 39; 131

DOI: 10.1080/00420980220099113

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# Excess Commuting and the Modifiable Areal Unit Problem

Mark W. Horner and Alan T. Murray

[Paper first received, March 2001; in final form, May 2001]

**Summary.** Excess commuting has emerged during the past two decades as an important construct for evaluating the spatial relationships between employment and residential locations. During this time-period, there has been an on-going debate regarding how one should measure excess commuting in urban regions. This paper contributes to the debate by focusing on the spatial issues inherent in excess commuting evaluation. We demonstrate how scale and unit definition (the modifiable areal unit problem) are manifested in the assessment of excess commuting, both in theoretical and empirical terms. To this end, a geographical information systems-based analysis is presented which explores spatial sensitivities in the excess commuting measure. Our results show that aggregation and spatial unit definition may have profound impacts on the estimation of excess commuting. This work provides a formal resolution to much of the recent debate regarding estimates of excess commuting in urban regions.

## 1. Introduction and Purpose

The deviation of an urban area's observed journey-to-work average trip length from a theoretical minimal average commute has been the subject of much empirical investigation in the literature (Frost *et al.*, 1998). This deviation is known as wasteful or excess commuting. Excess commuting is the non-optimal work travel undertaken as a result of a given spatial configuration of residences and workplaces defining urban form (Hamilton, 1982; White, 1988; Small and Song, 1992; Giuliano and Small, 1993). Mathematically, excess commuting is the difference between the actual observed average commute and the theoretical minimum average commute resulting from reassigning workers

to new residences in order to reduce total commuting costs to a minimum (Scott *et al.*, 1997). This difference is typically expressed as a percentage of the actual commute.

Consider the following notation:  $E$  = excess commuting;  $T_a$  = observed average commute; and  $T_r$  = theoretical minimum average commute. Excess commuting may be defined as follows

$$E = \left( \frac{T_a - T_r}{T_a} \right) * 100 \quad (1)$$

Excess commuting,  $E$ , is simply the ratio of the difference between the observed average commute,  $T_a$ , and theoretical minimum commute,  $T_r$ , over the observed commute, ex-

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pressed as a percentage. Given that  $T_r$  is the single unknown in equation (1), a major question in the literature has been how it may be estimated. The linear optimisation model known as the transportation problem, first specified by Hitchcock (1941), has been proposed as one method for calculating  $T_r$  (White, 1988). The transportation problem identifies the optimal flow pattern between origins and destinations minimising system travel costs (Taaffe *et al.*, 1996). The other principal method of estimating  $T_r$  is by using monocentric-model-based approaches (Hamilton, 1982). The rationale for using the transportation problem is provided by White (1988), and was later corroborated by Small and Song (1992) who argue that the theoretical minimum commute,  $T_r$ , found using the transportation problem approach is appropriate for assessing whether a city's observed commuting is truly excessive. This is because the transport problem uses an actual spatial representation of urban structure as opposed to monocentric-model-based approaches that do not explicitly take residential and workplace locations into account.

Areal units known as traffic analysis zones (TAZs) often are used as origins and destinations in transportation problem-based excess commuting assessment. In fact, TAZs are the fundamental unit of analysis in most transport studies. The sizes of these zones vary among metropolitan areas, but generally, TAZs are sized similarly to census tracts or block groups. It is noteworthy that more aggregate areal unit systems have been used in transportation problem-based excess commuting assessment (White, 1988; Hamilton, 1989; Small and Song, 1992; Merriman *et al.*, 1995). Interestingly, variations in the scale of analysis across different studies of different cities have produced quite divergent assessments of excess commuting. This suggests that the scale of the spatial data used in the analysis and other geographical unit definition issues are important when evaluating excess commuting.

The literature to date has failed to address fully the spatial uncertainties in estimating excess commuting. While the issue of scale

is alluded to in the literature as a concern regarding the application of the transportation problem for measuring excess commuting (Hamilton, 1989; Giuliano and Small, 1993; Merriman *et al.*, 1995; Frost *et al.*, 1998), relatively little has been done to provide a theoretical explanation of spatial influences on excess commuting. Our research fills this gap by discussing how the spatial data characteristics emanating from the modifiable areal unit problem may affect estimates of excess commuting.

