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Empirical Polycentricity: The Complex Relationship Between Employment Centers

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Abstract

Our paper empirically demonstrates that employment subcenters in large urban areas have important economic relationships with each other, and not solely with the central business district. Using data for Houston, Texas, USA, polycentric density functions are estimated using a specification additive for subcenter influence. We show that estimated gradients using total derivatives, allowing for the relationship between all employment centers, are much different than gradients using only own center coefficients. Further, we model asymmetry in the density function by showing density is very different for centers with overlapping areas of influence. We conclude that subcenters have important yet heterogeneous linkages to each other in addition to the CBD, and that therefore the polycentric city is more complex than simply additional centers mimicking the CBD.

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1. INTRODUCTION

The goal of our research is to expand understanding of the economic importance of multiple employment centers in large cities. We find that the role of employment centers outside of the Central Business District (CBD), which we call subcenters, has as much to do with interactions between subcenters as it does with the CBD.[1] We empirically demonstrate that these interactions are quantitatively important through an examination of both population and employment densities. On the surface, no one would be surprised that both residents and firms desire access to more than one employment center. Our work, however, accomplishes three objectives that make addressing the existence of employment center interactions worthwhile. First, we explore several important attributes in the specification of a polycentric density function, including a method of specifying the boundaries of each subcenter, and a method for having subcenters be additive in density over the classic relationship with the CBD. Further, we show that the estimated coefficients in a polycentric specification do not fully describe the gradient, the total derivative is required because more than one subcenter is statistically important. A second contribution is that the density functions around each employment center are asymmetric, and are asymmetric in several dimensions. We find that some employment centers are linked by population, others by employment. Some of the estimated relationships between employment centers are balanced, in that the relation goes in both directions, but many of them are not. The observed asymmetries suggest that further understanding of urban polycentricity is necessary for understanding how large cities generate gains for their residents. Finally, our work illustrates that despite the apparent complexity of the relationship between

[1] We use the term “employment centers” or “centers” to refer to all employment centers, including the CBD. We distinguish the CBD from the other employment centers by referring to the other employment centers as “subcenters.”

employment centers, that in fact commuting areas capture most of the interaction between subcenters.

Employment centers are identified empirically based on employment density.[2] We estimate our polycentric density function using all of the identified employment centers, using both population, and for employment. Our specification has the advantage that the influence of the subcenters is additive to the density arising from the CBD. We further use the estimates to illustrate that the density gradient can only be found using a total derivative that captures the influences of multiple employment centers. We proceed to estimate density functions around each employment center individually for those that are found to exert influence.[3] The process allows us to show that asymmetry in the density function around each employment center is associated with overlapping areas of influence between employment centers.

The primary insight from the polycentric estimation is that the density function around any given employment center is asymmetric, in contrast to the standard monocentric model. This insight implies a significant change in the modeling of polycentric cities, where conditional on distance to the CBD the assumption has been that density equidistant from a subcenter centroid should be equal everywhere. Our finding of asymmetry is consistent with significant economic or other factors that generate demand for access to more than one employment center. While

[2] We use the McMillen method to select the subcenters, the alternative using the Readfearn (2007) strategy produces similar areas. It is unsettled as to whether a subcenter should have a total employment minimum, this decision is unimportant for our demonstration.

[3] One debate has been whether the employment center definition should include only employment concentration, or in addition should require influence on surrounding areas (Craig and Ng, 2001; McMillen, 2004). We believe our work here makes this argument moot, because influence can depend on the dimension being examined (for example not just employment, but entertainment or shopping, or various elements of between-firm interactions). Our work here shows both possible definitions (influence or not) result in asymmetric densities.

consistent with beliefs about polycentric cities, our findings are the first to empirically demonstrate density asymmetry.

The other type of asymmetry in our exploration of polycentric density functions is in the subcenters themselves. That is, classic theory suggests subcenters arise when the usual "diminishing" assumptions that cause the formation of traditional downtowns reverse- that the marginal congestion costs outweigh the marginal agglomeration benefits (Mills, 1967; Fujita and Ogawa, 1982; Berliant and Wang, 2008; Agarwal, Guiliano and Redfearn, 2012). In this way each subcenter tends to "mimic" the CBD.[4] The raw data shows mild support for the notion, in that employment centers are more similar to each other than to the rest of the city. On the other hand, asymmetry signifies that residents and firms have demand for multiple centers of employment concentration, which suggests that substitution for the CBD is not the only motivation for subcenter formation.[5]

An important issue in the empirical exploration of polycentricity has been to consider the boundaries of employment centers, and especially of subcenters excluding the CBD. A natural method consistent with the theory is to estimate the bounds using patterns of commuting to work, which is the procedure we follow here (Craig and Ng, 2001; McMillen 2001, McMillen and Smith, 2003; Redfearn, 2006; Kohlhase and Ju, 2007).[6] Our search for subcenter interactions

[4] Another implication of this simplistic view is that theory generally specifies that not one, but two subcenters would arise simultaneously, on directly opposite sides of the CDB. The existence of relationships between subcenters strongly suggests a different pattern.

[5] This point supplants, in our view, the discussion about whether subcenters are complements or substitutes with the CBD (Heikkila, Dale-Johnson, Gordon, Kim, Peiser, and Richardson, 1989; Sivitanidou, 1996; Anas, Arnott, and Small, 1998), because the relationship between subcenters also needs to be taken into account.

[6] It is conceptually difficult to distinguish the size of an employment center (for example whether partial or multiple census tracts) from its area of influence. Our approach essentially allows the data to dictate the answer, as we are not able to determine the within tract distribution

provides a natural method to test for the validity of using commuting boundaries. Specifically, we test for interactions beyond the boundaries, and find little additional interaction.

We proceed by first specifying the polycentric density function in section 2, and our tests for whether subcenters are related to each other as well as to the CBD. [7] The estimation is conducted using Census data from 2000 for the Houston MSA, as described in section 3. Section 4 describes how we use the data to select the employment centers that are analyzed in section 5. There we find the expected relationships between the CBD and the subcenters, and we also find that at all subcenters have relationships with other subcenters, although not with all of them.

2. POLYCENTRIC DENSITY FUNCTION SPECIFICATION

The purpose of estimating the polycentric density function is to determine whether the primary pattern in the city is that the subcenters exist only in relation to the CBD, or whether the interaction between the subcenters is an essential element of the city's economy. Our specification of the polycentric function requires two attributes that allow the economic organization of the city to be explored. The first is to resolve a series of issues around the definition of an employment subcenter. Among the questions we address are whether there should be a minimum employment size, and how to limit the extent to which a given subcenter influences the rest of the city. The second element is to specify the subcenter influence on an area as supplemental to the central influence of the CBD. This second step is key to the innovation in our work, however, because it allows us to incorporate asymmetry. Specifically, it

of employment. Redfearn (2007) does not really discuss the area of influence, but his method provides an alternative estimation procedure, although distinguishing the definition of the subcenter from its area of influence may be immaterial (or un-identified).

[7] We estimate the polycentric density function utilizing a specification due to Perdue (2012). The Perdue specification defines proximity as distance from an employment center boundary, rather than distance from an employment center centroid.

is impossible to change distance to one location without simultaneously changing the distance to other locations. Thus the coefficients themselves cannot be individually interpreted, a total derivative needs to be calculated which allows the overlap between areas of influence to be taken into account.

Identification of Employment Centers

We identify candidate employment areas of concentration using McMillen's (2001, 2003) locally weighted regression (LWR) procedure.[8] Application of the LWR procedure identifies 21 concentrations in the Houston area. For a portion of our work we use influence on population to limit the analysis as suggested in Craig and Ng (2001) and McMillen and Smith (2003), but this is inconsequential to our basic point about influence between subcenters. We also find that limitations based on the absolute size of the subcenter as suggested in Giuliano and Small (1991) do not materially affect the interactions.

Figure 1 shows a map of the Houston metropolitan area, with the 21 identified employment concentrations. While most of the concentrations are within the central county of the Houston metropolitan area (Harris); there are eight in five of the outlying counties.[9] Table 1 illustrates the wide differences between the areas with employment concentrations. The CBD, for example, has over 150,000 employees, while Cleveland has fewer than 1,000. Similarly, the densities vary from slightly over 100 workers per square mile to well over 80,000 in the CBD.

[8] One difference in our procedure is that we specify the bandwidth based on miles, rather than the number of tracts, so as to uphold symmetry in the treatment of employment concentrations centrally located from those concentrations on the fringe (since the size of census tracts varies with density). In robustness checks, we find the identified areas are not very sensitive to reasonable variation in bandwidth, which suggests the results from the LWR procedure are not vastly different from the cross-validation procedure proposed by Redfearn (2007).

[9] As of the 2000 Census region definition.

Table 2 presents the location quotients for the subcenters based on both occupation (2a) and industrial (2b) categories. The tables present the employment share by industry or occupation divided by the employment or occupation share in the metropolitan region. For reference, the first substantive column shows Houston's location quotient compared to the country as a whole, while the second column presents the aggregate of the employment centers compared to the metropolitan region. The relative shares in this table suggest there is little distinction between the large and small employment enters by absolute size. It does show, however, that the larger employment centers are generally more diverse, in that their location quotient is likely to be different from one for a broader set of industries or occupations. It also suggests that outside of the Medical Center that it is difficult to categorize individual areas based on their specialization.

Polycentric Density Function Specification and Definition of Employment Centers

Our specification of the polycentric density function is first proposed by Perdue (2012). This specification has two distinct advantages. First, it uses commuting patterns of households to empirically limit the area of the city that an individual employment center can influence. Despite finding the CBD to have a limited commuting area, we nonetheless empirically do not limit the influence of the CBD in keeping with the central role generally ascribed to the CBD. And so the in the second attribute of our specification, we allow density from the subcenters to be in addition to that generated by the CBD. This is accomplished by using proximity to the subcenter centroid, which is defined as the distance from the employment center edge (thus proximity rises closer to a center). We use both population and employment density functions to measure potential attractiveness.

The proximity measure in our density function calculates distance from the edge of the commuting area on a ray toward the centroid for each employment center (Perdue, 2012).[10] That is, if r^j is the commuting area radius for employment center j, and if d_i^j is the distance between the centroid of tract i and the centroid of employment center j, then we define proximity m_i^j as the distance from tract i to the border of the area of influence for j, defined as the distance between tract i and the commuting radius of employment center j so that:

$$(1) \qquad m_i^j = r^j - d_i^j$$

Our specification of the polycentric density function then follows the usual specification of including the identified employment centers in a multiplicative way. The difference in this specification is that we use m_i as defined in (1) rather than using distance from the employment center centroid.

The border of the area of influence used above is defined by commuting patterns, where the influence of an employment center is assumed to go to zero after 90% of the commuters are represented. Many papers have imposed a similar limitation, the advantage of our specification is that we use data to justify the assumption.[11] The resulting specification of the polycentric population density function is therefore:

$$(2) \qquad D_i = A\prod_{j=1}^{J}\exp(\beta_j m_i^j I_i^j)\exp(u_i)$$

[10] This specification is most valuable in a polycentric situation where the range of influence from subcenters is restricted to be less than the entire area.

