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16. Abstract

This report assesses alternative accessibility measures using data from the Dallas/Fort Worth, Texas metropolitan area. The measures are evaluated against the following considerations: good theoretical basis of the measure, reasonable data needs, and good empirical performance. The report also discusses the aggregation of accessibility measures over the dimensions of purpose, time of day, mode, and space.

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ASSESSMENT OF ACCESSIBILITY MEASURES

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 -- INTRODUCTION

Past research and the application scope of the current research project point to several considerations relevant to the evaluation of alternative accessibility measures for transportation planning. These considerations include: a) the theoretical basis of the measure; b) the ease of aggregation over time, space, activity, mode, and individual or household type; c) the data needed for estimation; and d) application and performance of the accessibility measure.

The focus of this report is on assessing alternative accessibility measures using data from the Dallas/Fort Worth, Texas metropolitan area. The measures will be evaluated against the following considerations: good theoretical basis of the measure, reasonable data needs, and good empirical performance. The issue of aggregation will be considered at the end. The report is organized as follows: Chapter 2 presents a review of earlier studies comparing different accessibility measures. Chapter 3 examines the evaluation considerations proposed in this study in detail.

Chapter 4 describes the Dallas/Fort Worth data used for the application of the different measures and explains the different measures proposed for evaluation. Chapter 5 evaluates the performance of the proposed accessibility measures. Finally, Chapter 6 summarizes the evaluation of the proposed accessibility measures against the proposed considerations and discusses a general approach to the issue of aggregation.

CHAPTER 2 – EMPIRICAL CONSIDERATIONS

Accessibility is a combined result of the transportation system and land use patterns. The transportation dimension of the measure is typically referred to as the impedance and may be measured as travel time or distance. The land use dimension of accessibility may be referred to as the attractiveness, opportunity, or activity. Accessibility measures considered in the literature are of five primary types characterized by how these dimensions are related. These five types are: spatial separation, cumulative opportunities, gravity, utility, and time-space. Spatial separation measures use the distance between a location and every other location in the study area as the value of accessibility. Cumulative opportunities measures consider the attractiveness of a journey in their formulation. A summation of these attractions, or opportunities, within a specified travel time, or distance, provides the accessibility value of cumulative opportunities measures.

A third type of accessibility measures is gravity measures. These are continuous measures that sum attractions in a study area but discount them with increasing time or distance from the origin. Utility measures are based on an individual's perceived utility for different travel choices. These measures take the form of the natural log of the sum of the travel choices. Time-space measures add a third dimension to the conceptual framework of accessibility. They take into account the time constraints of the individuals being considered.

Not surprisingly, different measures computed from the same data set can lead to different conclusions. Therefore, a systematic method of analysis is necessary. Several earlier studies have compared different formulations of the accessibility measures described above using the same data (Kwan 1998, Guy 1983, Song 1996). As described below, this research provides insight into a method to compare alternative measures.

For example, Kwan undertook a comprehensive comparison of accessibility measures, including twelve gravity-type measures, six cumulative-opportunity measures, and twelve space-time measures (see Table 2.1). The twelve gravity-type measures were further broken down into three types of impedance functions: inverse power, negative exponential, and modified Gaussian. Twelve time-space measures were also considered. Using data from the Columbus, Ohio area

Kwan (1998) found the gravity and cumulative-opportunity measures to generally correlate with each other but to have poor correlation with the space-time measures.

Kwan presented his data in three-dimensional maps. The x-y plane represented the physical study area and the z coordinate represented the accessibility value. Using this portrayal of his results for comparison, he found that the gravity and cumulative-opportunity measures produce distinctive spatial patterns, while the space-time contours are "somewhat haphazard" (Kwan 1998: 208). The various impedance functions used in the different measures primarily affected the size of peaks and troughs and hence their respective ability to amplify small underlying differences.

Table 2.1 – Accessibility Measures Used in Empirical Comparisons

Guy (1983)	$A_i = \sum_j S_j d_{ij}^{-b}$ The Gaussian form: $A_i = \sum_j S_j \exp\left[-\frac{1}{2}\left(\frac{d_{ij}}{d*}\right)^2\right]$ $A_i = \sum_k d_{ij(k)} E_k \Big/ \sum_k E_k$	S_j = "size" of opportunity at j (set at 1.0 pending information about the "size" of shops) d_{ij} = straight-line distance between home, i, and opportunity j b = constant (calculated for four intervals rising from 1.0 by intervals of 0.5) $d*$ = distance after which access to shops is "awkward" $d_{ij(k)}$ = Euclidean distance to a shop j in which good k is available E_k = mean expenditure per household on good k

Table 2.1 Continued

	$A_i =$ $O_i(D)\left[D-\left(\sum_{j=1}^{O_i(D)} d_{ij} \Big/ O_i(D)\right)\right]$	$O_i(D)$ = total number of opportunities available to home i within distance D from the home d_{ij} = straight-line distance between home i and opportunity j
Kwan (1998)	Gravity-type, inverse power $A_i = \sum W_j d_{ij}^{-\alpha}$ Gravity-type, exponential $A_i = \sum_j W_j e^{-\beta d_{ij}}$ Gravity-type, Gaussian $A_i = \sum_j W_j e^{-d_{ij}^2/v}$ Cumulative opportunity, rectangular $A_i = \sum W_j f(d_{ij})$ Cumulative opportunity, negative linear $A_i = \sum W_j f(d_{ij})$	Weighted average of opportunities based on building height W_j = weighted area of location j d_{ij} = travel time in minutes between locations i and j α = 0.8, 1.0, 1.5, 2.0 β = 0.12, 0.15, 0.22, 0.45 v = 10, 40, 100, 180 $f(d_{ij})$ = 1 for $d_{ij} \leq$ T ; 0 otherwise $f(d_{ij})$ = (1-t/T) for $d_{ij} \leq$ T ; 0 otherwise T = 20, 30, 40
Song (1996)	$A_i = \dfrac{\sum_{j \neq i} E_j d_{ij}^{-1}}{E}$	E = total employment in region d_{ij} = distance between two points

Table 2.1 Continued

	$A_i = \frac{\sum_{j \neq i} E_j d_{ij}^{-\lambda}}{E}$ $A_i = \frac{\sum_{j \neq i} E_j e^{-\lambda d_{ij}}}{E}$ $A_i = \frac{\sum_{j \neq i} E_j e^{-\lambda d_{ij}^2}}{E}$ $A_i = \frac{\sum_{d_{ij} \leq d_o} E_j}{E}$ $\overline{d}_i = \frac{\sum_{j \neq i} d_{ij}}{n-1}$ $WAD_i = \frac{\sum_{j \neq i} E_j d_{ij}}{\sum_{i \neq j} E_j}$	$\overline{d}_i$ = average distance measures WAD = weighted average distance (note: distance to the central business district was also used as a measure)

Guy (1983), using data from Reading, Berkshire, England, compared several different types of gravity-based accessibility measures (see Table 2.1) and found good correlation among these different gravity measures when evaluating accessibility at one point in time. However, the measures considered exhibited inconsistent correlation when applied over time.

Song (1996) looked at spatial separation, cumulative opportunities, and gravity measures using data from the Reno/Sparks, Nevada area. Regarding the fit to data the gravity measures were found to perform the best.

Criteria such as data availability, demographic stratification, and aggregation were not addressed by any of the researchers. The results of the research described above highlights the difference among different accessibility measures (Kwan 1998, Song 1996) as well as the difference within one type of measure (Guy 1983). This suggests that the form of the measure does matter and results should be evaluated as to expected outcomes on various levels (i.e. location, transportation system characteristics, socio-demographic characteristics).

CHAPTER 3 -- THEORY REGARDING ACCESSIBILITY MEASURES

Accessibility measures have been proposed for a variety of purposes, such as to measure the effectiveness of congestion mitigation programs (Meyer 1995), to measure the accessibility of low income households to jobs (Wachs and Kumagi 1973), and to measure access to medical services (Knox 1978).

Regardless of the application purpose of accessibility measures, they should satisfy certain basic considerations. Earlier studies have identified at least four such considerations: a) the theoretical basis of the accessibility measure, b) ease of aggregation over time, space, activity, mode, and individual or household type, c) data needed for estimation and application, and d) performance of the accessibility measure. A behavioral basis for an accessibility measure is desirable because the goal of an accessibility measure is to develop a model that represents the decisions facing individuals. In order to accomplish a certain activity, an individual may take into account circumstances such as time of day, or characteristics of the mode.

Ease of aggregation along a variety of dimensions provides alternative ways to analyze an area. For example, a social services agency might be interested in accessibility results aggregated by a socio-demographic group, or by a group for a particular mode.

Data needs for estimation and application provide a realistic assessment of the usefulness of an accessibility measure. Lastly, an accessibility measure for an area should meet certain performance expectations. For example, when measuring accessibility to shopping, malls and shopping districts should be local peaks in the results.

Regarding the sound theoretical basis of an accessibility measure, several researchers have proposed basic criteria that need to be addressed by any accessibility measure (Bach 1981, Morris et al. 1979, Pirie 1979, Weibull 1976, Weibull 1980). Because accessibility is a combined result of the transportation system and land use patterns, many researchers agree that any measure should respond to changes in either, or both, of these elements (Handy and Niemeier 1997, McKenzie 1984, Morris et al. 1979, Voges and Naudé 1983, Zakaria 1974).

Weibull developed several axioms for the form of an accessibility measure (Weibull 1976). Many researchers adhere to these basic properties (Koenig 1980, Miller 1999, Tagore and Sikdar 1996). The order of opportunities should not affect the value of the measure; the measure should not increase with increasing distances or decrease with increasing attractions; and opportunities with zero value should not contribute to the measure.

The first property describes a measure that is independent of the order of the data. The second describes a behavioral assumption of an accessibility measure – attractions have utility and travel has disutility. The third property addresses the area of relevance, and the proper coding of attractions when developing a measure.

Morris et al. (1979) propose several other desirable characteristics that are less rigorous in nature.

- A measure should have a behavioral basis;
- it should be technically feasible; and
- it should be easy to interpret.

The first characteristic suggests the need to incorporate sociodemographic factors that may influence activity participation. However, researchers do not necessarily agree as to what the behavioral basis should be. For example, several researchers (Breheny 1978, Handy and Niemeier 1997, McKenzie 1984, Pirie 1979) argue that observed behavior in a constrained environment is not necessarily an indicator of preferred behavior. The second characteristic presages today's performance measures. It highlights the real-world application of accessibility measures developed in the academic literature. In addition, researchers call for the use of data already gathered to increase feasibility. Lastly, having a measure that is easy to interpret facilitates policy-making and public involvement.

Others have proposed additional desirable characteristics and properties. Davidson (1977) indicates that accessibility should increase as another mode is added to an area, and conversely not decrease the accessibility of the original modes. A measure should explicitly acknowledge the addition of a new mode to the choice set. Voges and Naudé (1983) argue that disaggregation is an important quality of accessibility measures that allows evaluation along several different dimensions.

Before an accessibility measure is planned, Wilson (1971) proposes several questions that need to be answered. These are:

- what is the degree and type of disaggregation desired;
- how are origins and destinations defined;
- how is attraction measured; and
- how is impedance measured.

This last point is an important characterization of a measure. A distance measure does not account for level of service and a time measure is time-of-day dependent. Savigear (1967) suggests that parking availability should be a consideration when trying to determine accessibility to places – particularly central business districts (CBD).

Besides the specific characteristics outlined above, researchers have investigated other parameters potentially affecting an accessibility measure. Bach (1981) assessed the influence of separation measurement and different levels of aggregation on a measure's value. In terms of trading off accuracy and efficiency, Bach concludes that cities today generally have information available at a zonal level that is appropriate for determining the placement of public facilities (libraries, post offices, swimming pools, etc.). Bach cautions that the level of aggregation should be considered when trying to measure the accessibility of a location, because the level of aggregation can change but the location of the point in question is constant.

Also affecting the parameters of an accessibility measure is the difference between perceived and objective accessibility (Morris et al. 1979, Pirie 1979). Wilson (1971) argues that impedance factors need to be weighted to reflect individuals' perceptions. However, construction of perceived accessibility measures requires subjective data, and applications of such measures are more difficult from a data standpoint than using objective parameters in the accessibility measure.