We address the modifiable areal unit problem in excess commuting assessment in the following order. First, we begin with a review of the excess commuting literature. In our review, we explain the basic concept of excess commuting, then introduce the spatial issues pertinent to excess commuting assessment related to scale and area unit definition. Following this background information, we detail the basic spatial assumptions of the excess commuting measure, particularly scale and the representation of travel between zones. Next, the effects of scale and unit definition on measuring excess commuting are demonstrated through a geographical information systems (GIS) based simulation for the Boise, ID, metropolitan area. Finally, a discussion and conclusions are provided.

## 2. Basic Concepts

### 2.1 Excess Commuting

The concept of excess commuting emerged from the urban economics literature during the early 1980s as a measure of model fit (Hamilton, 1982). Based on the work of Alonso (1964), a variant of the urban monocentric model was used by Hamilton (1982) to measure commuting. This approach assumes that employment is mostly concentrated in the CBD and residential location is a function of consumers' trade-off between housing and commuting costs. Later work adapted the transportation problem as a more theoretically consistent measurement of excess commuting because it focuses on households and jobs in terms of their actual spatial

locations (White, 1988). The formulation of the transportation problem for estimating the minimal average commute is as follows

Minimise:

$$T_r = \frac{1}{W} \sum_{i=1}^n \sum_{j=1}^m C_{ij} x_{ij} \quad (2)$$

Subject to:

$$\sum_{i=1}^n x_{ij} = D_j \quad \forall j = 1, \dots, m \quad (3)$$

$$\sum_{j=1}^m x_{ij} = O_i \quad \forall i = 1, \dots, n \quad (4)$$

$$x_{ij} \geq 0 \quad \forall i, j \quad (5)$$

where,  $n$  = number of origin TAZ locations;  $m$  = number of destination TAZ locations;  $O_i$  = number of workers living in zone  $i$ ;  $D_j$  = total employment in zone  $j$ ;  $C_{ij}$  = travel costs between zone  $i$  and zone  $j$ ;  $W$  = total number of commuters; and  $x_{ij}$  = journey-to-work trips from zone  $i$  to zone  $j$ .

The objective function (2) minimises average travel costs. Constraint (3) ensures that no employment demand is left unfulfilled, while constraint (4) limits the supply of workers to the number residing in each zone. Constraint (5) restricts the decision variables to non-negative values. Note that the number of origins,  $n$ , and the number of destinations,  $m$ , are typically the same.

An important component of this approach is the travel cost,  $C_{ij}$ , associated with travel time or travel distance between zone centroids, according to the road network (Giuliano and Small, 1993) or straight-line (Euclidean) distances (Frost *et al.*, 1998). White's (1988) adaptation of the transportation model for use in studying excess commuting raises numerous spatial issues about its application, including scale, areal unit definition and the interpretation of  $C_{ij}$ . Furthermore, there is some ambiguity in the literature as to how travel costs can or should be represented. This is a concern because travel costs are central to the measurement of excess commuting.

## 2.2 The Modifiable Areal Unit Problem

The modifiable areal unit problem (MAUP)

has been an active area of research within geography and spatial analysis over the past few decades (Fotheringham and Wong, 1991; Miller, 1999). The MAUP is associated with the practical reality that, in a digital environment, a region may be spatially defined in different ways (Bailey and Gatrell, 1995). One facet of the MAUP is scale of analysis and the other is unit definition.

When aggregating areal units, perhaps from blocks to census tracts, the scale of analysis changes. Aggregation results in simply fewer, coarser areal units. On the other hand, changes in unit definition involve the many possible alternative zoning schemes for some fixed number of units to be delineated. For example, if we were given the task to divide an area into 100 area units, there is literally an infinite number of ways this could be performed. Both of these aspects of the MAUP have implications for spatial analysis because Openshaw and Taylor (1981), among others, showed empirically that changes in scale or unit definition altered findings in quantitative measures and statistical tests. However, not all spatial models have been found to be sensitive to MAUP effects (Murray and Gottsegen, 1997). For these reasons, the MAUP continues to attract much interest with the advent of new analytical tools such as GIS for studying spatial problems (Miller, 1999).