[11] Most research restricts the area of influence to avoid the situation where a small outlying concentration is estimated to influence the development of a location on the extreme opposite side of the city.

where i indexes the census tracts that are our units of observation, D_i is the population density in tract i, j =1, 2, …, 14 indexes the 13 influential subcenters plus the CBD, m_i^j is the proximity variable as defined in (1), I_i^j is an indicator variable that equals one if tract i is within the commuting area of employment center j and zero otherwise, and u is the error term..

One advantage of using the proximity variable defined in (1) is that it properly defines the distance from the edge of the commuting area as a "good," rather than as a "bad" which typifies the usual specification. The result of this change is that now the coefficients are expected to have positive signs, as the difference in density conditional on distance from the CBD is expected to increase as proximity rises. Further, in this way the influence of the subcenters will be additive to the influence of the CBD. This can be seen most easily by noting that at the edge of influence boundary for the subcenter, the proximity value is zero, meaning density reverts to that proscribed by the CBD. See Figure 2, where the solid line is from the specification in equation (2), while the dashed line would result if distance is measured from the centroid of the subcenter rather than from the edge.[12]

Calculating the Polycentric Gradient from the Total Derivative

We use the estimated coefficients from the polycentric density function in (2) to calculate the total gradient of how density changes between two locations. That is, in any polycentric specification such as (2), the gradient is not apparent from the estimated coefficients because moving a location closer to the CBD changes the location relative to the other subcenters as well. Because the relative influence of other subcenters changes continuously, the gradient resulting from the total derivative describes an asymmetric density function around any given subcenter.

[12] Another way of saying this is that the proximity specification allows the equivalent of a dummy variable for the center of the subcenter.

As a consequence, the generalized density gradient associated with a given center depends on the weighted sum of all the coefficients from within the commuting area. Of course, the weight on subcenters outside the commuting area will be zero, but we need to account for areas where the commuting areas overlap. The weights depend on how distance to other employment centers change when the distance to center *j* changes, defined by DST_j (in what follows we suppress the other subscript for simplicity). That is:

$$(3) \qquad \frac{\frac{dDen}{dDST_j}}{Den} = \beta_1 I_1^j \frac{dDST_1}{dDST_j} + \beta_2 I_2^j \frac{dDST_2}{dDST_j} + \beta_j + \ldots + \beta_{14} I_{14}^j \frac{dDST_{14}}{dDST_j}$$

where for the own-center $j, \frac{dDST_j}{dDST_j} = 1$. The I^j indicator variable indicates which of the fourteen employment centers has a commuting area which overlaps the own center *j*.

3. ASYMMETRY USING SINGLE EMPLOYMENT CENTER DENSITY FUNCTIONS

Using the total derivative in (3) based on estimation of the polycentric density function is found to powerfully suggest that the resulting gradient is not equal equidistant from the centroid of a subcenter. In a preliminary effort to better understand the resulting asymmetry in the density function, we have estimated density functions using as data only the areas of influence around each employment center.[13] This process allows the overlap area, denoted in equation (3) by the indicator variable *I*, to be differentiated between each subcenter where there is dual (or more) influence.

[13] For the individual regressions, we use only the 13 subcenters plus the CBD that were found to influence population.

In the single subcenter regressions, we therefore differentiate by source of overlap. Figure 3 graphically demonstrates our specification of asymmetry through the overlap in commuting areas. The Figure shows two employment centers, EC1 and EC2, where the solid circles around each centroid indicate the commuting areas of influence. The area marked by the vertical lines represents where the two areas of influence overlap, indicated below by the dummy variable *OL*. When we estimate the density function using as data solely tracts within the commuting area for EC1, we allow for the possibility that density in the shaded overlap area has not only a greater density than elsewhere, but may have a different gradient due to the relationship between the employment centers. Similarly, we test whether the same overlap area has a higher density using only the data around EC2, and as well test for a different gradient.

To estimate the density function while allowing for the differential effect of the overlap, we need to include the distance to each employment center creating the overlap. Therefore in the specification below, we use the proximity to the neighboring employment center interacted with the dummy variable indicating the overlap area.[14] Equation (4) shows the specification with slope dummy variables for the two-node example of Figure 3 with overlapping commuting areas:

$$(4) \qquad \ln D_i^s = \beta_0 + \beta_1 m_i^s + \beta_2 OL_i^{s,t} \cdot m_i^t + u_i$$

where D_i^s is the density in tract *i* in the commuting area of employment center *s*. $OL_i^{s,t}$ is the dummy variable which indicates census tracts with overlapping commuting areas for the own employment center *s* with a neighboring employment center *t*. As discussed above, the proximity variable on the *OL* dummy is measured with respect to the source of the overlap, area

[14] This is especially necessary when the overlap area includes the centroid of one of the subcenters, since the two distances are then not collinear.

t. If there were multiple sources of overlap with area *s*, each of them would be entered into (4) in the same additive way as area *t*.

This specification allows each source of asymmetry to be modeled separately. In theory, we expect the β_2 coefficients to be positive, as proximity to the neighbor holding constant own proximity should be valuable. If so, then the density function around area *s* will be asymmetric comparing the areas with and without overlap due to the influence of overlap.

We also use (4) to test an additional source of asymmetry by comparing the β_2 coefficients for each pair of employment centers *s* and *t*. Since the overlap area is identical for any pair of employment centers, we test whether the overlap area has a similar influence on each source. That is, if β_2 is found to be positive for some employment center *s*, we might expect it to also be positive when the other (*t*) center's data is used.[15]

A Test for the Definition of a Subcenter

To further explore the polycentric explanation for why employment centers might have influence in other ways than solving the agglomeration vs. congestion trade-off, we test a final element. Specifically, after allowing for overlap in the commuting areas between employment centers, we additionally test for asymmetry in density for areas that are not in the overlap, but which are nonetheless "close" to neighboring employment centers. If there is heterogeneity in the extent to which a subcenter is found to have influence beyond its commuting area (that is, if the commuting area is sufficient for some but not all subcenters), it will symptomatic that

[15] On the one hand, it might be expected that if the increment to the gradient is positive in one direction, it would be negative in the other. Whether this happens is a question of whether the data are rich enough to discern variation going both ways as the non-overlap data are of course different. A zero effect in one direction and not in the other, however, should reflect actual differences in demand from both sources of overlap.

potentially different causes of influence besides commuting are important. That is, we test for whether a neighboring subcenter influences the space outside of the commuting area in the same way we test for the overlap.[16]

Figure 4 graphically illustrates the distinction between *NEAR* and Overlap. Where the two commuting areas overlap is marked by the cross-hatched area. The dotted circle going through the centroid of employment center (EC) 1 demarks areas of EC1 that are as close to EC2 as the two centroids. These close areas that are not within the commuting area of EC2 are indicated by *NEAR*. The area in *NEAR* will have an increment to density if nearness to EC2 is valued in area 1. Since the *NEAR* areas are outside of the commuting area of EC2, the areas would be expected to be valued because of a motivation outside of employment.[17]

Equation (5) below shows the test for whether the commuting overlap fully contains the relationship between the two employment centers by adding the variable *NEAR*. *NEAR* is an area closer to the neighboring center but outside of the Overlap compared to the rest of the own tract. The specification of the density function, again for an employment center that has overlapping commuting areas with only one other area, is:

$$(5) \qquad \ln D_i^s = \beta_0 + \beta_1 m_i^s + \beta_2 OL_i^{s,t} \cdot m_i^t + \beta_3 NEAR_i^{s,t} \cdot m_i^s + u_i$$

[16] This final test can only be effective if there is asymmetry, that is, if the overlap area is found to have a gradient distinct from the basic influence of a subcenter.

[17] The area $NEAR_i^{s,t}$ may be significant because of deficiencies in how we measure commuting areas, or because the root cause of relationships between employment centers resides in individuals, rather than firms, or because of dimensions of demand not captured by commuting. We are agnostic on the cause, and simply endeavor to demonstrate relationships between employment centers on a variety of dimensions.

where D_i^s is the density in tract *i* in the commuting area of employment center *s*. The proximity variable *m* is defined as in (1), it is the distance from the commuting area boundary to tract *i*. $OL_i^{s,t}$ is the overlap dummy variable defined in (4) where the two commuting areas overlap, and $NEAR_i^{s,t}$ is a dummy variable showing the area towards a neighboring employment center but outside of its commuting area. We measure proximity with reference to the own employment center, where β_3 represents the change in gradient from that indicated in $\beta_{1.}$

The empirical role of *NEAR* could be used in a similar role as that of Overlap, it describes attributes of the relationship between employment centers. That such a relationship occurs outside of the commuting boundaries of subcenters, however, has different implications. Particularly, if the relationship is not defined by commuting boundaries for some, but not all employment centers, then there are other determinants of the between-subcenter relations. If that is the case, the search for a common definition of subcenters may be more complex than a single definition.

4. DATA

Our study uses employment and population data at the census-tract level for the Houston Metropolitan Statistical Area as defined in the year 2000. Houston was selected as the area of study based on the existence of previous work identifying employment centers (Craig and Ng, 2001; McMillen, 2001), and the City of Houston's status as being without an overall plan. While the City of Houston does have significant government involvement in land use decisions, it retains a unique status as the only large American city without centralized zoning. Its remaining regulations are on the whole no more restrictive or prescriptive than those in any other major American city (Lewyn, 2005).

Data on employment is from the Census Transportation Planning Package 2000 Part 2 Place of Work Data and Part 3 Journey to Work Data. The Place of Work data estimates the place of work for all workers using data from a sample of residents compiled from the Census long form; we use this data to calculate employment by census tract. We use the Journey to Work data to estimate commuting areas for each employment center. The commuting radii are determined by when a quadratic regression is extended until 90 percent of the workers to a specific employment center are captured.[18] Table 2 shows the resulting distances of the commuting area radii. Figure 5 shows how the estimated commuting areas overlap in the set of employment centers for Houston. Data from the 2000 Decennial Census (100% count) gives the total population for each tract.

5. EMPIRICAL RESULTS SHOWING EMPLOYMENT CENTER RELATIONSHIPS

The empirical results robustly show that subcenters are economically related to each other, and not just to the CBD. The finding is the result of two separate steps. One is that the polycentric density function estimates, for both population and employment, are used to show the total gradient is quite different than the partial gradient. Second, our individual employment center regressions show that asymmetry is typical, and is at least generally driven by overlaps in the commuting areas. We show that on average the overlap areas have higher population and employment density than equally distant other tracts around each center. Given the strength of this relationship, we also show that there is a gradient that is generally more positive toward the neighboring subcenter even controlling for the proximity to the own employment center. Thus, even though the CBD is shown to exert a broad reach over the entire metropolitan area, the

[18] We also tried using the 95% and the 99% cutoffs, and found the qualitative results to be unchanged.

density function around each subcenter is found to be asymmetric, and skewed not just toward the CBD but to other important areas as defined by employment concentrations as well.