Section 3.1 – Considerations to Evaluate an Accessibility Measure

The standards cited by the authors above can generally be categorized into the four considerations proposed to evaluate these accessibility measures: a) the theoretical basis of the accessibility measure, b) ease of aggregation over time, space, activity, mode, and individual or household type, c) data needed for estimation and application, and d) performance of the accessibility measure. Researchers agree that theoretically an accessibility measure should have a behavioral basis and be easy to interpret (Morris et al. 1979). Regarding the actual construction of the measure, researchers agree that an appropriate measure should not increase with increasing distance, decrease with increased opportunities, and the order of the opportunities should not affect the value of the measure (Weibull 1976). A theoretically sound suggestion, that is difficult to implement, is that an accessibility measure should reflect citizens' perceptions of impedance (Wilson 1971) and attractiveness.

There are several suggestions from the literature regarding the performance of an accessibility measure. First, it should be responsive to changes in land use and the transportation system (Handy and Niemeier 1997, McKenzie 1984, Morris, et al. 1979, Voges and Naudé 1983, Zakaria 1974). As a corollary, it should increase with increasing mode choice (Davidson 1977) and opportunities with zero value should not contribute to the value of the accessibility measure.

Several authors highlight the potential issues associated with aggregation (Bach 1981, Wilson 1971). On the other hand, disaggregation is also important in order to evaluate along different dimensions (Voges and Naudé 1983). None of the research evaluated for this project specifically addresses the issues related to data availability. However, Morris et al. (1979) suggest that an accessibility measure should be technically feasible. These are the broad areas that will be used to evaluate the measures described below.

CHAPTER 4 -- MEASURES FOR EVALUATION AND DATA SET

Of the five main types of accessibility measures described at the beginning of chapter 2, variations on two types will be evaluated. Spatial separation measures will not be evaluated because they do not have an activity component. Utility measures and gravity measures are essentially equivalent (as explained in Section 4.1), and so will be collapsed into one category referred to simply as gravity measures. Time-space measures will not be evaluated here due to high data needs. Therefore, the consideration of the data needs of a measure has already been used to exclude a type of accessibility measure from evaluation.

Two types of cumulative opportunities measures will be evaluated: one with a 15 minute cutoff (CO 15) and one with a 30 minute cutoff (CO 30). In addition, four types of gravity measures will be evaluated: activity/in-vehicle-travel-time$^{\alpha}$ (activity/IVTT), activity/distance$^{\alpha}$ (activity/DIST), Gaussian (GAUSS, with the average travel time used as the point of inflection), and a form that uses a parallel conductance form of impedance (also known as composite impedance, COMP IMP) (Bhat et al. 1999).

Table 4.1 - Accessibility Measures Evaluated

Type of Measure	Name (abbreviation)	Form of Measure	
Cumulative Opportunities	(CO15) (CO30)	$A_i = \sum_j O_{jt}$	O_{jt} = activity in zone j where j is within time t of zone i t = 15 minutes t = 30 minutes
Gravity Measures	Gaussian (GAUSS)	$A_i = \sum_j O_j \exp\left[-(t_{ij}/t_*)^2/2\right]$	t_{ij} = travel time between zones i and j t_* = average travel time to each type of activity based on local travel diary data t_* (work) = 24 min. t_* (shopping) = 16 min. t_* (recreation) = 15 min.

Table 4.1 Continued

	Composite Impedance (COMP IMP)	$$A_i = \ln\left[\frac{1}{J}\sum_{j=1}^{J}\left(\frac{O_j^{\alpha}}{C_{ij}^{\mu}}\right)\right]$$ where: C (equivalent auto in-vehicle time units) = $IVTT_{auto} + \beta * OVTT_{auto} + \gamma * Cost_{parking}$	J = total number of zones in the area $\alpha_{work} = 0.7554$ $\alpha_{shopping} = 0.2868$ $\alpha_{recreation} = 0.1376$ $\mu_{work} = 2.6507$ $\mu_{shopping} = 3.078$ $\mu_{recreation} = 2.677$ $\beta_{work} = 0.3385$ $\gamma_{shopping} = 0.0992$ all other parameters are insignificant
	Distance as impedance (DIST)	$$A_i = \ln\left[\frac{1}{J}\sum_j \frac{O_j}{d_{ij}^{\alpha}}\right]$$	$\alpha_{work} = 2.0347$ $\alpha_{shopping} = 2.5000$ $\alpha_{recreation} = 3.0751$
	In-vehicle-travel-time as impedance (IVTT)	$$A_i = \ln\left[\frac{1}{J}\sum_j \frac{O_j}{IVTT_{ij}^{\alpha}}\right]$$	$\alpha_{work} = 2.6194$ $\alpha_{shopping} = 3.1600$ $\alpha_{recreation} = 3.9191$

All these measures have been applied using parameters estimated from Dallas/Fort Worth data. See Appendix A for a complete description of the estimation process. For activity/$IVTT^{\alpha}$ and activity/distance$^{\alpha}$, α was estimated separately for each type of activity under consideration: work, shopping, and recreation. In the case of the Gaussian measure, the point of inflection, denoted by t_* in the equation (Table 4.1), is the average trip length for the activity as calculated from the 1996 study area travel diary data. See Table 4.1 for a complete list of the measures under consideration and their parameters. The full form of the composite impedance measure includes an impedance function consisting of three terms allowing for the inclusion of transit and walk modes. Section 4.2 explains this in more detail. The analysis here relies exclusively on the automobile mode, therefore the equation collapses to just the first term.

All the measures will use data for the Dallas/Fort Worth metropolitan area. The study area considered for analysis encompasses five counties (Collins, Dallas, Denton, Rockwall, and

Tarrant) plus portions of four others (Ellis, Johnson, Kaufman, and Parker). The study area spans a total of three million acres with four million inhabitants (Figure 4.1). The street and land use data for the study area are from 1995 and the travel diary data used to calibrate the measures are from 1996. These data are used to assess the accessibility to three different types of activities: work, shopping, and recreation. Total number of employees per zone is used as the attraction for accessibility to work. Number of employees in the retail sector is used as the attraction for accessibility to shopping. Park acreage is used as the attraction for accessibility to recreational activities. Only one mode is considered at this time -- auto, and one time of day – the peak period. See Appendix A for a complete description of the preparation of the data set for analysis and estimation of parameters.

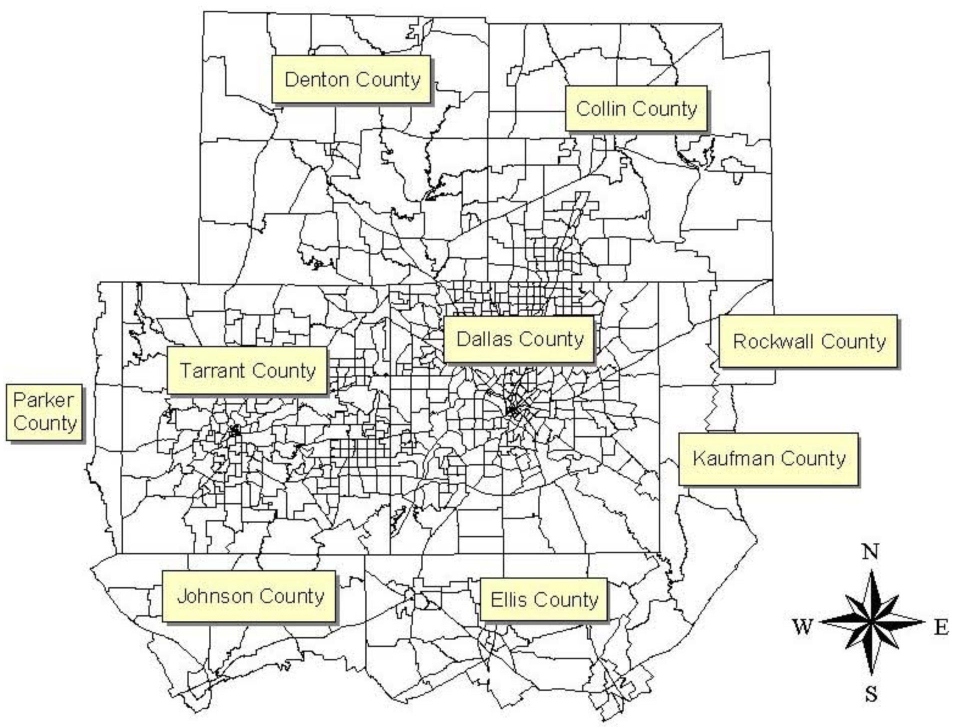

Figure 4.1 – North Central Texas Council of Governments (NCTCOG) Study Area Dallas/Fort Worth Area

Section 4.1 – Equivalence of Gravity and Utility Measures

As applied in this research the gravity and utility measures are essentially equivalent. In Table 4.1 the activity/distance and activity/IVTT measures are general gravity type accessibility measures. The natural log form is frequently not used, but it is essentially a scaling factor.

A utility accessibility measure begins with the utility of an activity in a zone *j* for a person in another zone *i*. Equation 4.1 represents a general utility function for accessibility to work.

$$V_{ij}^{work} = \gamma^{work} \times \ln(activity_{work})_j - \beta^{work} \times \ln(impedance)_{ij} \quad \text{(Eq. 4.1)}$$

The probability that an individual in zone *i* will choose to participate in an activity in zone *j* is given by equation 4.2.

$$P_{ij}^{work} = \left[\frac{\exp(V_{ij}^{work})}{\sum_k \exp(V_{ik}^{work})} \right] \quad \text{(Eq. 4.2)}$$

Assuming a multinomial logit form for destination choice, substituting equation 4.1 into the denominator of equation 4.2, and taking the logarithm of the average of this denominator gives equation 4.3. This is functionally equivalent to the non-Gaussian gravity measures in Table 4.1.

$$A_i = \ln\left[\frac{1}{J} \sum_j \exp(V_{ij}^{work}) \right] = \ln\left[\frac{1}{J} \sum_j \frac{activity_{work}^{\gamma_{work}}}{impedance_{work}^{\beta_{work}}} \right] \quad \text{(Eq. 4.3)}$$

Section 4.2 – A Closer Look at the Composite Impedance Measure

The unique characteristic of the composite impedance measure lies in its parallel conductance-based impedance formulation (Bhat et al. 1999). Equation 4.4 is the full form of the impedance component of the equation in Table 4.1. This form allows for the inclusion of different mode-specific combinations into the calculation of impedance for the measurement of accessibility.

$$H = (1-y_t)(1-y_w)C + y_t(1-y_w)\left(\frac{C}{1+\frac{C}{T^{\beta}}}\right) + y_w(1-y_t)\left(\frac{C}{1+\frac{C}{W^{\gamma}}}\right) + y_t y_w\left(\frac{C}{1+\frac{C}{T^{\beta}}+\frac{C}{W^{\gamma}}}\right) \quad \text{(Eq. 4.4)}$$

The transit dummy variable y_t, takes a value of 1 if transit is available between two zones, and zero otherwise. Similarly the walk dummy variable y_w, takes a value of 1 if walk is available between two zones and zero otherwise. The term *C* is the highway impedance (including cost and out-of-vehicle travel time in equivalent in-vehicle travel time units). There is a similar term for transit, *T*, and *W* is walk time. The exponents on these terms are derived from local data.

If both non-auto modes are not available the first term applies and the composite impedance is the auto impedance only. If transit is available, but walk is not, the second term applies. If walk is available, but transit is not, the third term applies. If all modes are available the fourth term applies.

The composite impedance measure of accessibility intrinsically adheres to Davidson's (1977) principle of accessibility that it should increase with increasing mode choice options. If two zones *i* and *j* have the same auto impedance to a third zone *k* and only zone *i* also has transit service to zone *k*, then the overall impedance between zones *i* and *k* will be less that the overall impedance between zones *j* and *k*.
See Appendix A for a description of the estimation of the parameters for the composite impedance, activity/distance, and activity/IVTT measures.