Techniques sensitive to scale effects produce different results when the input data are (dis)aggregated (Openshaw and Taylor, 1981). As the level of aggregation varies, the results of a technique sensitive to scale effects are likely to change. Similarly, techniques sensitive to unit definition or the zoning effect produce different results when the boundaries of the areal units on which they are performed change (Fotheringham and Wong, 1991). To illustrate the point, if we return to our area of 100 zones, a technique sensitive to the zoning effect would be likely to produce different results for different zoning configurations. Moreover, the scale effect and zoning effect are related in the sense that zoning systems are rarely constructed in a manner consistent with the phe-

nomena being studied (Openshaw and Taylor, 1981). If a zoning system were to be constructed consistent with the phenomena of study, one would not only need to know the appropriate number of zones (scale issue), but also their appropriate arrangement (zoning issue) (Openshaw and Taylor, 1981). So, unless there are 'natural' spatial units for studying excess commuting, one must be cognisant of MAUP issues and their potential effects. Given that the transportation problem is used to measure excess commuting, the issues of scale and zoning need to be explored in order to assess their impacts because spatial information is utilised and MAUP issues are known to be a concern in geographical analyses.

### 2.3 Evidence of the MAUP in Excess Commuting

Previous work on excess commuting may be characterised as a debate over methodological and data issues, particularly the question of spatial unit definition. It is interesting that these issues are well studied in the spatial analysis literature related to the MAUP, yet excess commuting work has not been placed in this context.

Arguably, evidence of MAUP effects in measuring excess commuting first appeared when White (1988) formulated  $T_r$  as a transport problem dependent on areal data. In White's (1988) analysis, the observational units were census jurisdictions. Jurisdictions are much more aggregate, or many times larger, than the census tract or TAZ. For the sample of cities White (1988) examined, no city contained more than 32 jurisdictional units, whereas a city divided at the TAZ level typically consists of several hundred units (Small and Song, 1992). White (1988) reported that 11 per cent of commuting was wasteful on average for a sample of cities. This is far less than what would have been expected given Hamilton's (1982) previous research, which found an average of 87 per cent excess commuting for a sample of cities. These differing findings largely motivated the subsequent work and debate appearing on

excess commuting (Hamilton, 1989; Cropper and Gordon, 1991; Small and Song, 1992; Merriman *et al.*, 1995; Frost *et al.*, 1998). The large observational (areal) units utilised by White (1988) effectively bias  $T_r$  upwards since larger units lead to more intrazonal travel (Hamilton, 1989). Large shares of intrazonal travel have the net effect of making an urban area's excess commuting appear minimal.

A more precise way to state this observation is as follows. Assuming an equal number of origin and destination zones, excess commuting tends to zero as the number of zones in the study area,  $n$ , approaches one. This is due to the idea that the minimum commute,  $T_r$ , approaches the observed average commute,  $T_a$ , as the number of zones decreases (as aggregation occurs). There is a decreasing likelihood that travel will be assigned outside a zone as the zone increases in size (as greater aggregation is performed). Hence,  $T_r$  converges to the regional average  $T_a$ . Mathematically, this relationship may be stated as

$$\lim_{n \rightarrow 1} E = 0 \quad (6)$$

The implication of equation (6) is that  $T_r \rightarrow T_a$  as  $n \rightarrow 1$ . Equation (6) illustrates the scale effect inherent in the excess commuting measurement. The increased partitioning of zones has a direct effect on the likelihood that a commute is assigned outside a zone. Such assignments reflect excess commuting by definition.

Small and Song (1992) demonstrate the scale effect posited in equation (6) in an empirical context. They applied the transportation problem-based measure of excess commuting in Los Angeles using TAZ-based journey-to-work flows combined in two different vertical aggregations. Small and Song (1992) found that using small numbers of zones (larger areal units) understates excess commuting. Their findings confirm Hamilton's (1989) criticisms of White's (1988) study and are consistent with our theoretical assessment of scale variation and its effects on the estimate of excess commuting. More

recently, Merriman *et al.* (1995) utilised the transportation problem-based measure of excess commuting in a study of Tokyo and found significantly less excess commuting than was reported in Small and Song (1992). They also performed their analyses on areal unit data at multiple aggregations, but they observed that the level of excess commuting was relatively stable across the different scales of analysis. Thus, they conjecture that aggregation does not affect analytical results. The 211 units utilised in their work appear to be very aggregate already, particularly when one compares them with the TAZ data used in Small and Song (1992). As Merriman *et al.* (1995) aggregate the 211 units, they do not observe drastic changes in excess commuting levels, although their estimate of  $T_r$  does approach  $T_a$  at the more aggregate scales. This leads one to question whether their spatial units were too aggregate to begin with. Given the significance of the excess commuting measure as an indicator of urban form, this discrepancy is problematic. Clearly, further investigation is warranted to determine how space may impact the estimate of excess commuting.