Our final examination is whether commuting areas are a good approximation to the reach of each subcenter. We generally find that despite the strong relationships between subcenters, the influence of neighboring areas does not generally extend beyond the commuting area. The important exception to this finding, however, is that the CBD is found to be a magnet for the entire metropolitan area.

Selection of Employment Centers

Table 3 presents the results for both the log population density function and the log employment density functions. The first column includes the raw data on the number of employees, by which the employment centers are sorted in all of the following tables. The coefficient results use the polycentric specification from equation (2), which encompasses the proximity definition from (1) so that the influence of the subcenters is additive over the influence of the CBD. Further, this specification incorporates the commuting areas to limit the areas of influence for subcenters. The exception, as mentioned earlier, is that we allow the influence of the CBD to extend over the entire metropolitan area. The table shows all of the 21 employment concentrations based on the LWR regressions. The coefficient estimates on the employment concentrations are all found to be positive as expected from the additive specification except for one area.[19] Six of the employment concentrations are not found to have significant impacts on

[19] We are puzzled by the Galleria results, because it is the second largest employment concentration behind only the CBD. We speculate that one problem is the collinearity with the other close-to-CBD employment concentrations. Anas, Arnott, and Small (1998) encounter a similar problem along Wilshire Boulevard. An alternative is to define the subcenter as a line (in our case down US 59 to the CBD), in the case of Anas, Arnott, and Small (1998) it would be the

population density, and seven for employment density. In the rest of our work we restrict our analysis to the significant positive thirteen employment subcenters in addition to the CBD as found in the population results. The selection of employment centers would have been similar, though not identical, had we used the employment results to select the areas, although our qualitative discussion would be essentially identical.[20] Similarly, had we not restricted our analysis and used all 21 areas of employment concentrations, our qualitative results about asymmetry in employment center interactions would be identical. Finally, we present our results in each table in the order of the size of total employment by employment center, and as can be observed the results would be unchanged were we to exclude the subcenters with small total employment levels.[21]

Evidence of Significant Interaction Between Subcenters

The first method we use to demonstrate that subcenters interact with each other, rather than solely with the CBD, is to investigate the total gradient from estimation of the polycentric density specification in equation (2). We accomplish this by showing that the total gradient found utilizing all subcenters with overlapping commuting areas is quite different than the partial gradient using only the own coefficients.

The results of this examination are shown in Table 4a for population, and in Table 4b for employment. Because of nonlinearity in the location of subcenters relative to the CBD, the total

entire boulevard. We originally discussed alternative subcenter shapes in an unpublished working paper (Craig, Kohlhase, and Pitts, 1996).

[20] That is, Freeport would have been added while West Chase and Lake Jackson dropped. Freeport is close to Lake Jackson. In both regressions, the Galleria is the only location with a negative point estimate.

[21] For example in Tables 6 and 7 the smaller (as well as larger) subcenters are found to have substantial interaction with overlapping subcenters.

gradient varies based on location, thus this table shows the gradient for the last mile to the subcenter centroid on a ray from the CBD.[22] The first column shows the calculation of the partial density gradient, using only the own coefficient and that of the CBD. The second column, in contrast, shows the total gradient allowing for simultaneous changes in distance to other subcenters with overlapping commuting areas, these other areas affect both the estimated gradient as well as its standard error (see equation 3).

Table 4a shows a dramatic change for some, but not all of the calculated gradients. As shown in the third column, ten of the 13 subcenters have a statistically significant difference between the simple gradient and the gradient calculated including the influence of all subcenters for population. This result strongly suggests that the relationship between the subcenters themselves, not just with the CBD, is statistically important for shaping the population pattern within the city. Table 4b shows that the relationship between subcenters is not as important for employment, although even here seven of the 13 subcenters have statistically different gradients based on the total derivatives. The finding that the gradient calculated using the total derivative is significantly different from the simple gradient for the majority of subcenters indicates the relationship between the subcenters themselves is important in many areas. It remains to be seen whether the relationships between subcenters are more important for shopping and entertainment, as the population results are stronger than the employment results. Further, there appears to be some heterogeneity between subcenters, as even for population three of the gradients are unchanged when the other subcenters are introduced.

[22] The non-linearity is evident in equation (3), which weights the relative coefficients by $\partial Dist_i / \partial Dist_j$ where j is the own employment center, and i is the neighbor. The choice of location is thus important only for calculating the change in distance between the other employment centers and the own center.

Estimation Results Using Single Employment Centers with Overlap

We expand our investigation into the nature of employment center linkages by estimating regressions using only the data from the commuting area of each employment center individually. The advantage of this analysis is that we are able to examine the specific influence of each individual subcenter that overlaps the own, rather than the average effect from the polycentric specification. The results from the individual employment center regressions strongly support the polycentric regression results. We find a strong set of relationships between the individual subcenters, even after we control for the relationship with the CBD. The first illustration of these relationships uses a dummy variable indicating overlap between the commuting areas of two or more employment centers. This test shows whether the average density is higher in the overlap area than otherwise equivalent areas with access only to the own employment center. In the second illustration, we add a slope dummy variable allowing the estimated density to vary with distance to other employment centers. This test shows the change in gradient within the overlap area compared to the rest of the center's commuting area.[23]

Table 5 presents test results for whether overlapping commuting areas have higher density than portions of the city under the influence of a single employment center. The objective of the test is to show whether overlap areas have higher overall density, indicating a greater value within a center's area for access to neighboring subcenters. The results are dramatic, because for virtually every instance where a statistical test is possible, whether for population or employment, densities are greater in areas under the influence of multiple

[23] We would only expect the gradient to change if the density level is higher as indicated by the dummy variable test.

employment centers.[24] Out of the nine employment centers for which a test can be performed, 6 are found to have levels of employment density in the Overlap area that is significantly greater than elsewhere within the commuting area, even after controlling for proximity to the employment center centroid. All of the remaining three areas are among the farthest from the CBD, and two of them have less than 40 observations available for the test. The third area is Galveston, an area bordering the Gulf Coast beach.[25] The same pattern of results holds for population, except that there is an additional area, Greenspoint, where we do not find significantly higher population density.

Given the strong dual attraction results presented in Table 5, we present results in Tables 6 and 7 on how the density gradient changes within the overlap areas for population and employment, respectively. In these cases, the coefficient we report is on proximity to the neighboring subcenter that creates the Overlap. The expectation is that if access to both subcenters is desirable, then controlling for proximity to the own subcenter, we would expect proximity to the neighboring subcenter should be more valuable resulting in a positive increment to the gradient going toward the neighboring area. In these regressions, in contrast to those reported in Table 5, we separately identify the source subcenter of the overlapping commuting areas. Each column of the tables thus represents a single regression, using only the data in a given center's commuting area. The rows indicate with which areas the overlap occurs in the specification from equation (5). The coefficients indicate how density responds in the overlap areas when proximity to the neighboring subcenter rises (distance falls). For example, the first column of Table 6 shows that after controlling for proximity to the CBD, proximity to the other

[24] Three subcenters plus the CBD are entirely covered by multiple subcenters, leaving no area with which to identify the differential impact of Overlap.

[25] Based on the analysis of Overlap, it is possible to question whether any of these three areas should be in the statistical definition of the Houston metropolitan region.

subcenters results in a positive increment to the population density gradient for every subcenter except Westchase.

Going across the rows of Table 6 shows that every employment center is found to have a significant statistical interaction with at least one other area as estimated using population density. That is, there are no subcenters which respond only to the CBD. In addition to the significant interaction, the bottom four rows summarize the employment center interactions for each center (the column regressions). We find significantly positive interactions between centers in 47 out of the 52 statistically significant coefficients even when, holding constant the proximity to the own center. The significant interactions, however, are a little less than half the total possible as 58 of the potential interactions are found to be insignificant. It remains for future research to determine whether the pattern is because of the dynamic growth and decline of subcenters, or because of other phenomena.

Table 7 reports on the importance of employment center interactions using employment density. These results more powerfully suggest the importance of subcenter interactions than do the population results. 62 of the 67 significant interactions show positive interactions between the employment centers excluding the own coefficient. This is over 58% of the possible interactions, compared to about 46% for population. Nonetheless, like population, not all employment centers have interactions with all possible locations.[26]

The results in Tables 6 and 7 are thus found to show the range of importance for employment center interactions. Table 8 presents an alternative look at the center relationships, by reporting on the extent to which the same centers have relationships both with population and

[26] We leave for future work a more careful analysis of the causes of subcenter interactions. We were unable to uncover compelling regularities using the data here, including occupation or industrial patterns, or location. Our analysis with overlap does present, however, compelling evidence in our view that such interactions are important and merit further work with different data.

employment within Tables 6 and 7. Table 8 reports there are 42 employment centers that are significant in both the population and employment tables, and 22 which are significant in one but not the other. While employment interactions (second column) are more common than those for population (first column), there are nonetheless seven subcenters that have significant population interactions without apparent employment relationships. This evidence is consistent with an understanding that part of the cause of subcenter interactions is outside of employment.[27]

The other potentially interesting aspect of the subcenter interactions is the extent to which they are reciprocal. That is, if the density gradient is positive towards a neighboring subcenter, it is not necessarily true that the gradient is positive when the roles are reversed. Table 9 shows the results for the non-duplicative relationships.[28] For both population and employment, the number of non-reciprocal relationships is found to be more extensive than it is for reciprocal relationships. If the relationships between subcenters are primarily driven by firms, it might be expected that all of the relationships would be reciprocal, because firms are attracted to customers as well as suppliers. On the other hand, if residents are attracted to centers due to entertainment or shopping, it is difficult to see why the relationship would be reciprocal. In either case, however, we see that the level of reciprocity is similar for both population and employment, and we see that relationships between subcenters are more likely to be one way than reciprocal.

[27] That is, even the different sources of potential agglomeration economies (Rosenthal and Strange, 2004; and Ellison, Glaeser, and Kerr, 2010) would not be expected to be apparent in population without impacting employment in some way.

[28] We call results in the table as the upper triangle because the report for the CBD includes all relationships, while for Katy (the smallest) there is no possible unrecorded reciprocity.

Test of Commuting Area Influence

Our framework allows a test of whether the commuting area is an effective method by which to limit how far a subcenter might influence population or employment density. As discussed for equation 5, we specify a dummy variable *NEAR* which equals one if an area is closer to a neighboring center than the centroids. If commuting patterns define the totality of employment center interactions, the coefficients on *NEAR* should all be zero. On the other hand, if there are other factors which influence population or firm demand for multiple employment centers, it may be that these additional factors will be manifested in the coefficients on *NEAR*.