CHAPTER 5 -- PERFORMANCE OF ACCESSIBILITY MEASURES

The land use and transportation network data for the Dallas/Fort Worth region were used to compute accessibility values at the transportation analysis and process (TAP) zone level for the Dallas/Fort Worth region. The accessibility values computed for each measure and for each activity were normalized to a range of 1-100; and divided into ten equal intervals for representing accessibility of each TAP. For certain types of analysis, a review of accessibility indices by quantiles may be important, and such quantile maps are presented in Appendix B for work.

Results across the whole study area are presented in Figures 5.1 through 5.9 for accessibility to work, shopping, and recreation using the equal interval approach. In evaluating the results over the whole study area, it is expected that there should be high accessibility in areas with high levels of activities (i.e. city centers compared to largely rural areas). Also, there should be some local peaking in the smaller communities in the larger study area. Due to uneven development and an uneven transportation system, it is hypothesized that there is variation across large areas, such as counties.

Figures 5.1 through 5.3 show the results of the different measures for the whole study area depicting accessibility to work. The CO 15 and CO 30 measures assign medium and high accessibility levels to only a few zones in the Dallas and Fort Worth metro areas. The Gaussian measure assigns more zones to the higher categories. Some of the smaller communities in the southeastern part of the study area show higher accessibility than their surrounding zones. The composite impedance measure assigns much higher local peaks to the surrounding communities in the northern and southern parts of the study area. However, all of Dallas County and the majority of Tarrant County have high accessibility. Both the activity/IVTT and activity/distance measures show local peaking in the smaller communities in the northern and southern parts of the study area. While the majority of the high zones are concentrated in Dallas and Tarrant Counties there is generally more variation in the levels of accessibility.

Figures 5.4 through 5.6 show accessibility to shopping. Here the CO 15 and CO 30 measures perform marginally better than for accessibility to work. A few of the communities in the northern part of the study area show local peaks, but they are not dramatically higher than the surrounding zones. The Gaussian measure performs only marginally better than the CO 30 measure. The composite impedance, activity/IVTT, and activity/distance measures all perform approximately the same. They all show local peaking in the surrounding communities as well as some variation within Dallas and Tarrant Counties.

Accessibility to recreation is presented in Figures 5.7 through 5.9 for each measure. Here the CO 15 measure shows high accessibility in zones with large parks (such as in the northwestern part of the study area) however, there is no gradation in the surrounding zones. This is due to the "cut off" nature of the measure. There may also be issues associated with using the same cut off time for all activities. People may be willing to travel longer or shorter distances depending on the nature of the activity at the trip destination. The CO 30 zone continues to show the core metro areas with high accessibility and few zones with high accessibility, although there are several large parks in the counties surrounding Dallas and Tarrant Counties. The Gaussian measure picks up the surrounding zones with large areas of parkland, especially in the north, but largely ignores zones with parkland in the northeastern part of the study area and in the south. The composite impedance, activity/IVTT, and activity/distance measures all show local peaking in these areas with parkland.

It is assumed that it is desirable for a measure to show variation in the region. There should not be a preponderance of zones of a very high or a very low level. One way to evaluate this aspect of a measure's performance is by looking at a frequency diagram. This is presented in Figures 5.10 through 5.12. All the diagrams are presented at the same scale, except for the activity/distance$^{\alpha}$ and activity/IVTT$^{\alpha}$ results since they are heavily skewed to a high number of low accessibility zones. Since all these results are normalized to a scale of 100 based on the highest and lowest values, it only takes one outlier to skew the normalized values to the other end of the scale.

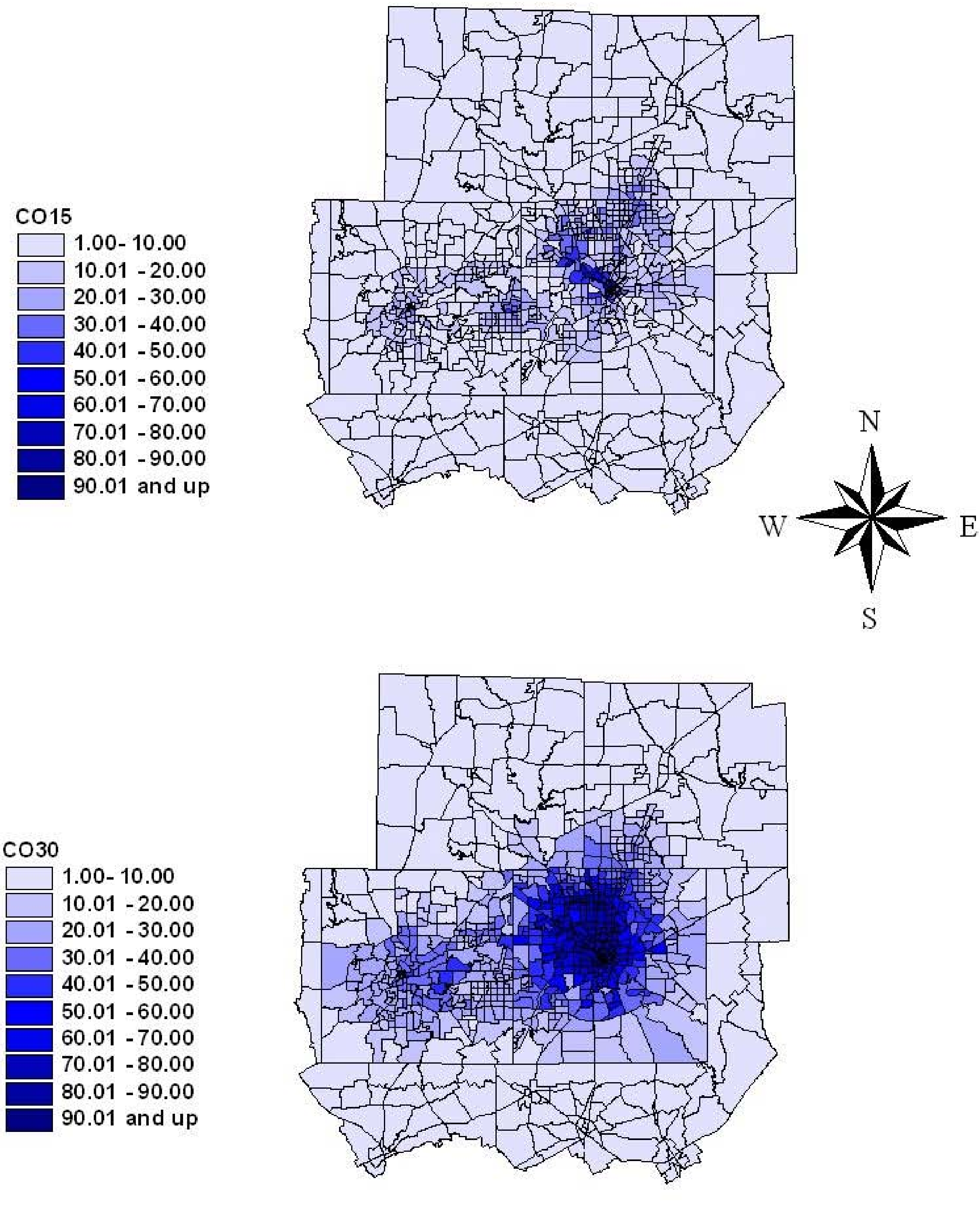

Figure 5.1 – Cumulative Opportunities Accessibility to Work 15 and 30 minute intervals