*Estimations of travel costs.* One need look no further than the issue of travel costs to understand how the modifiable areal unit problem manifests itself in excess commuting analyses. Unless reasonable estimations of travel costs are used to measure excess commuting, the analysis is essentially flawed. Intuitively, as scales and zoning schemes change for a given set of areal units, the travel costs between units must change as well. Thus, care must be taken to remove as much spatial bias as possible by ensuring that the zonal cost structure used is the most appropriate representation.

There are a number of technical issues associated with both interzonal,  $C_{ij}$ , and intrazonal,  $C_{ii}$ , travel costs that need to be clarified before empirical work may be undertaken. Interpretation and implementation of the metrics for measuring excess commuting vary throughout the literature (Hamilton, 1989; Small and Song, 1992; Frost *et al.*,

1998). Travel costs,  $C_{ij}$ , are typically expressed as the travel time or travel distance between zone centroids according to an actual road network or straight-line distances. Two relevant issues to the MAUP and excess commuting need to be addressed. One issue is how time or distance may represent travel costs. Embedded in this discussion is a second issue associated with how intrazonal costs,  $C_{ii}$ , should be defined and how these costs may affect the estimation of excess commuting.

Both road networks (Giuliano and Small, 1993) and Euclidean metrics (Hamilton, 1982; Frost *et al.*, 1998) are commonly used to calculate interzonal and intrazonal distances,  $C_{ij}$  and  $C_{ii}$ , respectively. The measurement of  $C_{ij}$  is straightforward using either the network or the Euclidean metric, assuming that travel begins and ends at the zone centroid. Alternatively, determining  $C_{ii}$  is not as easy as it might seem because, in the strictest sense, when we assume travel begins and ends at the centroid, this implies  $C_{ii} = 0$ , (no intrazonal travel cost). Obviously, all travellers must contribute something to  $T_r$ , even if they are assigned to their zone of residence. Thus, when network lengths are used to measure excess commuting, the elements of  $C_{ii}$  are set equal to the individual zone's average trip length, as was done in Small and Song (1992). When using Euclidean distance, one might assume each zone is circular, take its total area and then work backwards to deduce a radius corresponding to the average intrazonal trip length (Frost *et al.*, 1998). This method of  $C_{ii}$  estimation, using Euclidean distance and the circle deduction, is most appropriate for very disaggregate zoning schemes. For more aggregate zoning systems, this method would provide a less accurate assessment of  $C_{ii}$  as there would be too much intrazonal geographical variation for the geometric estimate to be meaningful.

Euclidean measures are not appropriate for calculating travel times, as they are obviously suited to geometric (length) measurement, so both  $C_{ij}$  and  $C_{ii}$  must be network-based measures of impedances if

travel times are to be used. Interpreting  $C_{ij}$  as travel time may be strictly the travel time to work (Small and Song, 1992) or it may also take into account other time-consuming activities occurring at either end of the work trip, such as walking to the car, parking the car, etc. (Merriman *et al.*, 1995). Considering travel time,  $C_{ii}$  typically is the reported average travel time within the zone. For zoning systems consisting of very small areas, usage of the average intrazonal travel time as  $C_{ii}$  is appropriate, keeping in mind that in doing so there is an implicit assumption that  $C_{ii}$  is internally optimised, as suggested by Hamilton (1989). As we use more aggregate data, the assumption of  $C_{ii}$  being accurate becomes increasingly fallacious (Hamilton, 1989). Hence, the clear message is that aggregation, in terms of the MAUP, affects the true representations of travel times in excess commuting (and Euclidean distance as pointed out earlier). Again, we note that since travel costs are *the* fundamental assessment of commuting duration, it is essential that they be measured correctly.

In summary, this section has presented several methodological inconsistencies in the excess commuting literature. It has been shown theoretically that the MAUP will be likely to impact measures of excess commuting. Particular emphasis has been placed on understanding how zonal travel costs are potentially affected by the MAUP. The next section demonstrates these effects in an empirical context.

### 3. Empirical Study

It has been suggested that aggregation bias may affect measures of excess commuting. However, these effects have not been empirically explored in a controlled environment. Small and Song's (1992) illustration of aggregation bias only partially analysed the problem since too few tests were conducted. Today, advances in GIS technology allow for a more comprehensive exploration of MAUP effects in excess commuting estimates.