Table 10 presents the results for *NEAR*, showing that our specification of using commuting areas to limit the extent of influence of subcenters is generally effective. There are two areas with positive and significant coefficients on density, the CBD and Katy. Katy is the smallest subcenter that is also among the farthest from the CBD. Significance there suggests that people want to be closer to the center of the city compared to being farther away, irrespective of where they work. The results for the CBD are interesting, because they suggest that specifying the CBD as having influence throughout the metropolitan area fairly represents that the CBD is a 'magnet' for a metropolitan area as a whole. It is also interesting, however, by suggesting that other roles for a subcenter outside of commercial opportunities may be important, which is consistent with subcenters being attractive to residents of other areas.

6. SUMMARY AND CONCLUSION

Our paper provides an empirical exploration of the importance of employment centers to both individuals and firms. We perform our analysis by first estimating a polycentric density function for population and employment, and second by estimating individual density functions for each employment center. Our methodology is novel in four dimensions. Our empirical specification uses proximity, defined as distance from the boundary, so that we are able to specify subcenters as adding to the density that would otherwise be expected given proximity to the CBD (Perdue, 2012). Second, we estimate a polycentric density function where we restrict the geographic area of influence of each identified employment center using an objective statistical measure, the reach of commuters to work. Third, we properly interpret the polycentric density function results using the total derivative to generate the estimated gradient. Finally, we separately examine how overlapping commuting areas cause densities around each employment center to be asymmetric to the extent that densities are found to rise going toward a neighboring center. The results from our empirical examination imply that the urban economic impacts of employment concentrations are far more important than simply the trade-off between congestion and agglomeration, suggesting the need for a richer theoretical framework that explicitly models relationships between subcenters.

We use our polycentric specification to illustrate the distinction between the gradients calculated including the relationships between centers compared to those using only the own and CBD coefficients. The significant distinction between these two calculations is powerful evidence that subcenter interactions are important at explaining the density pattern of large urban areas. Our individual subcenter regressions go further at illustrating the importance of the distinctions that underlie this finding. Estimation of the individual density functions illustrates the asymmetry where we specify the overlap in areas of influence for each separate pair of employment centers. Examination of the resulting relationships also shows the variety in the relationships. We find attractions for both population and employment, but not necessarily to the same neighboring centers. We find that a little less than half of the relationships are reciprocal, which suggests to us a consumer orientation for at least some of the relationships.

Finally, we use our estimates to examine whether commuting patterns capture all of the influence of employment centers on each other. This test examines whether there is further attraction in areas outside the overlapping commuting areas. The results generally support that commuting patterns are effective limitations. An important exception is that we find the CBD is an important center of the metropolitan area outside the commuting patterns of the neighboring subcenters.

The multi-dimensional characteristics of the linkages between employment centers should provide an important impetus to the theoretical literature for understanding polycentric urban economies. Specifically, recent literature has established that cities are attractive to residents because of their consumption variety (Albouy, 2008). In some sense, urban economists have considered employment subcenters as an efficiency consequence of congestion, but not as a positive attribute to urban lifestyles in their own right. To the extent that alternative clusters of employment contribute not only to the productive efficiency of cities, but to efficiency in other dimensions such as consumption or entertainment, then a focus on production will be too limited. In the expanded polycentric view, no subcenter will exactly mimic the CBD, each will have a distinct sense of place, and will be attractive to firms and individuals for a variety of reasons.

Finally, we believe our work speaks to the search for the appropriate definition of subcenters themselves. Craig and Ng (2001) and others (McMillen, 2001; 03; Redfearn 2007) advocate for a consistent statistical definition, but the polycentric view of subcenters suggests the definition of subcenters may be sensitive to context.[29] We thus await theoretical developments to guide the specification explaining the different functions of the non-CBD employment clusters.

[29] See Agarwal, Giuliano, and Redfearn (2012) for a recent review of the progress of the literature in this direction, it is still incomplete.

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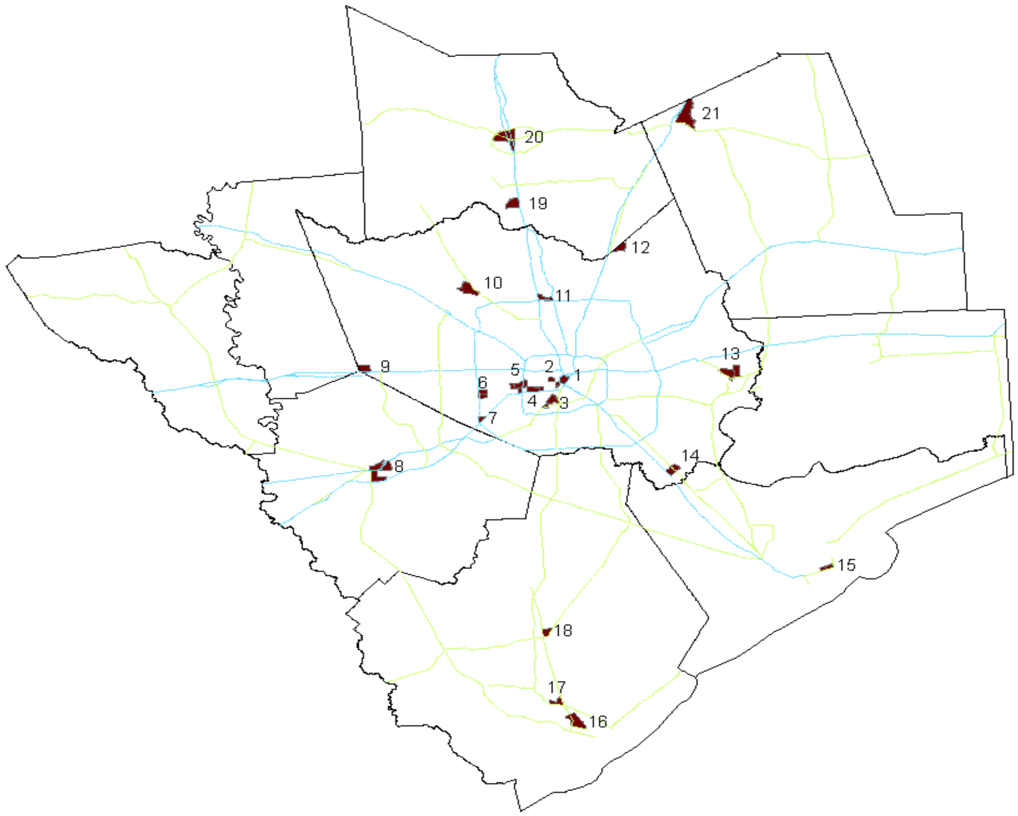

Employment Concentrations[3]

1 CBD
2 Allen Parkway
3 Medical Center
4 Greenway Plaza
5 Galleria
6 Westpark
7 US 59 & BW 8
8 Richmond
9 Katy
10 SH 249 & FM 1960
11 Greenspoint
12 Kingwood
13 Baytown
14 Webster
15 Galveston
16 Freeport
17 Lake Jackson
18 Angleton
19 Woodlands
20 Conroe
21 Cleveland

Figure 1- Employment Concentrations in the Houston Metropolitan Area1, 2

Notes:
1. Metropolitan Statistical Area (MSA) as defined by the Office of Management and Budget.
2. Employment Concentrations defined as locally statistically significant concentrations of employment following first stage of McMillen (2001).
3. Employment concentrations identified using local names, major highway intersection, or political jurisdiction.

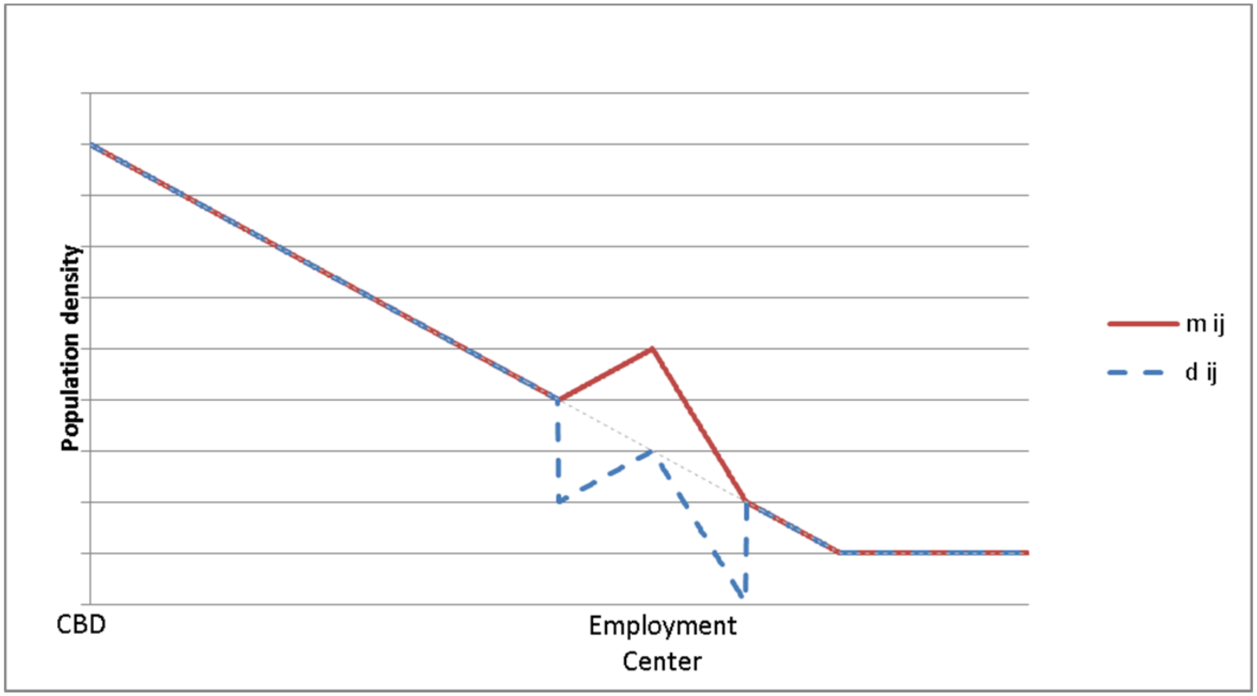

Figure 2: Two-Node Specification with Proximity Compared to Centroid

Notes: If the employment center centroid is the peak in the figure, then the proximity specification (m) allows the estimates to capture increased density from the otherwise monocentric specification, while estimating density from the centroid of the employment center (d) sets up a reduction in density because the subcenter centroid is on the monocentric line, while everything else within the commuting area is offset.