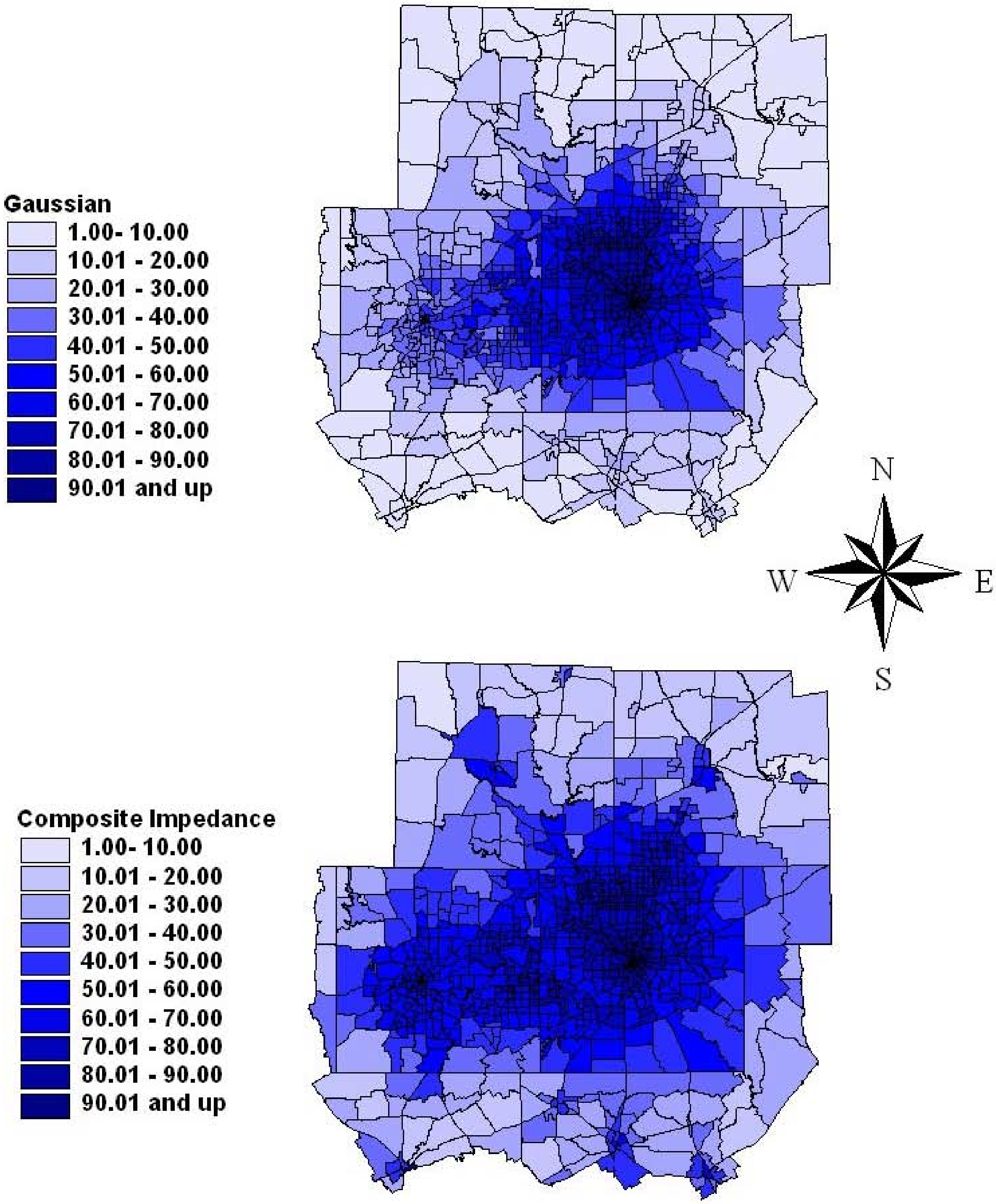

Figure 5.2 – Gaussian and Composite Impedance Accessibility to Work

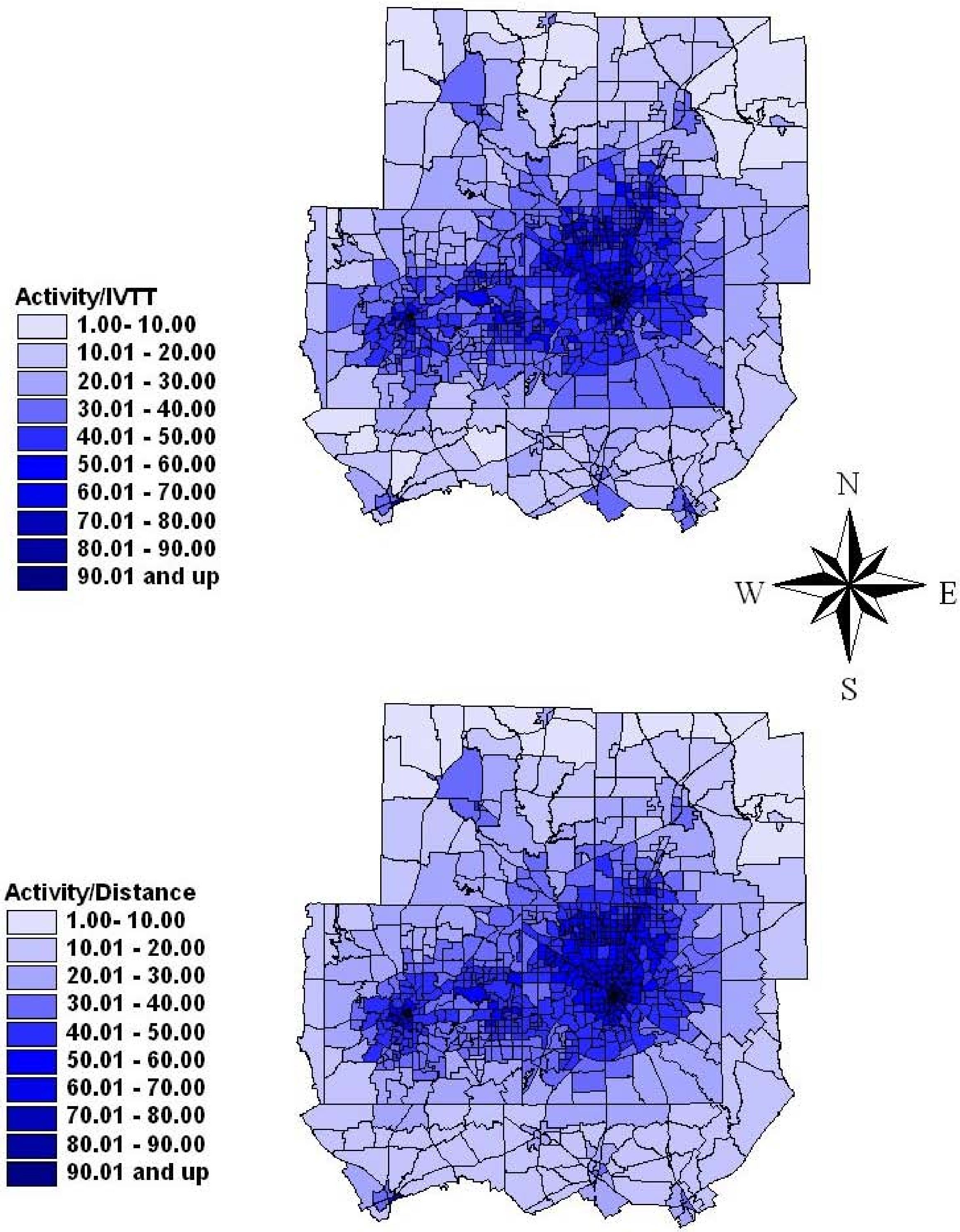

Figure 5.3 – IVTT and Distance Impedance Accessibility to Work

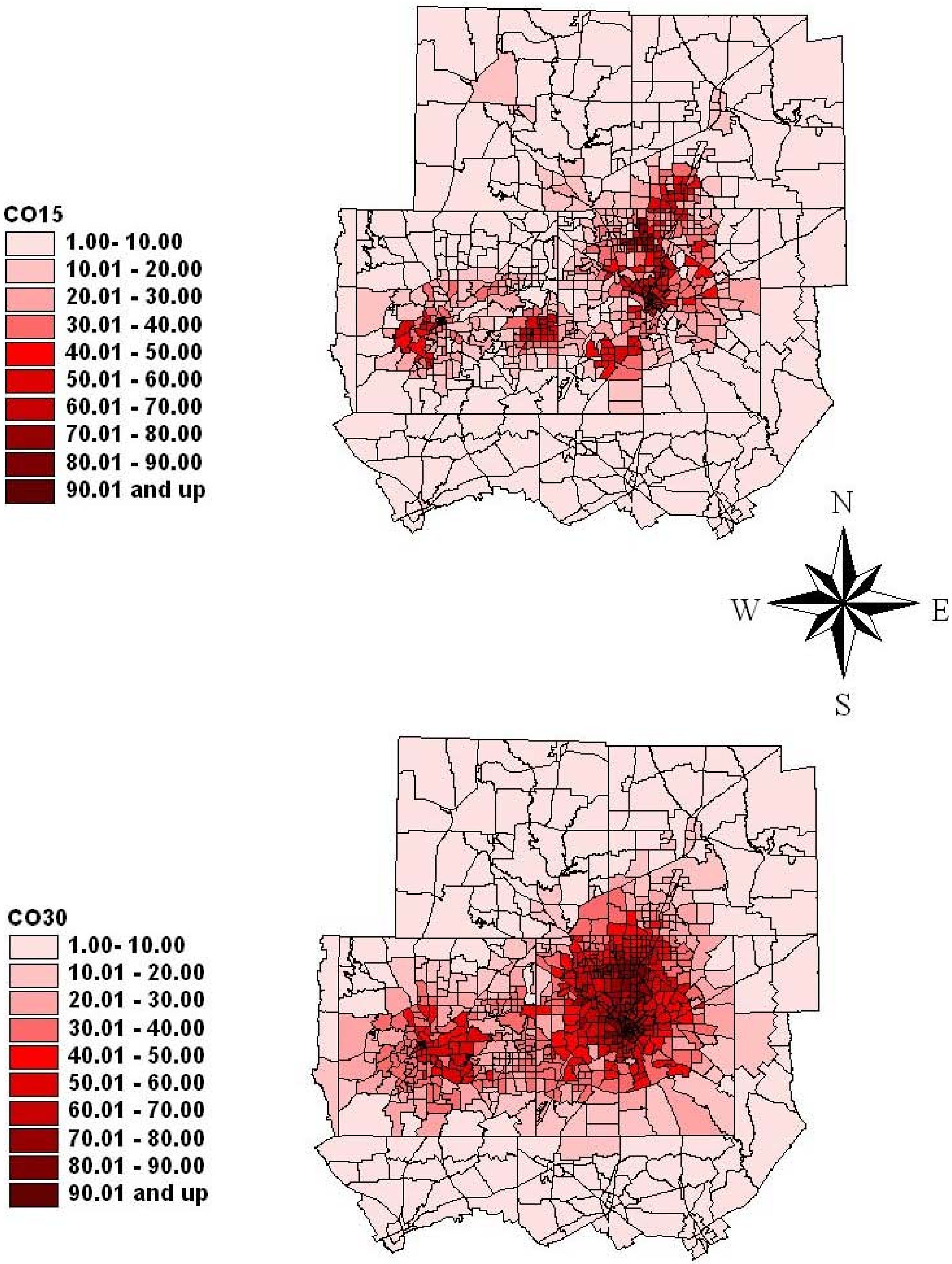

Figure 5.4 – Cumulative Opportunities Accessibility to Shopping 15 and 30 minute intervals