Boise, Idaho, is utilised as the study area in our analysis. It is a smaller urban area with

a population of about 206 000 and approximately 87 000 workers (1990 estimates). In our analysis, we do not differentiate among worker types; rather, we consider all workers to be interchangeable as did White (1988), Hamilton (1989), Merriman *et al.* (1995) and Frost *et al.* (1998) among others. Boise is divided into 286 TAZs which are quite disaggregate in terms of their size. To place their size in context, Boise's TAZ areas average 3.68 square miles, whereas Merriman *et al.*'s (1995) Tokyo zones average about 15.4 square miles.

Using GIS, our 286 zones are systematically aggregated and used to estimate excess commuting. The aggregation procedure used here is the Theissen region approach that has appeared in other research (Fotheringham and Wong, 1991; Murray and Gottsegen, 1997). This approach randomly selects a user-specified number of seed units and creates Theissen polygons (or Voronoi diagrams) around them. Zones are then merged with their closest seed zone. When two or more zones are combined in the procedure, their workers, employment and land area are summed such that any zone coverage produced by the aggregation procedure has equivalent attributes as the original coverage of 286 zones. Travel costs are taken to be the straight-line (Euclidean) distances between zone centroids. Intrazone commutes,  $C_{ii}$ , are estimated similar to the method used by Frost *et al.* (1998), where  $C_{ii}$  is taken to be the radius of a circle having an area equal to that of the zonal area.

In our analysis, 100 unique zonal representations are created for a range of zonal aggregation levels,  $n$ . Specifically, aggregations of the original 286 Boise zones ( $n=286$ ) are generated for  $n=275$  down to  $n=25$ , in increments of 25 zones. To place our input data in context, combinations of zones greater than 200 are generally analogous to many cities' TAZ geography in terms of average area size, whereas aggregations with fewer units (less than 50) correspond to coarser aggregations appearing in the literature, such as those by White (1988) and Merriman *et al.* (1995). Consistent with our

prevailing argument, we would hypothesise that increasing the level of aggregation (reducing the number of zones) *decreases* the chances of finding excess commuting.

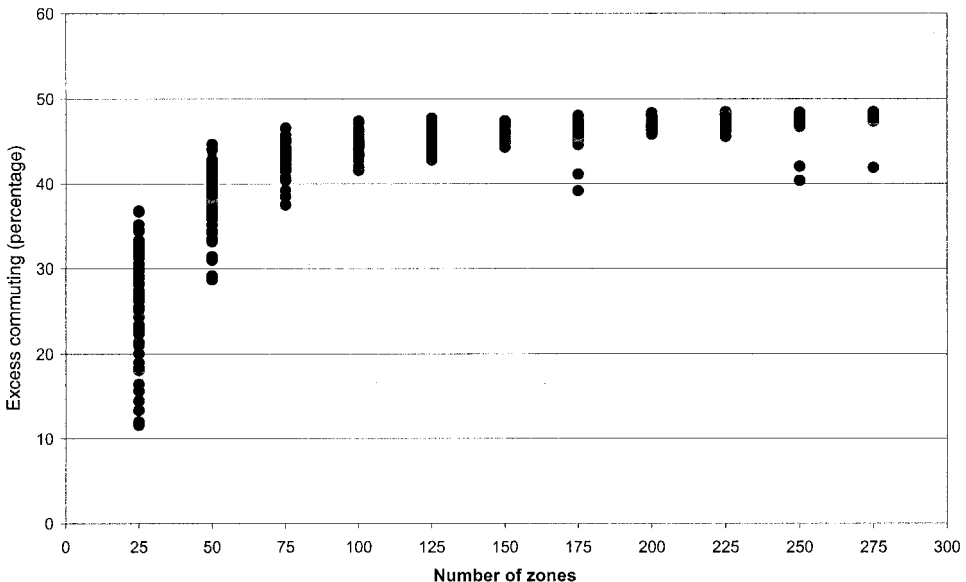
We used ArcView 3.2, a commercial GIS package operating on a Pentium III-733 mhz (under Windows NT 4.0) to perform the manipulation and aggregation of the Boise TAZ data. The Theissen aggregation approach was implemented using an Avenue script in ArcView. Solutions to the transportation problems for measuring excess commuting were found using a transportation simplex routine coded in Visual Fortran (version 6.1), accessed as a dynamic link library (DLL) from ArcView via an Avenue script. In terms of computational effort, the transportation problem based on the most disaggregate case ( $n=286$ ) solved in approximately 128 seconds, whereas transportation problems based on the most aggregate cases ( $n=25$ ) solved in less than 0.01 seconds.