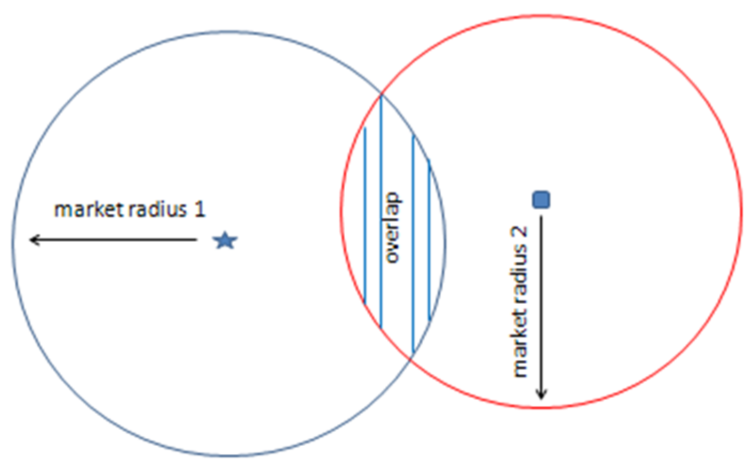

FIGURE 3: Overlapping Commuting Areas

Notes: The solid circles represent the extent of the area of influence based on commuting data for each subcenter. We desire to test whether the density in the area marked "overlap" is equal, conditional on distance from the commuting area edge, to other areas within the same subcenter not marked "overlap." We perform this test both in subcenter 1, and in subcenter 2.

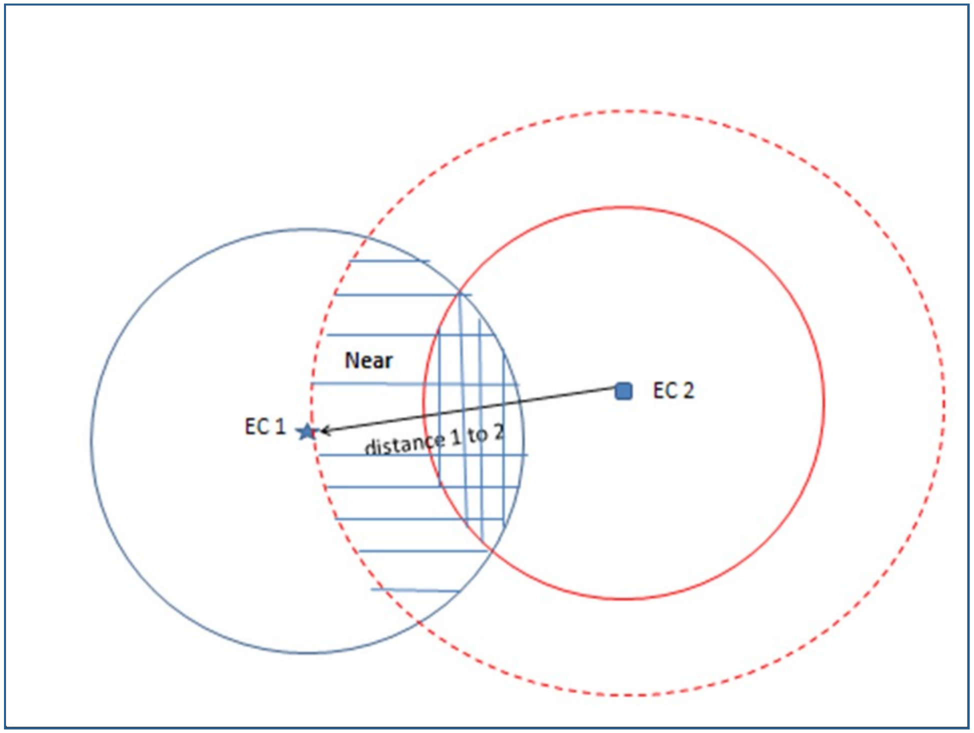

Figure 4: Overlap (defined as double cross hatch) and Near (horizontal lines)

Notes: See Figure 3. The dotted circle through the centroid of EC 1 delineates the area in EC 1 that is closer to EC 2 than otherwise. The cross-hatched area is OL (see Fig 3), the area marked NEAR with the horizontal lines represents proximity to EC 2 but that is outside of the communting area of influence.

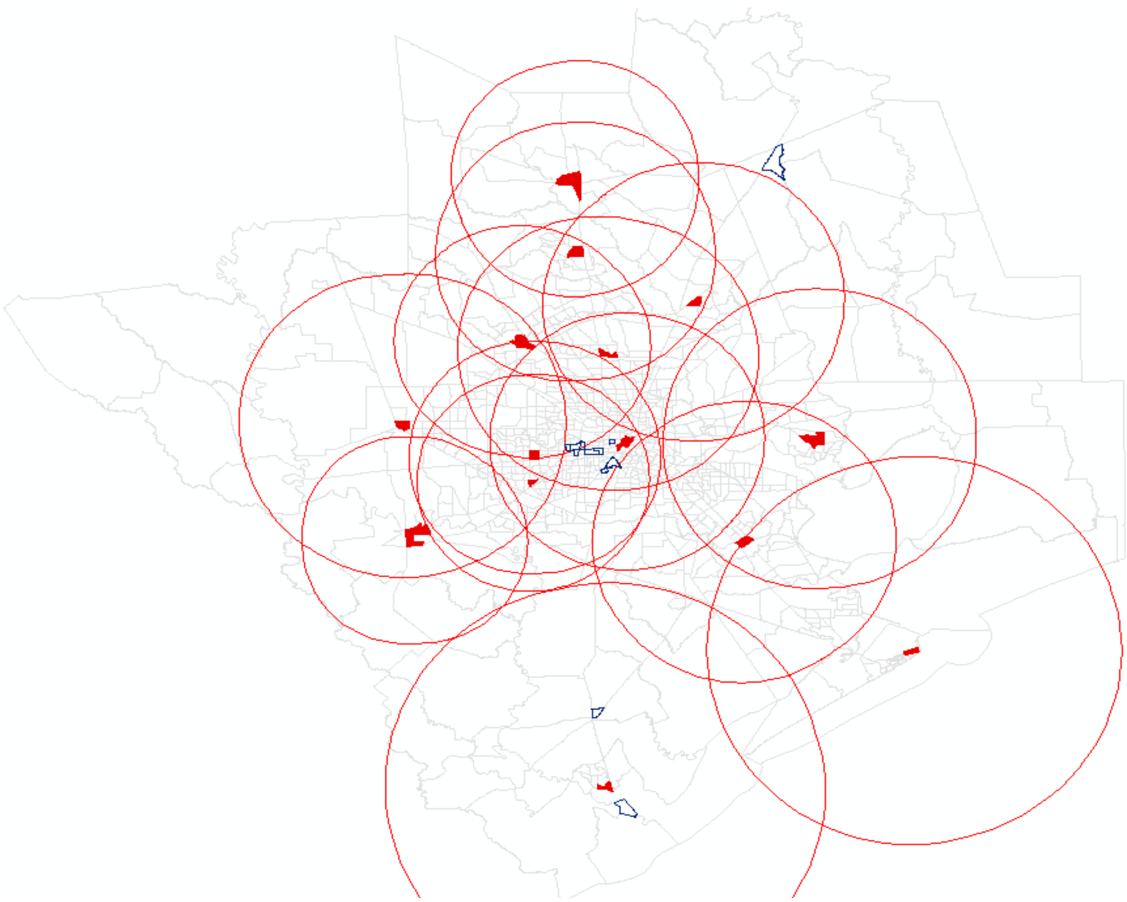

FIGURE 5: Estimated Commuting Areas of Influence for 14 Employment Centers

TABLE 1: Characteristics of Employment Centers

Employment Center[1]	Number of Census Tracts	Total Workers[2]	Workers/ sq. mile	Share of Metro Area Workers[3]	Share of Subcenter Workers	Commuting Area Distance (miles)[4]
CBD	2	155,105	84,033	7.70%	32.00%	18.25*
Galleria	4	68,067	27,708	3.40%	14.00%	15.61
Med. Center	2	58,067	30,073	2.90%	12.00%	16.28
Grnwy Plaza	2	53,057	28,543	2.60%	11.00%	17.49
Galveston	2	16,509	15,997	0.82%	3.40%	26.18
Greenspoint	1	16,502	11,836	0.82%	3.40%	19.68
Willowbrook	1	16,361	5,234	0.81%	3.40%	16.14
Westchase	1	15,538	11,197	0.77%	3.20%	16.87
Conroe	3	13,048	2,358	0.64%	2.70%	16.46
Webster	1	10,520	5,890	0.52%	2.20%	20.03
Woodlands	1	10,306	4,820	0.51%	2.10%	18.40
Freeport	1	10,015	3,177	0.49%	2.10%	51.34
Allen	1	9,578	19,341	0.47%	2.00%	15.58
Baytown	2	8,475	2,304	0.42%	1.70%	21.26
Richmond	3	6,752	1,258	0.33%	1.40%	14.47
Alief	1	5,277	9,529	0.26%	1.10%	15.59
Lake Jackson	1	4,453	3,583	0.22%	0.92%	29.56
Katy	1	2,310	1,246	0.11%	0.48%	21.81
Angleton	1	2,101	1,577	0.10%	0.43%	17.62
Kingwood	1	1,836	1,371	0.09%	0.38%	19.98
Cleveland	1	739	118	0.04%	0.15%	24.01
Total		484,629		24.00%	100%	

Notes:

1. Employment centers defined as locally statistically significant concentrations of employment following first stage of McMillen (2001). Employment data from 2000 Census Transportation Planning Package Part 3 Journey to Work.
2. Workers located within each employment center that reside within the Houston Metropolitan Area.
3. Proportion of total metropolitan employment contained within the employment center.
4. The distance is estimated using a quadratic specification that captures 90 percent of the subcenter's workers.

* We allow the CBD to influence the entire metro area.

TABLE 2A: Occupational Location Quotients by Employment Center

Occupations	Houston vs. Entire US	Employment Centers vs. Houston	CBD	Medical Center	Galveston	Greenspoint	Willowbrook
Legal	**1.17**	**4.33**	**8.22**	0.29	**1.53**	**2.16**	0.73
Healthcare practitioners and technicians	0.88	**2.92**	0.53	**10.96**	**6.45**	0.69	0.48
Computer and mathematical	**1.11**	**2.12**	**2.48**	**1.25**	**1.35**	**2.18**	**5.10**
Life, physical, and social science	**1.36**	**2.12**	**1.20**	**4.83**	**3.59**	**4.60**	0.40
Business and financial operations	**1.16**	**1.84**	**2.77**	0.69	**1.03**	**1.93**	**1.41**
Protective services	0.96	**1.48**	**2.24**	0.50	**2.67**	0.50	0.79
Healthcare support	0.76	**1.36**	0.41	**4.12**	**2.70**	0.38	0.06
Office and administrative support	0.99	**1.28**	**1.45**	**1.03**	**1.35**	**1.29**	1.00
Architecture and engineering	**1.50**	**1.24**	**1.15**	0.21	0.30	**2.36**	**3.77**
Management	**1.11**	**1.15**	**1.29**	0.77	0.84	**1.52**	**1.85**
Armed forces	0.11	**1.02**	**1.08**	0.21	**6.57**	**1.19**	0.00
Arts, design, entertainment, sports, and media	0.82	0.91	**1.07**	0.41	0.75	0.85	**1.05**
Community and social service	0.71	0.80	0.61	**1.22**	**1.59**	0.27	0.38
Building and grounds cleaning and maintenance	**1.06**	0.78	0.74	0.95	0.98	0.53	0.30
Food preperations and serving related	0.90	0.70	0.60	0.48	0.66	0.88	0.33
Sales and related	**1.07**	0.62	0.52	0.19	0.35	0.95	0.65
Construction and excavation	**1.26**	0.61	0.66	0.51	0.34	0.95	0.08
Transportation and material moving	0.97	0.57	0.65	0.37	0.45	0.56	0.44
Installation, maintenance and repair	**1.06**	0.54	0.48	0.35	0.31	0.46	0.59
Personal care and service	0.88	0.51	0.47	0.47	0.39	0.22	0.62
Production	0.80	0.48	0.43	0.20	0.35	0.44	**1.51**
Education, training and library	0.99	0.47	0.22	0.82	**1.01**	0.07	0.49
All farming related	0.23	0.39	0.58	0.02	0.07	0.00	**1.33**
Of tot. subcenter export occupations, how many does this center export?			9.00	5.00	9.00	8.00	4.00
Of tot subcenter non-export occups, how many does this center export?			1.00	1.00	2.00	0.00	3.00

Notes: Location Quotients (LQ) calculated by the net method.
LQs are the share of an occupation out of total workers in a subcenter (or any area) divided by the share of the same occupation for the total jurisdiction net of that subcenter (area).
LQs greater than one are generally considered 'export' occupations.