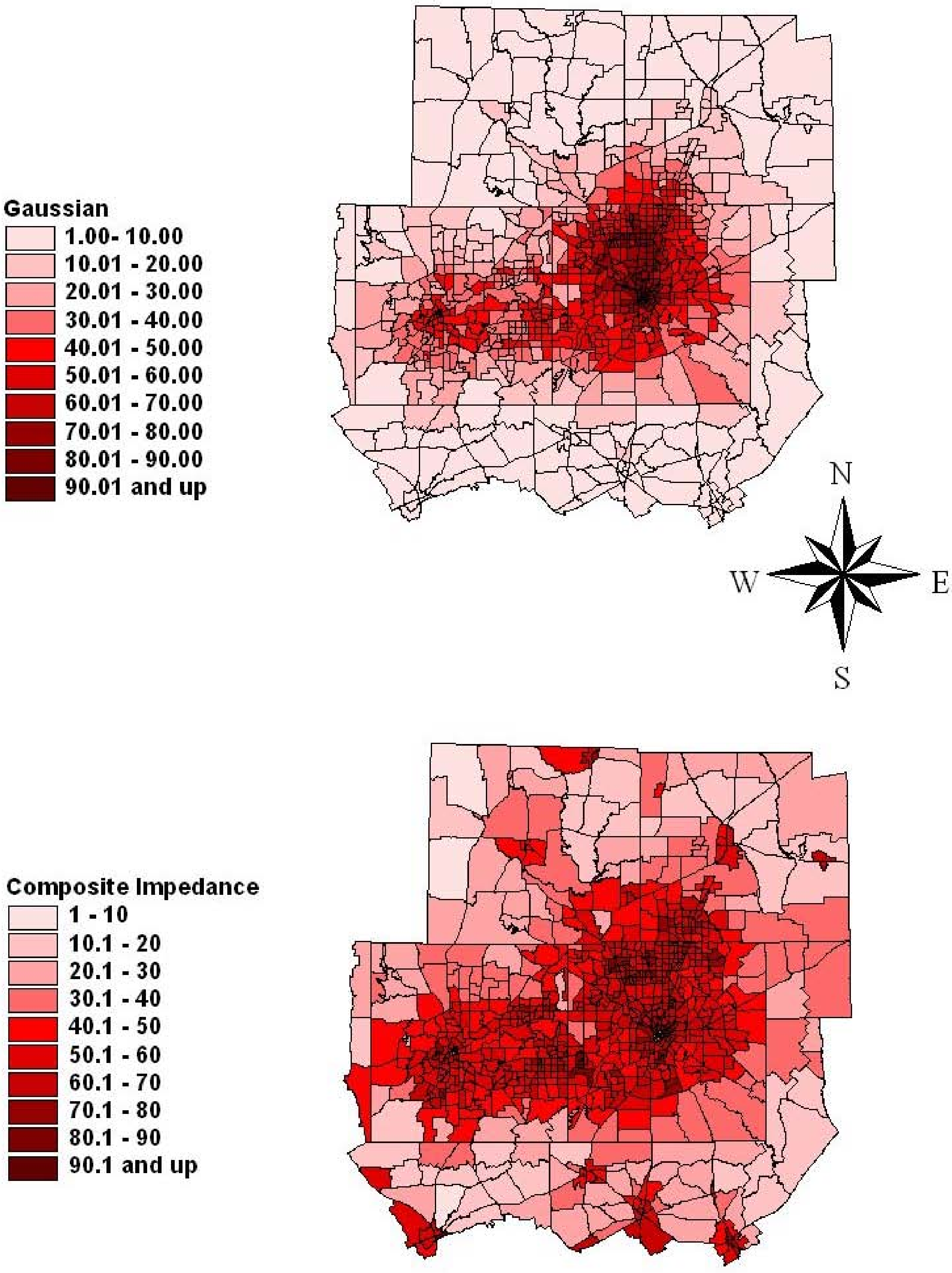

Figure 5.5 – Gaussian and Composite Impedance Accessibility to Shopping

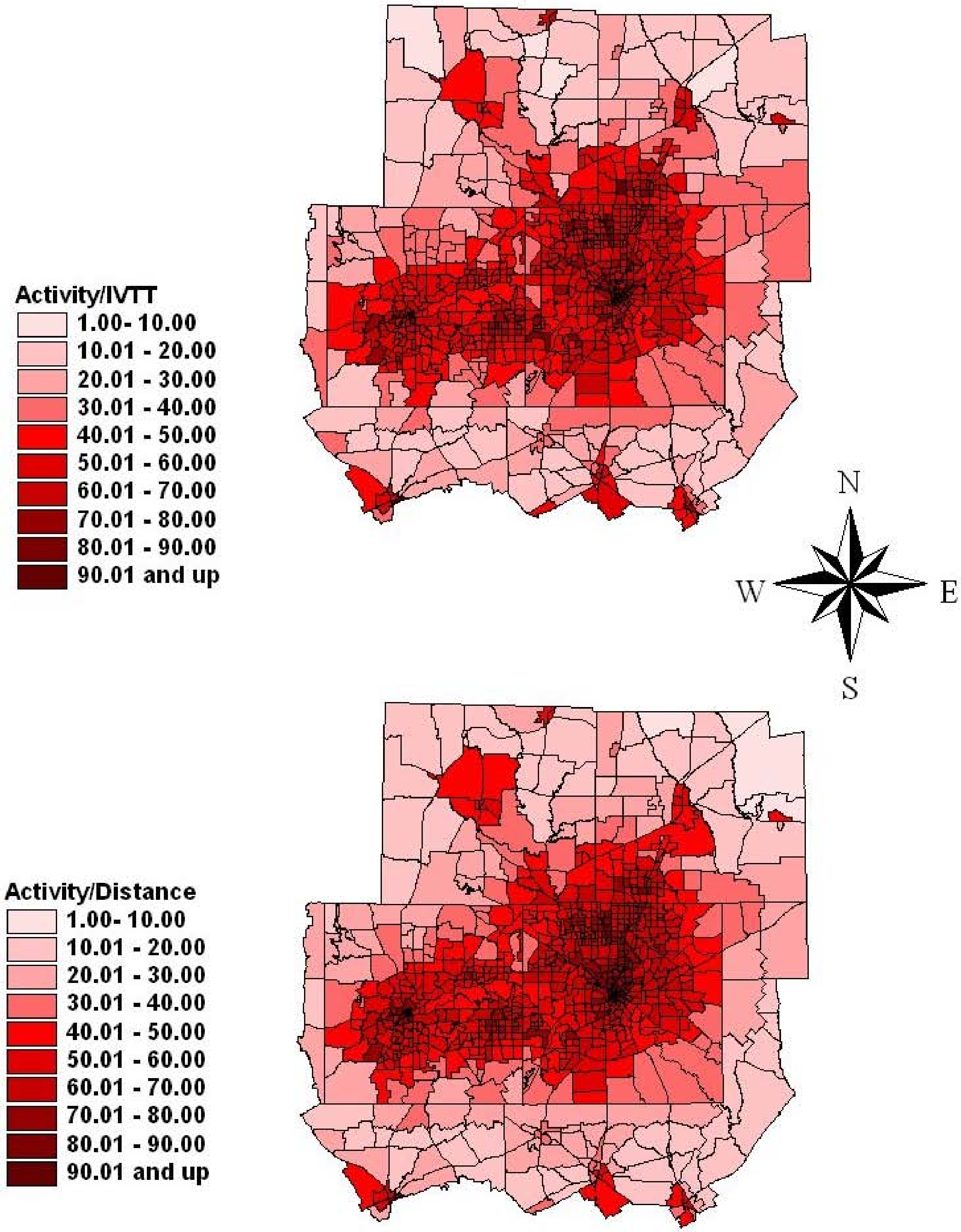

Figure 5.6 – IVTT and Distance Impedance Accessibility to Shopping

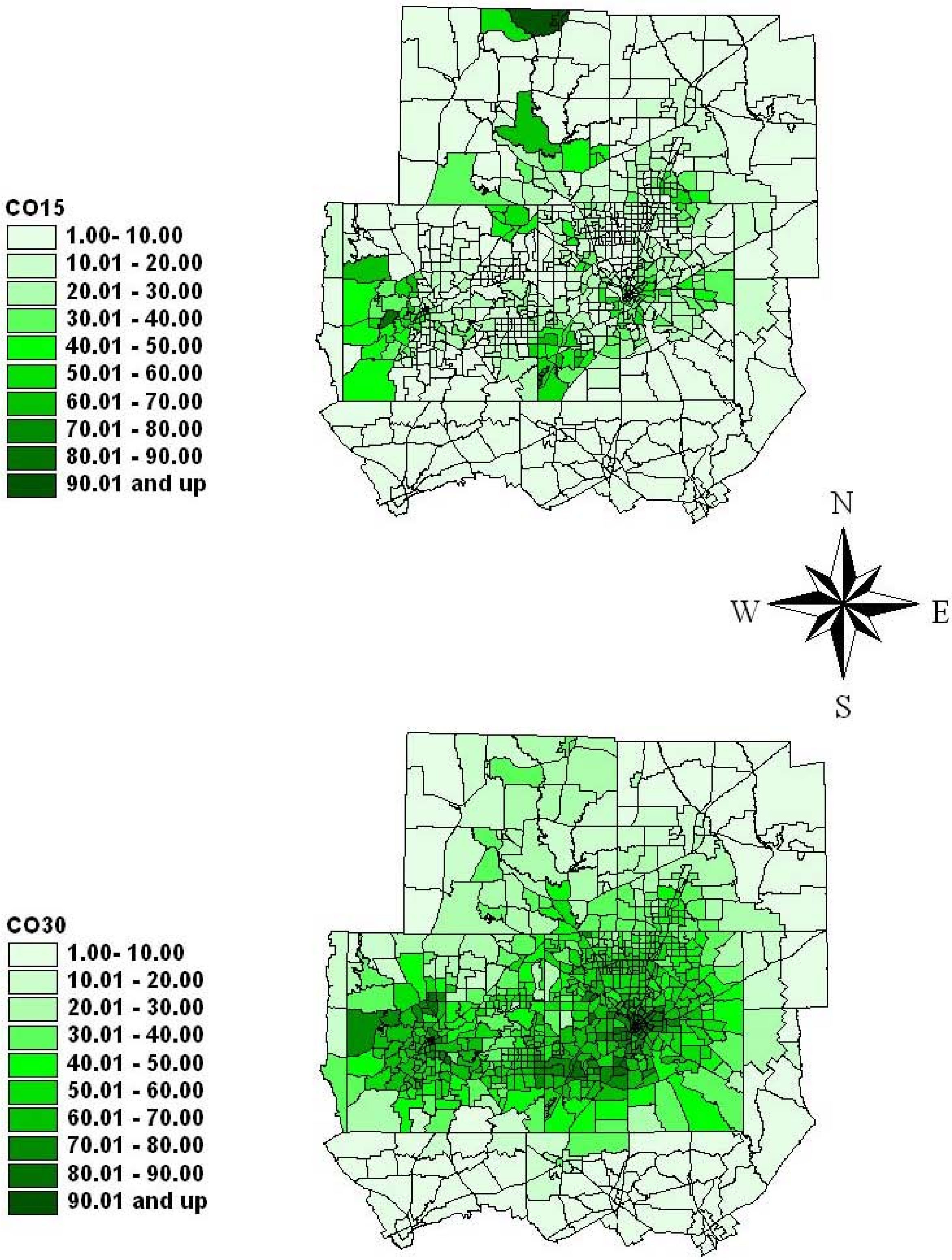

Figure 5.7 – Cumulative Opportunities Accessibility to Recreation
15 and 30 minute intervals