Excess commuting,  $E$ , is 48.07 per cent using Boise's disaggregate zones ( $n=286$ ). For the aggregation instances of Boise, the empirical results are displayed in Figure 1 at the varying levels of scale. Within each scale specification, the results indicate estimated excess commuting for the 100 different unit

specifications. For example, the solutions of the 100 problems for  $n=175$  are shown in Figure 1 to have levels of excess commuting ranging from a low of 39.16 per cent to a high of 48.03 per cent. The average value of excess commuting for  $n=175$  is approximately 46.51 per cent.

The results in Figure 1 show that aggregation does affect the estimate of excess commuting, with the most profound bias occurring for  $n < 100$ . As  $n$  decreases, the realities of the urban area are not captured by the zoning scheme; the units are simply too aggregate to yield meaningful results. In the most aggregate case of  $n=25$ , the average estimate of excess commuting for the 100 different zoning configurations is 26.21 per cent—far less than the disaggregate estimate of 48.07 per cent. When one moves up in scale from  $n=275$  to  $n=25$ , one notices that the average excess commuting estimate is clearly decreasing at an increasing rate. Overall, these findings are in agreement with equation (6), indicating that excess commuting approaches zero at more aggregate scales.

The results in Figure 1 also show that the zoning system used affects the estimation of excess commuting. Fixing the number of



**Figure 1.** Excess commuting estimates for different scale and unit definition instances in Boise, ID.



zones,  $n$ , and allowing their configurations to vary (100 times), the results in Figure 1 show that there is a range of possible excess commuting estimates. This variation is associated with the fact that there are 100 possible realisations in our experiment. At the most disaggregate case, ( $n = 275$ ), there is about a 10 per cent spread in the range of excess commuting estimates. As aggregation occurs, or the number of zones decreases, the range in the excess commuting estimates becomes much larger. This suggests that the zoning configuration produces more instability in the excess commuting estimate at more aggregate scales. Once the most aggregate set of units,  $n = 25$ , is reached, we find an unacceptable range in the percentages of excess commuting estimates (from a low of 11.6 per cent excess commuting to a high of 37.13 per cent excess commuting). Clearly, our analysis shows that there is much uncertainty in the estimation of excess commuting at more aggregate scales due to the simultaneous effects of scale and unit definition.

#### 4. Discussion and Conclusions

We have shown, through a careful review of the literature and empirical work in Boise, ID, how much of the debate regarding excess commuting to date revolves around issues of scale and unit definition. Understanding the modifiable areal unit problem (MAUP) and its effects on elements of the excess commuting measure is critical if excess commuting are to be measured correctly. If zonal data are to be used, they should be as disaggregate as possible. This finding clarifies much of the uncertainty and debate in the excess commuting literature.

Unfortunately, it may not be sufficient simply to acknowledge the existence of MAUP effects in an analytical context without attempting to resolve the situation. Tobler (1989) notes that the results of analysis using geographical data should not be dependent on the areal units used. Tobler posits that analyses should be frame-independent, meaning results should not depend on the level of spatial resolution or zone definition. How-

ever, true frame-independence from MAUP effects is only achieved when using individual-level data. We suggest that future research in excess commuting might look to incorporate individual-level data into its analyses (see Cropper and Gordon, 1991, for an example).

It should also be reiterated that our analysis did not address the issue of jobs/housing heterogeneity (see Giuliano and Small, 1993). Introducing heterogeneity among worker types would impart an additional element of uncertainty in a controlled excess commuting experiment such as the one we have demonstrated. We simply address the spatial sensitivities of the original conception of excess commuting (see White, 1988; Hamilton, 1989; Merriman *et al.*, 1995; and Frost *et al.*, 1998, for examples) and must leave this topic for future research.

Given that the Census Bureau will soon release journey-to-work data collected from the 2000 decennial census, we would anticipate its substantial utilisation in excess commuting assessment. The nature of the new data to be released lends itself to comparisons with prior years (1980, 1990). Comparative work from multiple time-periods is already being done in the UK (Frost *et al.*, 1998). Hence, any further work along either of these themes should be cautious of MAUP issues surrounding the measurement of excess commuting. Research conducted in international contexts should also be cognisant of these reported findings.

Excess commuting should continue to attract interest due to its timeliness and policy relevance. With the recent upsurge of attention being placed on sustainability and sustainable transport, notions of efficiency will become increasingly important (Scott *et al.*, 1997; Black, 1997). At a minimum, researchers studying excess commuting in policy applications need to be aware of the spatial issues we have outlined and use the most disaggregate data possible.

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