TABLE 2A: Occupational Location Quotients by Employment Center (cont.)

Occupations	Aleif	Westhcase	Conroe	Webster	Woodlands	Baytown	Richmond	Lake Jackson	Katy	Number of Subcenters Export Occupations
Legal	**2.70**	0.93	**3.25**	**2.30**	**1.02**	0.91	0.68	0.42	**1.24**	8.00
Healthcare practitioners and tech	**5.03**	0.33	**1.03**	**2.09**	**2.24**	**3.25**	**2.33**	**1.75**	**2.05**	10.00
Computer and mathematical	**1.62**	**2.90**	0.33	**1.85**	**1.42**	0.55	0.49	0.34	0.27	9.00
Life, physical, and social science	**1.74**	**2.96**	0.03	0.22	**3.55**	**1.46**	0.38	0.24	0.00	8.00
Business and financial operations	**1.06**	**1.81**	0.87	0.87	**1.48**	0.81	0.38	0.45	0.42	7.00
Protective services	0.26	0.61	**1.01**	0.91	**1.03**	0.98	**1.24**	0.88	0.47	5.00
Healthcare support	**3.12**	0.60	**1.07**	**1.53**	**1.14**	**1.97**	**2.06**	**1.51**	0.86	9.00
Office and administrative support	**1.19**	**1.67**	**1.11**	**1.04**	**1.08**	**1.29**	0.96	0.91	0.98	10.00
Architecture and engineering	0.63	**3.16**	0.26	**1.59**	**1.08**	**1.78**	0.45	0.52	0.83	7.00
Management	0.90	**1.36**	0.86	0.91	**1.21**	0.72	0.87	0.80	0.68	5.00
Armed forces	0.00	**1.90**	**2.22**	**1.54**	0.00	0.00	0.00	0.00	0.00	6.00
Arts, design, entertainment, sport	**2.13**	0.95	0.78	0.92	0.61	0.89	0.59	0.66	**2.42**	4.00
Community and social service	0.75	0.38	**1.34**	0.96	0.50	0.67	**2.70**	**1.74**	**2.02**	6.00
Building and grounds cleaning and	0.42	0.76	**1.42**	0.97	0.42	0.56	**1.73**	**1.18**	**2.81**	4.00
Food preperations and serving rel	**1.18**	0.65	**1.35**	**1.29**	**1.40**	0.86	0.93	**1.42**	0.46	5.00
Sales and related	**1.15**	0.63	**1.27**	**1.11**	**1.63**	0.88	**1.22**	**1.38**	**1.43**	7.00
Construction and excavation	0.22	0.69	0.74	0.57	0.36	0.72	0.40	**1.25**	0.90	1.00
Transportation and material movi	0.44	0.55	0.98	0.76	0.47	0.56	0.82	0.77	0.35	0.00
Installation, maintenance and rep	0.62	0.51	**1.19**	**1.01**	0.61	0.92	**1.24**	**1.26**	**1.10**	5.00
Personal care and service	0.84	0.33	0.79	0.75	0.46	0.82	**1.03**	0.94	**1.47**	2.00
Production	0.25	0.44	0.50	0.56	0.57	**1.15**	0.50	0.65	0.55	2.00
Education, training and library	0.47	0.25	**1.30**	0.89	0.21	0.77	**1.65**	**1.16**	**1.14**	5.00
All farming related	0.00	0.18	0.61	0.35	0.00	0.00	**1.03**	0.66	0.00	2.00
No.of Export Occupats.	7.00	7.00	6.00	7.00	10.00	5.00	3.00	2.00	2.00	
No. of Import Occs. Export	3.00	0.00	6.00	3.00	2.00	1.00	7.00	7.00	7.00	

TABLE 2B: Industrial Location Quotients by Employment Center

Occupations	**Houston vs. Entire US**	**Employment Centers vs. Houston**	**CBD**	**Medical Center**	**Galveston**	**Greenspoint**
Public administration	0.69	**2.04**	**3.22**	0.37	**3.02**	0.40
Professional, scientific, mngmnt, admin, and waste mngmnt	**1.28**	**1.48**	**2.22**	0.41	0.47	**1.48**
Agriculture, forestry, fishing and hunting, and mining	**1.44**	**1.48**	**1.67**	0.08	0.04	**7.27**
Educational, health, and social services	0.89	**1.40**	0.32	**4.69**	**3.45**	0.23
Transportation and warehousing, and utilities	**1.33**	**1.30**	**2.22**	0.16	0.52	**1.15**
Armed services	0.12	**1.21**	**1.35**	0.51	**5.37**	0.31
Finance, insurance, real estate and rental and leasing	0.99	**1.19**	**1.62**	0.24	**1.44**	**1.22**
Information	0.74	0.96	**1.27**	0.18	0.38	0.96
Wholesale trade	**1.31**	0.74	0.96	0.39	0.12	**1.48**
Arts, entertainment, recreation, accomodation, and food	0.88	0.71	0.72	0.35	0.59	0.91
Manufacturing	0.87	0.70	0.53	0.10	0.20	0.75
Retail trade	0.95	0.59	0.37	0.19	0.26	0.83
Construction	**1.31**	0.59	0.63	0.44	0.25	0.92
Other services	**1.09**	0.47	0.41	0.35	0.42	0.30
Of total subcenter export industries, how many does this center export?			6.00	1.00	4.00	4.00
Of total subcenter non-export industries, how many does this center export?			1.00	0.00	0.00	1.00

Notes: Location Quotients (LQ) calculated by the net method.

LQs are the share of an industries workers out of total workers in a subcenter (area) divided by the share of the same industry workers for the total jurisdiction net of that subcenter (area).

LQs greater than one are generally considered 'export' industries.

TABLE 2B: Industrial Location Quotients by Employment Center (cont.)

Occupations	Willow-brook	Aleif	Westhcase	Conroe	Webster	Woodlands	Baytown	Richmond	Lake Jackson	Katy	Subcenter Export Industries
Public administration	0.28	0.29	0.35	**2.57**	**3.36**	0.49	0.95	**1.49**	0.96	0.72	5.00
Professional, scientific, mn	0.63	0.92	**2.57**	0.91	0.91	0.94	0.65	0.51	0.42	**1.44**	4.00
Agriculture, forestry, fishir	0.40	0.03	**4.90**	0.29	0.20	**2.12**	0.12	0.34	0.21	0.00	4.00
Educational, health, and sc	0.43	**2.39**	0.28	**1.22**	**1.26**	0.81	**1.72**	**2.13**	**1.48**	**1.15**	9.00
Transportation and wareh	0.34	0.14	**1.66**	0.54	0.54	0.80	0.29	0.55	0.35	0.16	3.00
Armed services	0.00	0.00	**2.42**	**2.12**	**1.29**	0.00	0.00	0.00	**1.70**	0.00	6.00
Finance, insurance, real es	0.57	**1.77**	**1.31**	**1.29**	**1.09**	**1.29**	0.96	0.83	0.65	0.90	8.00
Information	0.29	**2.90**	**1.51**	0.77	0.69	0.79	0.24	**1.61**	**1.74**	**2.49**	6.00
Wholesale trade	0.60	0.47	0.75	0.71	0.49	0.87	0.19	0.37	0.66	0.29	1.00
Arts, entertainment, recre	0.28	0.90	0.79	**1.13**	**1.09**	**1.22**	0.80	0.99	**1.40**	0.91	4.00
Manufacturing	**4.82**	0.19	0.57	0.25	0.70	0.93	**1.82**	0.25	0.30	0.63	2.00
Retail trade	0.70	**1.06**	0.54	**1.74**	**1.49**	**1.83**	**1.18**	**1.57**	**1.67**	**1.30**	8.00
Construction	0.09	0.20	0.75	0.66	0.52	0.57	0.46	0.45	**1.49**	0.87	1.00
Other services	0.38	0.85	0.21	**1.09**	0.90	0.40	0.80	**1.12**	**1.07**	**1.95**	4.00
No.of Export Industries	0.00	2.00	5.00	4.00	4.00	2.00	1.00	2.00	2.00	2.00	
No. of Import Inds Export	1.00	2.00	1.00	3.00	2.00	2.00	2.00	3.00	5.00	3.00	

Notes: Location Quotients (LQ) calculated by the net method.
LQs are the share of an industries workers out of total workers in a subcenter (area) divided by the share of the same industry workers for the total jurisdiction net of that subcenter (area).
LQs greater than one are generally considered 'export' industries.

TABLE 3: Polycentric Estimates for Employment and Population[1]

Total Workers	Employment Center	ln(Emp Density)	ln(Pop Density)
155,105	CBD	0.079***	0.075***
		(0.01)	(0.01)
68,067	Galleria	-0.020	-0.172**
		(0.09)	(0.07)
58,067	Medical Center	0.108	0.108*
		(0.07)	(0.06)
53,057	Greenway	-0.028	0.020
		(0.11)	(0.09)
16,509	Galveston	0.263***	0.205***
		(0.02)	(0.01)
16,502	Greenspoint	0.085***	0.053**
		(0.03)	(0.02)
16,361	Willowbrook	0.155***	0.085***
		(0.02)	(0.02)
15,538	Westchase	0.071	0.101**
		(0.06)	(0.05)
13,048	Conroe	0.298***	0.147***
		(0.04)	(0.02)
10,520	Webster	0.176***	0.112***
		(0.02)	(0.01)
10,306	Woodlands	0.095***	0.048***
		(0.02)	(0.02)
10,015	Freeport	0.006	-0.053***
		(0.02)	(0.02)
9,578	Allen Parkway	0.114	0.017
		(0.07)	(0.06)
8,475	Baytown	0.170***	0.049**
		(0.02)	(0.02)
6,752	Richmond	0.206***	0.096***
		(0.04)	(0.03)
5,277	Alief	0.145***	0.112***
		(0.04)	(0.03)
4,453	Lake Jackson	0.213***	0.230***
		(0.05)	(0.04)
2,310	Katy	0.138***	0.045**
		(0.03)	(0.02)
2,101	Angleton	-0.053	-0.069
		(0.09)	(0.08)
1,836	Kingwood	0.113***	0.034
		(0.03)	(0.02)
739	Cleveland	0.053	0.033
		(0.05)	(0.02)
	Constant	-0.539	2.840***
		(0.43)	(0.28)
	Observations	877	877

Notes: Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

1. Coefficients are those on proximity (distance from subcenter boundary as in eqn 1) in a ln density function with a constant including all subcenters (see eqn 2).
2. Data are by census tract for the entire Houston MSA.