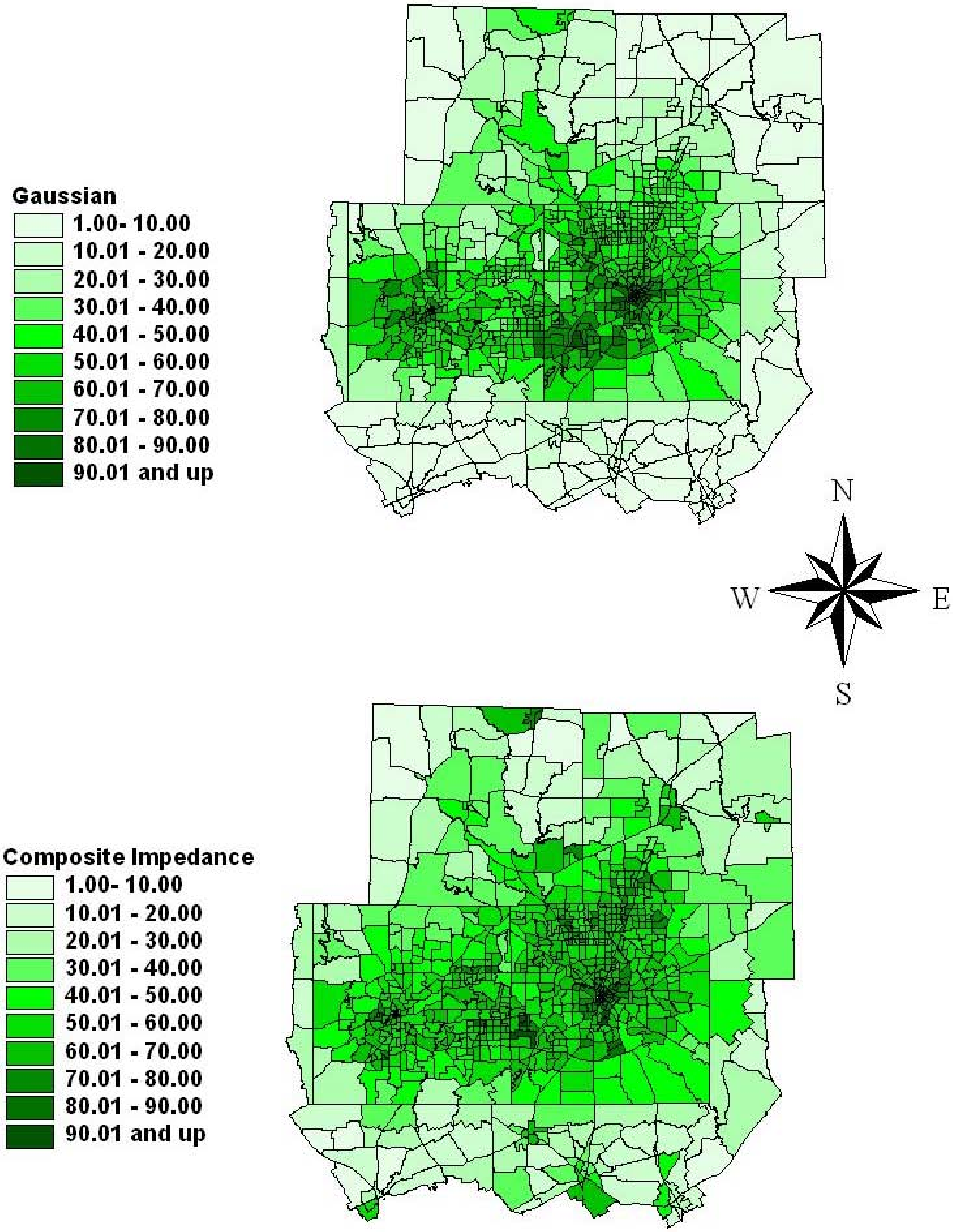

Figure 5.8 – Gaussian and Composite Impedance Accessibility to Recreation

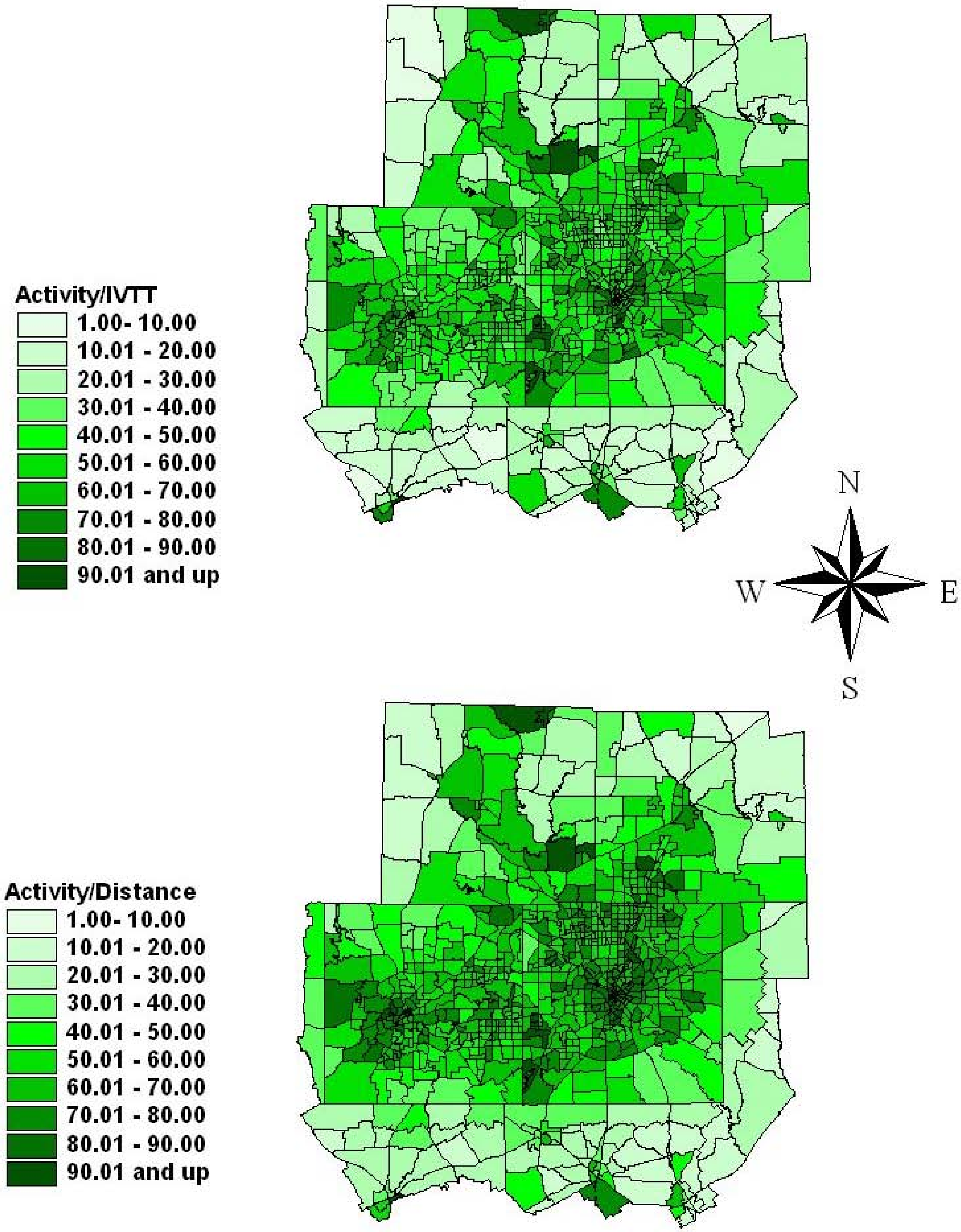

Figure 5.9 – IVTT and Distance Impedance Accessibility to Recreation

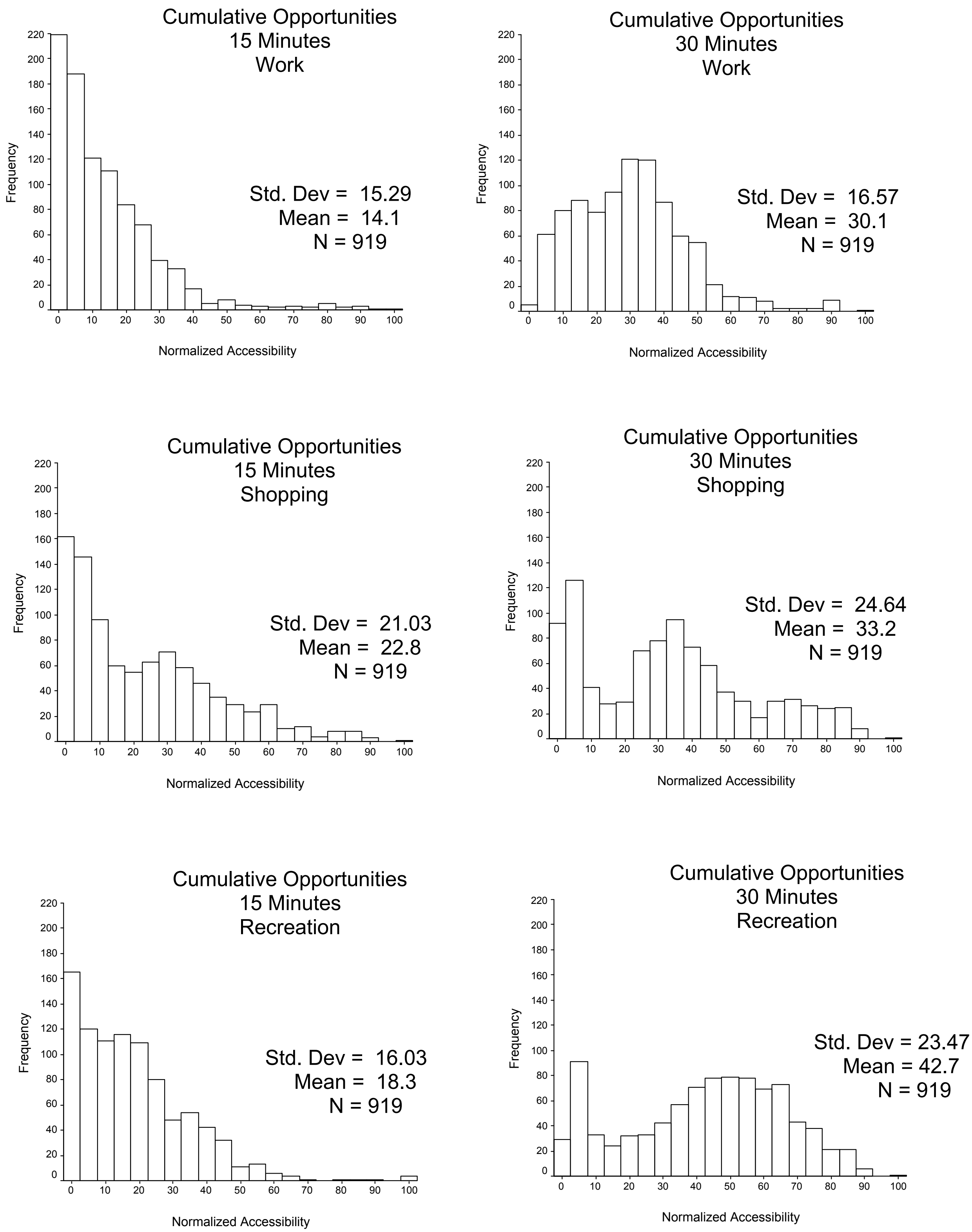

Figure 5.10 – Cumulative Opportunities Measures Frequency of Results

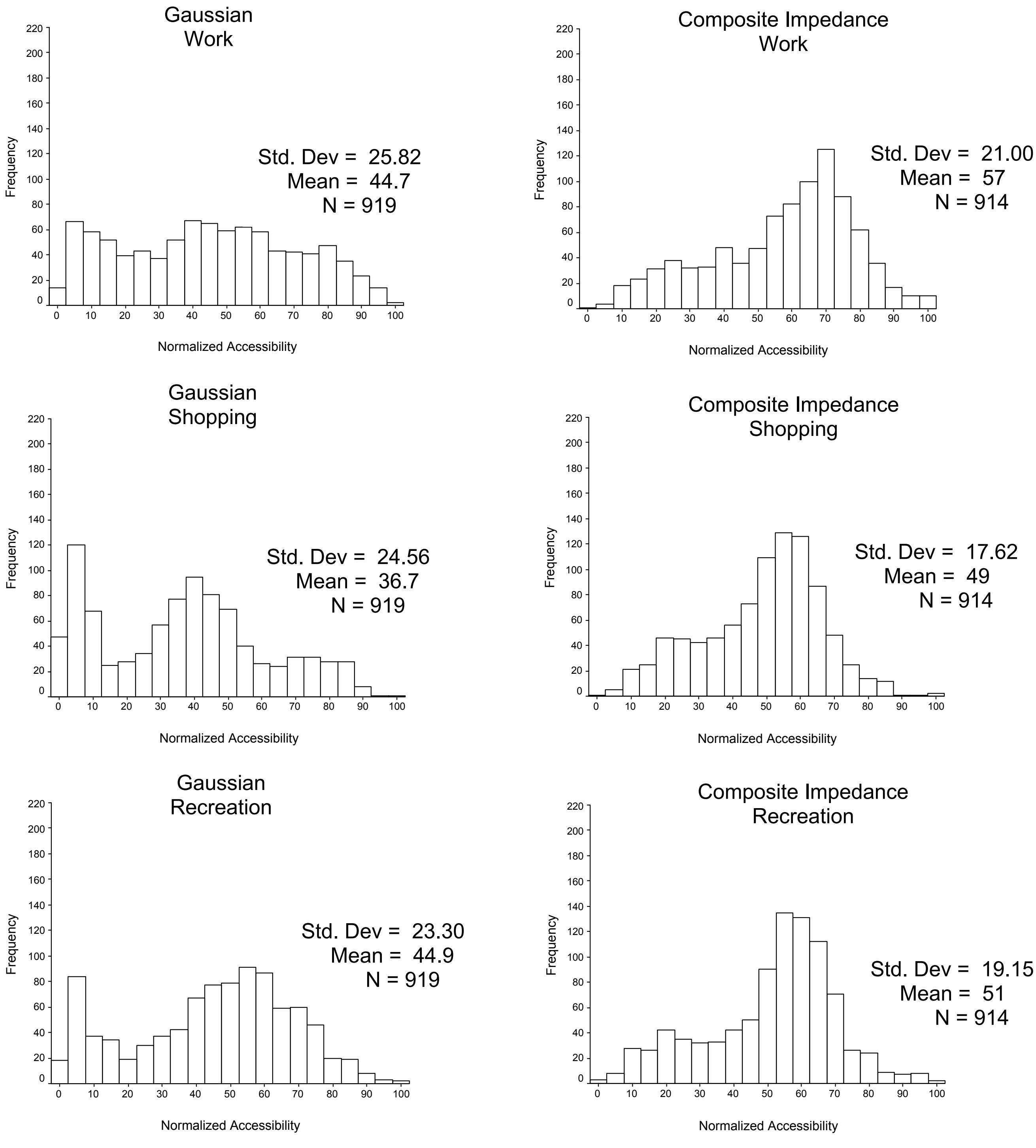

Figure 5.11 – Gaussian and Composite Impedance Measures Frequency of Results

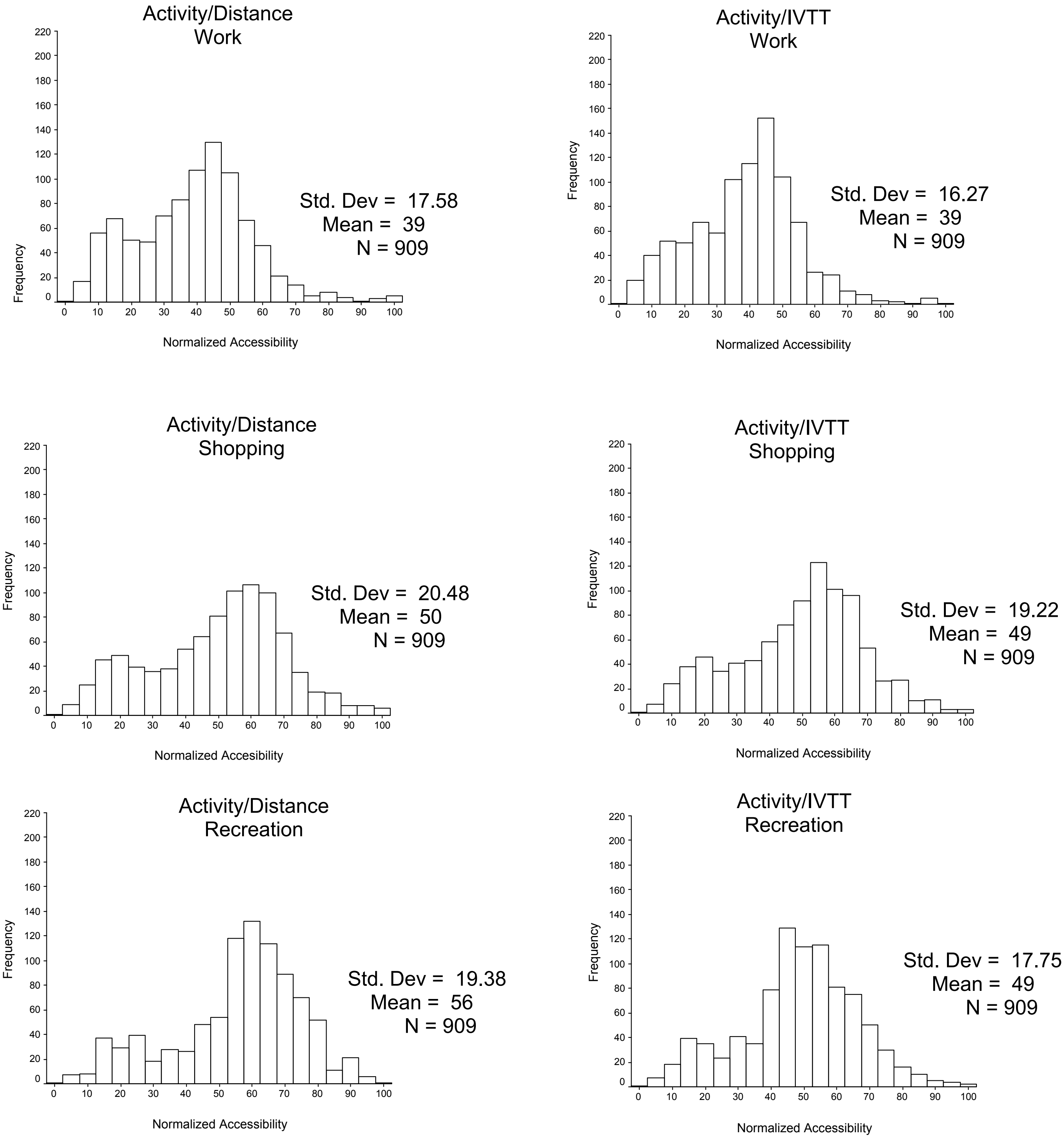

Figure 5.12 – IVTT and Distance Impedance Gravity Measures Frequency of Results

A review of Figures 5.10 through 5.12 suggests that all the measures perform reasonably well, although the CO 15 measure is skewed a little towards the low end of the scale. Next it is important to look at how these results vary for different locations. It is hypothesized that the downtown areas will have high accessibility and the smaller communities to the north and south of the major cities should indicate regionally higher accessibility levels.