TABLE 4a: Estimated Population Gradient Moving to each Subcenter from the CBD[1]

Employment Centers[2]	Estimated Own Gradient[3]	Estimated Total Gradient[4]	Difference (own minus total)
Medical Center	0.108*	0.132**	-0.025
	(0.06)	(0.06)	(0.09)
Galveston	0.205***	0.129***	0.075***
	(0.01)	(0.01)	(0.02)
Greenspoint	0.053**	-0.050	0.103*
	(0.02)	(0.06)	(0.06)
Willowbrook	0.085***	-0.087	0.172***
	(0.02)	(0.05)	(0.06)
Westchase	0.101**	-0.030	0.131
	(0.05)	(0.07)	(0.08)
Conroe	0.147***	0.023	0.123***
	(0.02)	(0.03)	(0.04)
Webster	0.112***	0.225***	-0.1134***
	(0.01)	(0.02)	(0.03)
Woodlands	0.048***	-0.001	0.050*
	(0.02)	(0.02)	(0.03)
Baytown	0.049**	-0.079***	0.128***
	(0.02)	(0.03)	(0.03)
Richmond	0.096***	0.006	0.089*
	(0.03)	(0.04)	(0.05)
Alief	0.112***	-0.088	0.200**
	(0.03)	(0.09)	(0.09)
Lake Jackson	0.230***	0.154***	0.075
	(0.04)	(0.04)	(0.06)
Katy	0.045**	-0.130**	0.175***
	(0.02)	(0.06)	(0.07)

Notes: Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

1. Calculation of total derivative assumes moving the last mile to the subcenter centroid from the CBD.
2. Employment Centers identified as local statistically significant concentrations of employment with
3. Estimated own gradient calculated using the own and CBD coefficients from Table 3.
4. Total gradients calculated as linear combinations of the partial derivatives of distance incorporating the nearby employment centers using equation (3), standard errors of the coefficients

TABLE 4b: Estimated Employment Gradient Moving to each Subcenter from the CBD[1]

Employment Centers[2]	Estimated Own Gradient[3]	Estimated Total Gradient[4]	Difference (own minus total)
Medical Center	0.108	0.098	0.010
	(0.07)	(0.07)	(0.10)
Galveston	0.263***	0.184***	0.079***
	(0.02)	(0.01)	(0.02)
Greenspoint	0.085***	0.048	0.036
	(0.03)	(0.07)	(0.08)
Willowbrook	0.155***	0.066	0.089*
	(0.02)	(0.04)	(0.05)
Westchase	0.071	-0.060	0.132
	(0.06)	(0.09)	(0.11)
Conroe	0.298***	0.124**	0.174***
	(0.04)	(0.05)	(0.07)
Webster	0.176***	0.309***	-0.133***
	(0.02)	(0.03)	(0.03)
Woodlands	0.095***	0.106***	-0.011
	(0.02)	(0.03)	(0.04)
Baytown	0.170***	0.008	0.162***
	(0.02)	(0.03)	(0.04)
Richmond	0.206***	0.084**	0.122**
	(0.04)	(0.04)	(0.06)
Alief	0.145***	0.038	0.108
	(0.04)	(0.09)	(0.10)
Lake Jackson	0.213***	0.134***	0.079
	(0.05)	(0.05)	(0.07)
Katy	0.138***	0.059*	0.079*
	(0.03)	(0.03)	(0.04)

Notes: *** p<0.01, ** p<0.05, * p<0.1.

1. Calculation of total derivative assumes moving the last mile to the subcenter centroid from the CBD.
2. Employment Centers identified as local statistically significant concentrations of employment with effects on population (see text).
3. Estimated own gradient calculated using the own and CBD coefficients from Table 3.
4. Total gradients calculated as linear combinations of the partial derivatives of distance incorporating the nearby employment centers using equation (3), standard errors of the coefficients calculated using the delta method.

TABLE 5: The Impact on Density of Overlapping Commuting Areas

		Single Employment Center Density Functions	
		ln(Pop)	**ln(Emp)**
	Observations	**Coeff. on Overlap Dummy**	**Coeff. on Overlap Dummy**
CBD	878	1.76***	3.72***
		(0.25)	(0.43)
Medical Center	495	n/a[a]	n/a[a]
		.	.
Galveston	66	-0.97	-1.28*
		(0.62)	(0.65)
Greenspoint	467	0.39	0.58***
		(0.27)	(0.16)
Willowbrook	245	0.72**	2.02***
		(0.31)	(0.31)
Westchase	465	n/a[a]	n/a[a]
		.	.
Conroe	37	-0.67	-1.20
		(0.89)	(1.21)
Webster	253	1.08***	1.12***
		(0.23)	(0.39)
Woodlands	122	0.81***	1.23**
		(0.29)	(0.53)
Baytown	216	n/a[a]	n/a[a]
		.	.
Richmond	70	2.78***	1.60***
		(0.35)	(0.28)
Alief	373	n/a[a]	n/a[a]
		.	.
Lake Jackson	37	1.67	1.28
		(1.06)	(0.98)
Katy	264	1.14**	0.63
		(0.47)	(0.51)

Notes: Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.
Each reported coefficient is on a dummy variable in a separate regression of density on proximity and a constant. The dummy designates tracts in the commuting area of two or more employment centers. Each regression uses only the data in each row's commuting area, controlling for proximity to that employment center and the CBD.

[a] Indicates there are too few observations that are not in overlapping areas to estimate the coefficient.

TABLE 6: Influence of Overlap Proximity on Population Density

Centers	CBD	Medical Center	Galveston	Greenspoint	Willowbrook	Westchase	Conroe	Webster
CBD	0.080***	0.178***	-0.015	0.082**	0.123**	0.095**	-0.190**	0.020
	(0.01)	(0.06)	(0.10)	(0.04)	(0.06)	(0.04)	(0.09)	(0.05)
Medical Center	0.091***	-0.043		-0.033	-0.004	0.031		0.031
	(0.02)	(0.06)		(0.05)	(0.09)	(0.05)		(0.07)
Galveston	0.219***		0.343***					0.053
	(0.01)		(0.06)					(0.06)
Greenspoint	0.036**	0.046		-0.011	0.026	0.061**	0.251**	-0.147*
	(0.02)	(0.03)		(0.03)	(0.06)	(0.03)	(0.11)	(0.08)
Willowbrook	0.061***	0.075**		0.054***	0.083***	0.047*	-0.068	
	(0.01)	(0.03)		(0.02)	(0.02)	(0.03)	(0.11)	
Westchase	-0.064**	-0.032		0.035	-0.007	-0.045		0.525***
	(0.03)	(0.04)		(0.03)	(0.05)	(0.03)		(0.18)
Conroe	0.183***			0.068	0.321**		0.077	.
	(0.02)			(0.13)	(0.13)		(0.05)	.
Webster	0.109***	0.127***	0.318**	0.124**		0.150**		0.022
	(0.01)	(0.03)	(0.12)	(0.06)		(0.07)		(0.03)
Woodlands	0.066***	0.011		0.036	0.051	0.151	0.329**	
	(0.02)	(0.18)		(0.04)	(0.04)	(0.11)	(0.08)	
Baytown	0.062***	0.053	0.278***	-0.048		0.108		0.023
	(0.02)	(0.03)	(0.10)	(0.05)		(0.15)		(0.03)
Richmond	0.146***	0.236**				0.033		
	(0.03)	(0.11)				(0.05)		
Alief	0.201***	0.170***		0.067*	0.079	0.162***		0.465***
	(0.03)	(0.04)		(0.04)	(0.06)	(0.04)		(0.15)
Lake Jackson	0.130***		0.395***					0.469***
	(0.01)		(0.15)					(0.14)
Katy	0.084***	0.038		-0.018	0.063	0.098***		
	(0.02)	(0.04)		(0.03)	(0.04)	(0.03)		
Constant	2.221***	-1.564	0.620	3.776***	1.245	1.988	5.861***	6.236***
	(0.28)	(2.40)	(2.13)	(1.36)	(1.94)	(1.68)	(1.31)	(1.86)
Observations	878	495	66	467	245	465	37	253

Summary of Results on Overlap Interactions (13 possible excluding own)

The number of centers (excluding own) with:

	CBD	Medical Center	Galveston	Greenspoint	Willowbrook	Westchase	Conroe	Webster
Positive & Sig.	12	5	3	4	2	6	2	1
Negative & Sig.	1	0	0	0	0	0	1	3
Insignificant	0	5	1	6	6	4	1	4
No Overlap	0	3	9	3	5	3	9	5

Notes: * p<0.10, ** p<0.05, *** p<0.01. Blanks indicate no overlap. Robust standard errors in ().
Estimates of Eq. (5), dependent variable is ln(population density) . The reported estimates are on the "overlap" slope dummies (except on the own EC), indicating the increment to the gradient of moving toward the neighbor (the left hand subcenter).
Each column is a regression using only the observations in the own EC's commuting area.