While it is instructive to look at the results for the whole region to observe phenomena such as local highs and isolated areas of high and low accessibility, there is also interest in the accessibility of different sociodemographic groups and different types of land use. Therefore, 12 parcels of zones were chosen from the complete data set to represent the different combinations of median income (low, medium, and high) and land use (downtown, urban, suburban, and rural). Refer Figure 5.13 which shows where these different zones are within the study area. Due to the scale of the maps, the downtown zones are not discernable. Also, due to the nature of the study area, the downtown parcels are not contiguous.

Figures 5.14 through 5.16 show the results from the twelve zones for the different accessibility measures by purpose. For accessibility to work (Figure 5.14) the CO15 measure consistently rates all the land use types with fairly low accessibility. The CO30 and Gaussian measures show a wider range from the downtown areas to the rural ones. The composite impedance, activity/distance, and activity/IVTT measures show a narrower spread between the downtown accessibility to work and the rural accessibility to work. All the measures value high income downtown and urban zones quite a bit higher than high income suburban and rural zones. This may be due to self-selection where the residents may choose to live in highly accessible downtown and urban areas and more inaccessible suburban and rural areas.

For shopping accessibility (Figure 5.15) the CO15 values are generally higher than for accessibility to work. Each measure is normalized for each activity. Because the range of shopping activities may be different than all jobs (the proxy for work accessibility) the accessibility values are going to produce different normalized values. Surprisingly the composite impedance, activity/distance and activity/IVTT measures all indicate relatively high values in the rural areas compared to the suburban ones. It may be that the large areas of single use zoning in the suburban areas are less accessible than the dense urban and downtown areas and less accessible than the less dense, but more mixed, rural areas. All the measures except for the composite impedance measure attribute relatively high accessibility to the high income urban areas.

The recreation results (Figure 5.16) are all quite a bit lower than the work and shopping results. Parkland is not distributed in the same manner as shops and other employment areas. Therefore, fewer people can access parkland in a short period of time. The CO30 and Gaussian measures rank the different zones similarly to each other. And the composite impedance, activity/distance, and activity/IVTT measures rank the zones similarly to each other. The CO15 measure places low values on all the zones in question.

Therefore, looking at the results for the 12 zones grouped by accessibility measure we see that the CO15 measure values all the zones relatively low and the CO30 measures shows a large difference between the downtown and urban zones compared to the suburban and rural zones. Although the different measures rank the income classes separately within a particular land use, they all essentially show this distinction. Except for the CO15 measure, the measures all perform reasonably well.

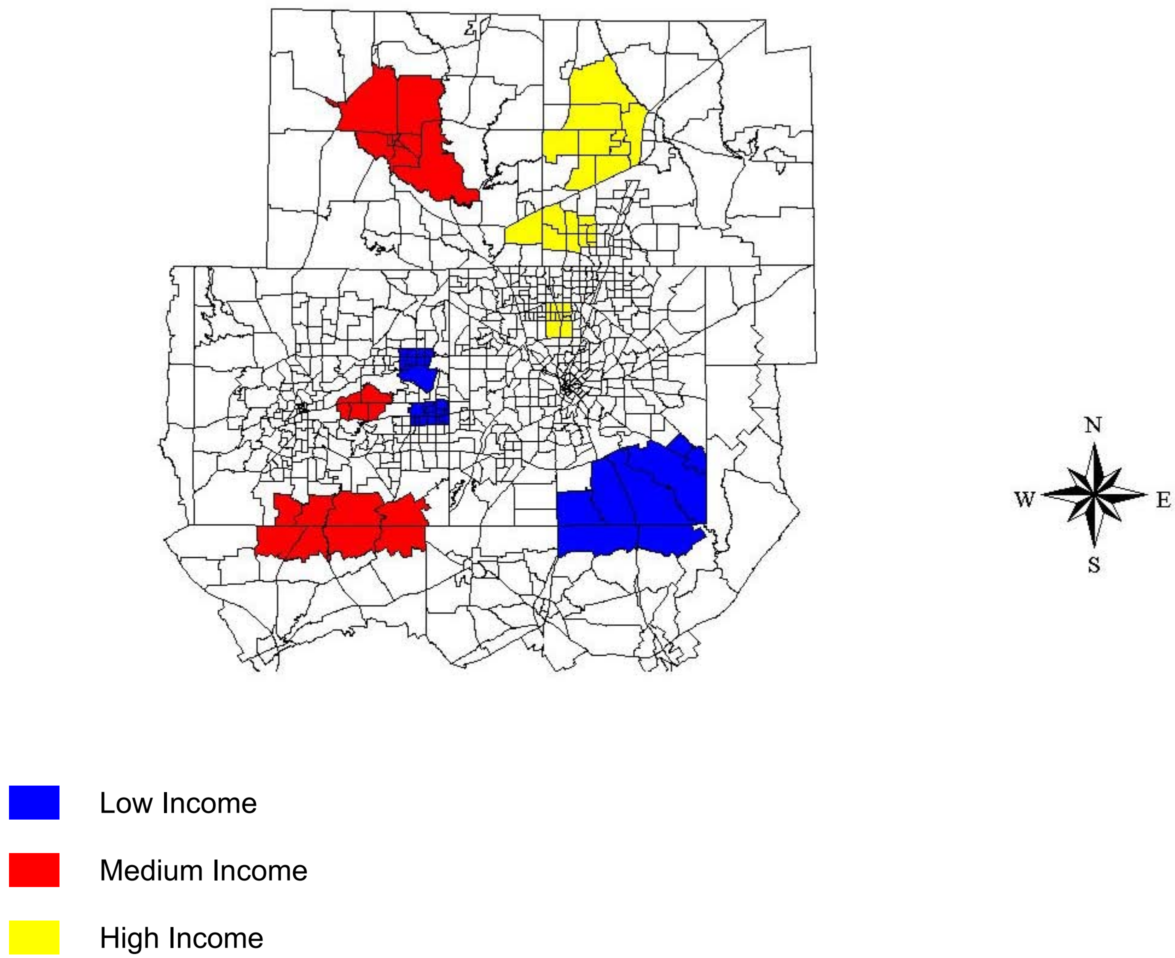

Figure 5.13 – Zone Clusters by Median Income

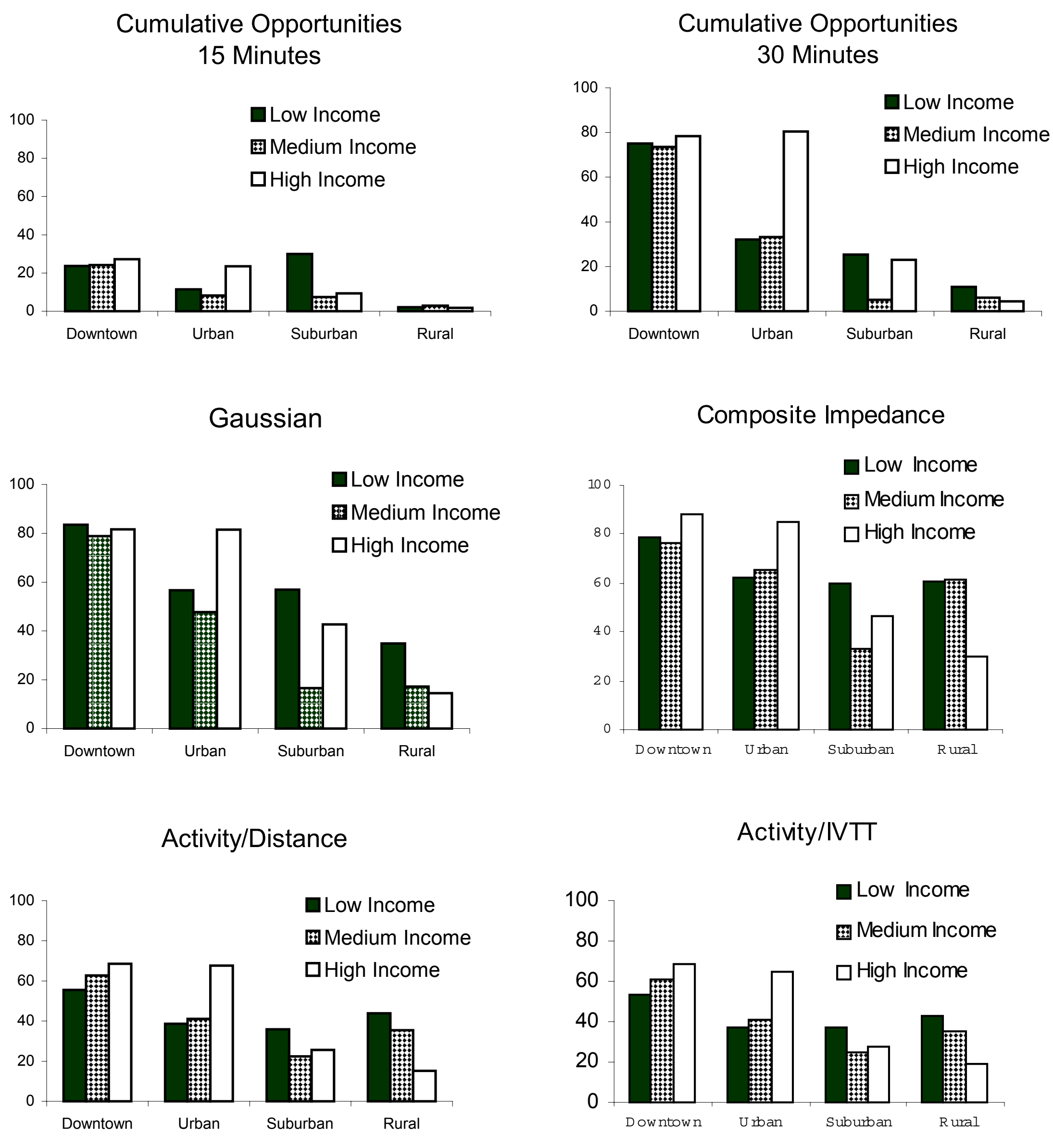

Figure 5.14 – Work Accessibility in the 12 Zone Clusters: Grouped by Accessibility Measure