TABLE 6: Influence of Overlap Proximity on Population Density

							Number of coeffs. that are:			
Centers	Woodlands	Baytown	Richmond	Alief	Lake Jackson	Katy	Pos & Sig	Neg & Sig	Insig	No Overlap
CBD	0.116**	0.051	0.300***	0.016	0.063*	0.173***	8	1	4	0
	(0.05)	(0.03)	(0.06)	(0.04)	(0.03)	(0.03)				
Medical Center	0.029	0.104	-0.013	0.094*		-0.007	2	0	8	3
	(0.22)	(0.07)	(0.12)	(0.05)		(0.05)				
Galveston		0.052			0.219		1	0	3	9
		(0.04)			(0.18)					
Greenspoint	-0.024	0.074		0.092**		-0.091*	4	2	4	3
	(0.06)	(0.04)		(0.05)		(0.05)				
Willowbrook	0.092***			0.049		0.102**	6	0	2	5
	(0.03)			(0.05)		(0.04)				
Westchase	-0.229	0.221	0.148	-0.048		0.018	1	1	8	3
	(0.15)	(0.15)	(0.20)	(0.05)		(0.06)				
Conroe	0.118***	.					3	0	1	9
	(0.04)	.								
Webster		0.121***		0.029	0.409***		7	0	1	5
		(0.02)		(0.07)	(0.14)					
Woodlands	0.028					0.124	2	0	5	6
	(0.02)					(0.09)				
Baytown		0.077***		0.667**			3	0	4	6
		(0.03)		(0.28)						
Richmond			0.117**	0.016		0.111***	3	0	2	8
			(0.04)	(0.04)		(0.04)				
Alief		-0.224	-0.253	0.157***		0.010	4	1	4	4
		(0.21)	(0.23)	(0.06)		(0.07)				
Lake Jackson					0.192***		2	1	0	10
					(0.03)					
Katy	-0.072		-0.000	0.079**		0.026	3	0	5	5
	(0.08)		(0.06)	(0.03)		(0.03)				
Constant	2.490*	3.374***	-3.375**	5.423***	1.278	0.005				
	(1.30)	(0.97)	(1.41)	(1.86)	(0.81)	(0.91)				
Observations	122	216	70	373	37	264				

						Totals
3	1	1	4	2	3	49
0	0	0	0	0	1	6
4	6	4	5	1	4	51
6	6	8	4	10	5	76

TABLE 7: Influence of Overlap Proximity on Employment Density

Centers	CBD	Medical Center	Galveston	Greenspoint	Willowbrook	Westchase	Conroe	Webster
CBD	0.099***	0.161*	-0.041	0.007	0.246***	0.132***	-0.324***	0.020
	(0.01)	(0.09)	(0.09)	(0.05)	(0.06)	(0.05)	(0.12)	(0.04)
Med Center	0.118***	0.054		0.162**	-0.113	0.107**		0.020
	(0.03)	(0.10)		(0.07)	(0.09)	(0.05)		(0.06)
Galveston	0.294***		0.501***					0.106*
	(0.02)		(0.06)					(0.06)
Greenspoint	0.092***	0.163***		0.110**	-0.007	0.103***	0.560***	0.106*
	(0.02)	(0.05)		(0.05)	(0.06)	(0.04)	(0.17)	(0.06)
Willowbrook	0.046**	0.051		0.059**	0.085***	0.135***	-0.128	
	(0.02)	(0.04)		(0.02)	(0.02)	(0.03)	(0.17)	
Westchase	0.081**	0.129***		0.082*	-0.088	0.061		0.711***
	(0.03)	(0.05)		(0.05)	(0.06)	(0.05)		(0.17)
Conroe	0.353***			0.050	0.366*		0.238***	.
	(0.04)			(0.19)	(0.19)		(0.07)	.
Webster	0.166***	0.187***	0.541***	0.126**		-0.007		0.097***
	(0.02)	(0.03)	(0.12)	(0.06)		(0.06)		(0.03)
Woodlands	0.049*	0.594**		0.071	0.097	0.055	0.437***	
	(0.03)	(0.28)		(0.07)	(0.06)	(0.16)	(0.11)	
Baytown	0.132***	0.181***	0.419***	0.123**		0.447***		0.102***
	(0.02)	(0.04)	(0.12)	(0.05)		(0.11)		(0.04)
Richmond	0.250***	0.370***				0.144***		
	(0.04)	(0.13)				(0.05)		
Alief	0.103***	0.098*		0.096*	0.244***	0.105*		-0.522***
	(0.04)	(0.06)		(0.06)	(0.08)	(0.06)		(0.15)
Lake Jackson	0.211***		0.818***					-0.383*
	(0.02)		(0.17)					(0.22)
Katy	0.103***	0.094*		0.077*	0.069	0.152***		
	(0.02)	(0.05)		(0.04)	(0.05)	(0.04)		
Constant	-0.941**	-3.952	-4.137**	3.635*	-4.857***	-2.449	5.863***	3.532*
	(0.41)	(3.91)	(1.99)	(1.91)	(1.87)	(2.12)	(1.68)	(1.99)
Observations	877	495	66	467	245	465	37	253

Summary of Results on Overlap Interactions (13 possible excluding own)

The number of centers (excluding own) with:

	CBD	Medical Center	Galveston	Greenspoint	Willowbrook	Westchase	Conroe	Webster
Pos & Sig	13	9	3	7	3	8	2	4
Neg & Sig	0	0	0	0	0	0	1	2
Insignificant	0	1	1	3	5	2	1	2
No Overlap	0	3	9	3	5	3	9	5

Notes: * p<0.10, ** p<0.05, *** p<0.01. Robust std errors in ( ). Blanks indicate no overlap. Estimates of Eq. (5), dependent variable is ln(employment density) . The reported estimates are on the "overlap" slope dummies (except on the own EC), indicating the increment to the gradient of moving toward the neighbor (the left hand subcenter). Each column is a regression using only the observations in the own EC's commuting area.

TABLE 7: Overlap Proximity on Employment (cont)

							Number of coeffs. that are:			
Subcenters	Woodlands	Baytown	Richmond	Alief	Lake Jackson	Katy	Pos & sig	Neg & sig	Insig	No Overlap
CBD	0.183***	0.102**	0.315***	0.126**	-0.002	0.167***	8	1	4	0
	(0.06)	(0.05)	(0.06)	(0.06)	(0.05)	(0.04)				
Med Center	-0.715***	0.142**	0.118	0.110*		0.044	5	1	4	3
	(0.25)	(0.07)	(0.16)	(0.06)		(0.06)				
Galveston		0.034			0.094		2	0	2	9
		(0.06)			(0.17)					
Greenspoint	0.055	0.064		0.041		-0.060	5	0	5	3
	(0.07)	(0.04)		(0.06)		(0.06)				
Willowbrook	0.052			0.052		0.134***	4	0	4	5
	(0.04)			(0.04)		(0.04)				
Westchase	-0.380**	-0.120	0.078	0.107		0.094	4	1	5	3
	(0.19)	(0.18)	(0.12)	(0.07)		(0.06)				
Conroe	0.258***	.					3	0	1	9
	(0.05)	.								
Webster		0.188***		-0.101	0.541***		6	0	2	5
		(0.03)		(0.09)	(0.16)					
Woodlands	-0.029					0.014	3	0	4	6
	(0.03)					(0.06)				
Baytown		0.147***		0.385			6	0	1	6
		(0.03)		(0.41)						
Richmond			0.122**	0.151***		0.153***	5	0	0	8
			(0.05)	(0.05)		(0.04)				
Alief		0.465	-0.241	0.009		-0.034	5	1	3	4
		(0.32)	(0.16)	(0.08)		(0.08)				
Lake Jackson					0.182***		2	1	0	10
					(0.04)					
Katy	0.067		-0.010	0.090**		0.035	5	0	3	5
	(0.09)		(0.05)	(0.04)		(0.04)				
Constant	-1.132	-0.783	-5.243***	-1.228	0.743	-1.644				
	(1.69)	(1.77)	(1.62)	(2.55)	(1.29)	(1.16)				
Observations	122	216	70	373	37	264				

Summary of Results on Overlap Interactions (13 possible excluding own)

The number of subcenters (excluding own) with:	Woodlands	Baytown	Richmond	Alief	Lake Jackson	Katy	**Total**
Pos & Sig	2	3	1	4	1	3	63
Neg & Sig	2	0	0	0	0	0	5
Insignificant	3	4	4	5	2	5	38
No Overlap	6	6	8	4	10	5	76

TABLE 8: Summary of Overalp Results

	Pop Overlap (13 Possible)	Emp Overlap (13 Possible)	Same Subcenter Significant for Pop & Emp	Unique to Pop or Emp
CBD	12	13	12	1
Medical Center	5	9	4	5
Galveston	3	3	3	0
Greenspoint	4	7	3	4
Willowbrook	2	3	2	1
Westchase	6	7	5	2
Conroe	2	2	2	0
Webster	1	4	1	3
Woodlands	3	2	2	1
Baytown	1	3	1	2
Richmond	1	1	1	0
Alief	4	4	2	2
Lake Jackson	2	1	1	1
Katy	3	3	3	0
Total	*49*	*62*	*42*	*22*

Notes: The number of significant coefficients excludes the own center.
The third column is the number of subcenters which have significant coefficients on the same subcenter in Tables 6 and 7, population and employment.
The fourth column reports on the number of subcenters for which only population or employment is significant, but not the other.

TABLE 9: Reciprocity of Subcenter Interactions
Geographically Reciprocal Relationships

	Population		Employment	
	Yes	**No**	**Yes**	**No**
CBD	7	6	8	5
Medical Center	1	3	4	4
Galveston	0	3	1	2
Greenspoint	1	2	2	4
Willowbrook	0	1	0	2
Westchase	1	1	0	3
Conroe	1	0	1	0
Webster	-	-	1	0
Woodlands	-	-	-	-
Baytown	-	-	-	-
Richmond	-	-	-	-
Alief	0	1	0	1
Lake Jackson	-	-	-	-
Totals	11	17	17	21

Notes: This table shows the unique relationships, so is the equivalent of the upper triangle of a matrix of interactions. It shows the number of significant coefficients in Tables 6 and 7 where an employment center relationship is positive and significant in regressions for the own testing the neighbor, and regressions for the neighbor testing the own.
The "-" indicates the relationship is captured in the centers above the dash in the table. The last subcenter (Katy) is captured entirely above.

Table 10: The Impact on Density of Areas Near But Outside Overlap

	Single Employment Center Density Functions		
		ln(Pop)	**ln(Emp)**
	Observations	**Coeff. on Near Dummy**	**Coeff. on Near Dummy**
CBD	878	0.54**	0.47*
		(0.22)	(0.27)
Medical Center	495	n/a[a]	n/a[a]
		.	.
Galveston	66	-0.73**	-0.53
		(0.35)	(0.55)
Greenspoint	467	0.13	0.11
		(0.13)	(0.15)
Willowbrook	245	-0.13	-0.59**
		(0.16)	(0.16)
Westpark	465	n/a[a]	n/a[a]
		.	.
Conroe	37	-1.04***	-1.63***
		(0.32)	(0.43)
Webster	253	-0.22	-0.42**
		(0.14)	(0.18)
Woodlands	122	0.11	-0.26
		(0.31)	(0.42)
Baytown	216	n/a[a]	n/a[a]
		.	.
Richmond	70	-0.21	-0.49
		(0.41)	(0.31)
Alief	373	n/a[a]	n/a[a]
		.	.
Lake Jackson	37	-0.51	0.49
		(0.46)	(0.65)
Katy	264	0.46*	0.47*
		(0.27)	(0.27)

Notes: Each row is a separate regression on own proximity, proximity to the neighbor, a constant, and a dummy variable (NEAR) that indicates an area closer to the neighboring subcenter than the distance between the two centroids, but outside Overlap. We report here only the coefficient on NEAR. Each regression uses only the data in each row's commuting area.

[a] Indicates there are too few observations that are not in NEAR areas to estimate the coefficient.