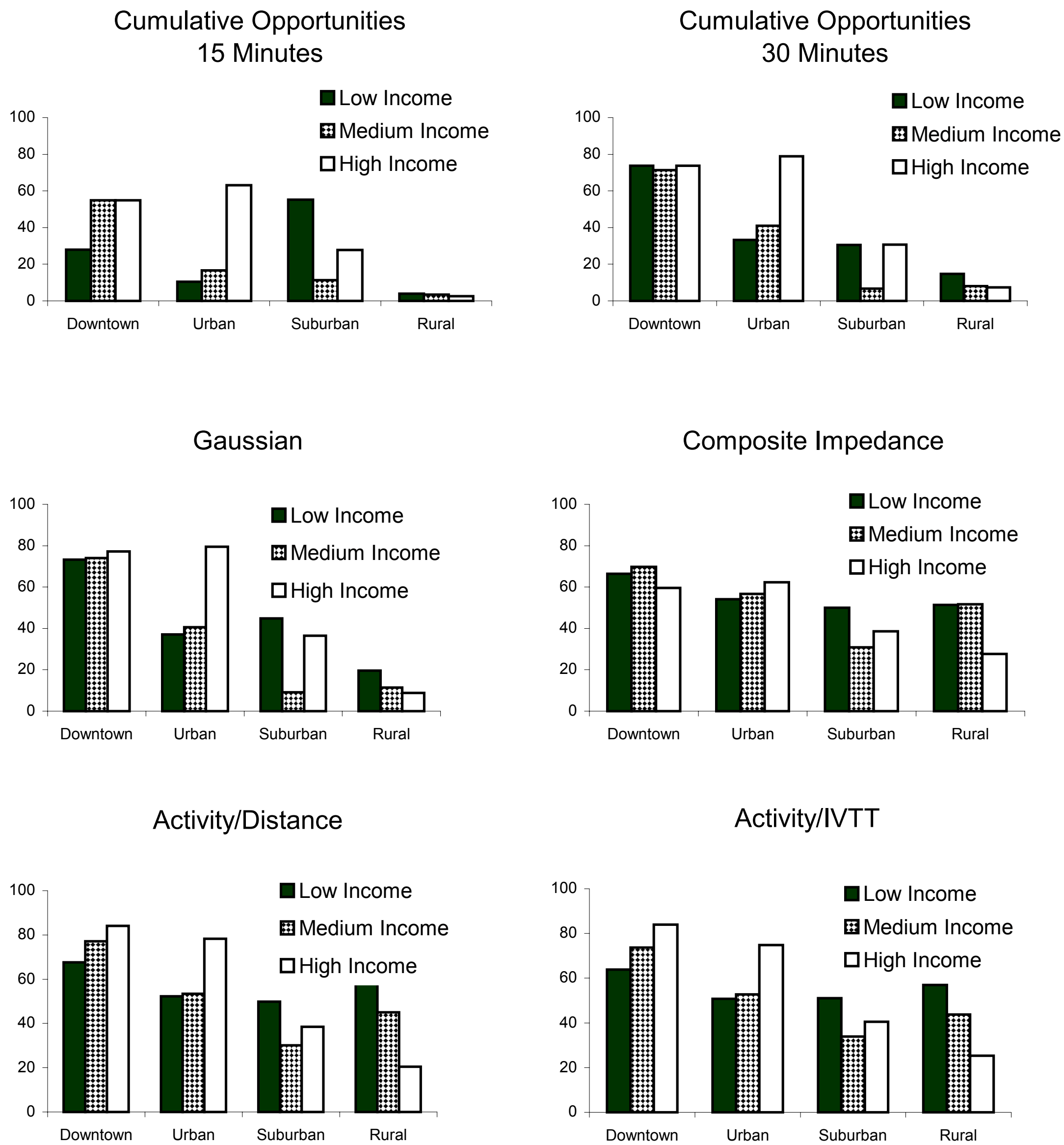

Figure 5.15 – Shopping Accessibility in the 12 Zone Clusters: Grouped by Accessibility Measure

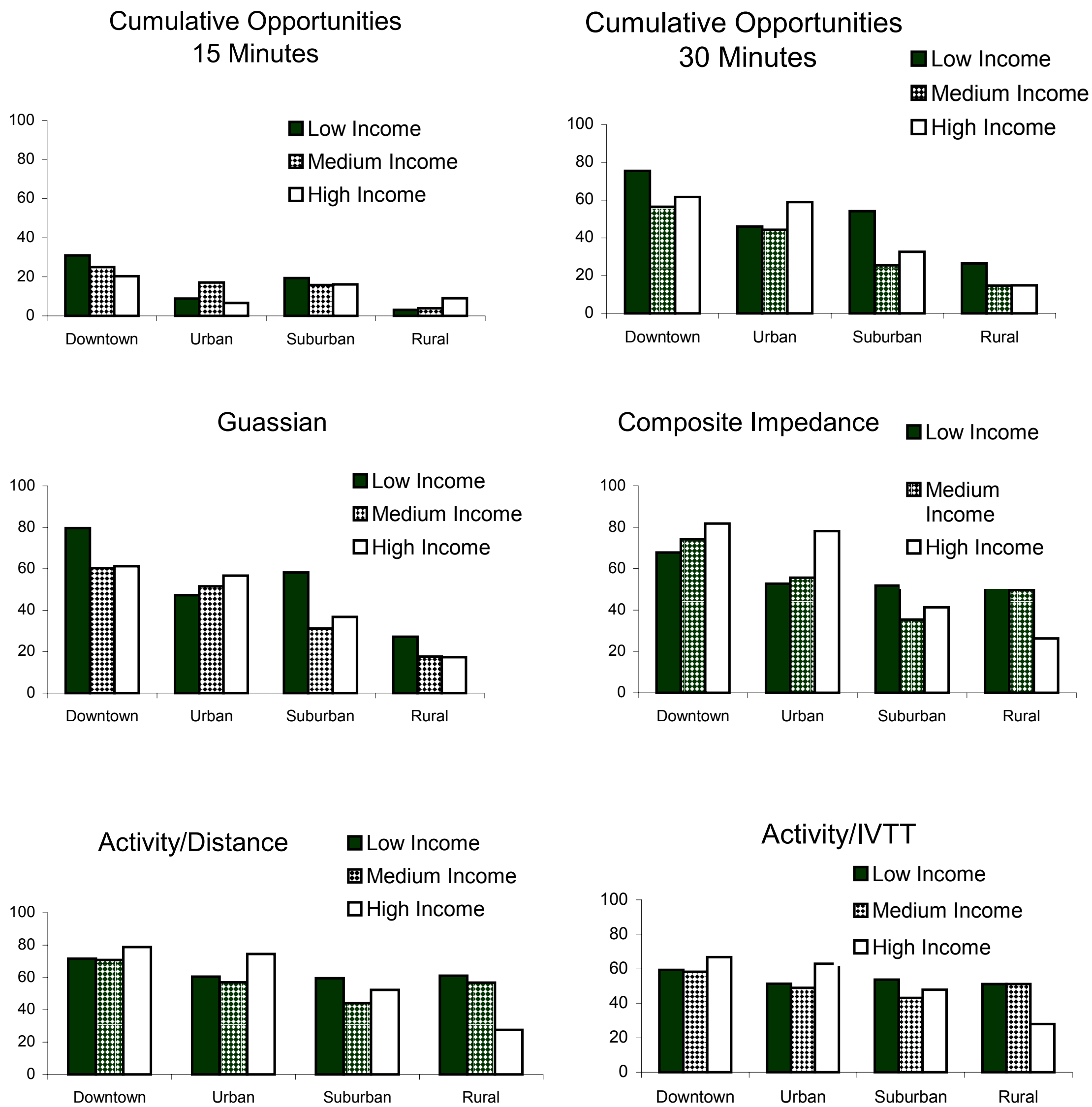

Figure 5.16 – Socio-recreational Accessibility in the 12 Zone Clusters: Grouped by Accessibility Measure

The next set of figures (5.17 – 5.19) shows the results for the accessibility measures grouped by land use type for the different income classes. In these figures the bars are arranged left from right: low income, medium income, and high income. The expectation for this representation of the results is that an appropriate accessibility measure would show some variation between different sociodemographic groups. This would provide the ability of the measure to be used as another criteria in assessing environmental justice concerns. As discussed above, this does not necessarily mean that high income zones will always have the highest level of accessibility.

For accessibility to work (Figure 5.17) each accessibility measure rates the different income classes the same except for the downtown area. The downtown zones are consistently high (except for the CO15 measure). The CO30 and composite impedance measures rank the zones the same. The activity/IVTT and activity/distance measures rank the zones the same, and only the Gaussian measure ranks the zones differently from all the others. We hypothesize that the downtown areas will have generally high accessibility and the differences between the different classes is fairly minor.

Accessibility to work in the urban areas show the high income zones consistently rated higher than the other income classes. The CO30, composite impedance, activity/IVTT, and activity/distance measures all rank the low income zones as the lowest. Interestingly the CO15 and Gaussian measures show similar results. In the suburban areas the low income zones are consistently ranked the highest. This could be because low income zones may be found as buffers between highways and other income groups, therefore, giving them higher accessibility. For the rural zones all the measures, except composite impedance, rank the different income classes the same. The low accessibility of the high income zones may indicate the intentionally inaccessible residential location choice of high income households in rural areas (e.g. gated communities).

Accessibility to shopping (Figure 5.18) has slightly different results than accessibility to work. All the downtown zones have high values of accessibility with little differentiation among the income classes. In the urban areas the high income zones are consistently valued the highest. These zones may be some of the earliest suburbs in the area that are now high mixed use areas and a desirable location for high income households due to their proximity to downtown. In the suburban areas the low income zones again show relatively high accessibility. This may be due to the buffering effect discussed above. The pattern for accessibility to shopping in the rural areas is similar to that noted above for accessibility to work.

It is interesting that for accessibility to recreation (Figure 5.19) in the downtown zones the CO15, CO30 and Gaussian measures all indicate that the low income zones have the highest accessibility, while the composite impedance, activity/distance, and activity/IVTT measures all attribute the highest accessibility values to the high income zones. The composite impedance, activity/distance, and activity/IVTT measures all use parameters derived from modeling of local data, this may be why they are behaving similarly in this situation. In the urban areas all the measures, except CO15, rank the high income zones consistently high. In the suburban and rural areas the low income zones have relatively higher accessibility to parks than high income zones. It may be that in suburban and rural areas there is more likely to be private parks, such as country clubs, than in downtown and urban areas.

From this presentation of the data the high accessibility of the downtown areas and the low accessibility of the rural areas is again evident. For a particular land use two or more measures may rank the income classes one way and differently for a different land use. This indicates that the measures are not essentially equivalent. However, except for a few minor places the composite impedance, activity/distance, and activity/IVTT measures all present similar results. The CO15 results are generally low while the CO30 and Gaussian measures present similar results to each other.

The last set of figures (5.20 – 5.22) presents the results for the 12 comparison zones grouped by the different accessibility measures and different land use types for the different accessibility target activities – work, shopping and recreation. In these figures the bars are arranged from left to right for the different land use types: downtown, urban, suburban, and rural. It is expected that an appropriate accessibility measure will show some variation among different locations. The land use – transportation system interaction takes on different forms in downtown areas compared to urban, suburban or rural areas. This difference is expected to be evident in an accessibility measure since it components are elements representing these two attributes.

Accessibility to work is presented in Figure 5.20. Here we again see many of the trends noted earlier. For all income classes the downtown zones consistently show a high value of accessibility. While accessibility to work downtown is higher than the other land use types for the low income zones, it is relatively high in all the zones. This may indicate the inability of low income households to live too far from their place of work. Results for the medium income zones is mixed among the different measures, but consistent for the high income zones.

Similarly for shopping (Figure 5.21), the results of the activity/distance and activity/IVTT measures indicate that low income zones are relatively close to shopping activities. As for working, this may be because they cannot afford to love too far away from necessary retail establishments such as grocery stores. The high income zones in the downtown and urban areas all have high accessibility values and much lower values in the suburban and rural zones.

For accessibility to recreation (Figure 5.22) for the low and medium income zones the CO15, CO30, and Gaussian measures rank the different land use types the same while the composite impedance, activity/distance, and activity/IVTT measures rank the land use types similarly to each other. Except for CO15, all the measures rank the high income zones the same.

The highest accessibility values for all the income classes is approximately the same. The main distinction between the income classes is highlighted by the different land use types. There is greater variation in the high income classes for all activity types, compared to the low income classes where there is little variation among land uses. The difference is more clearly shown in the composite impedance, activity/distance, and activity/IVTT measures.

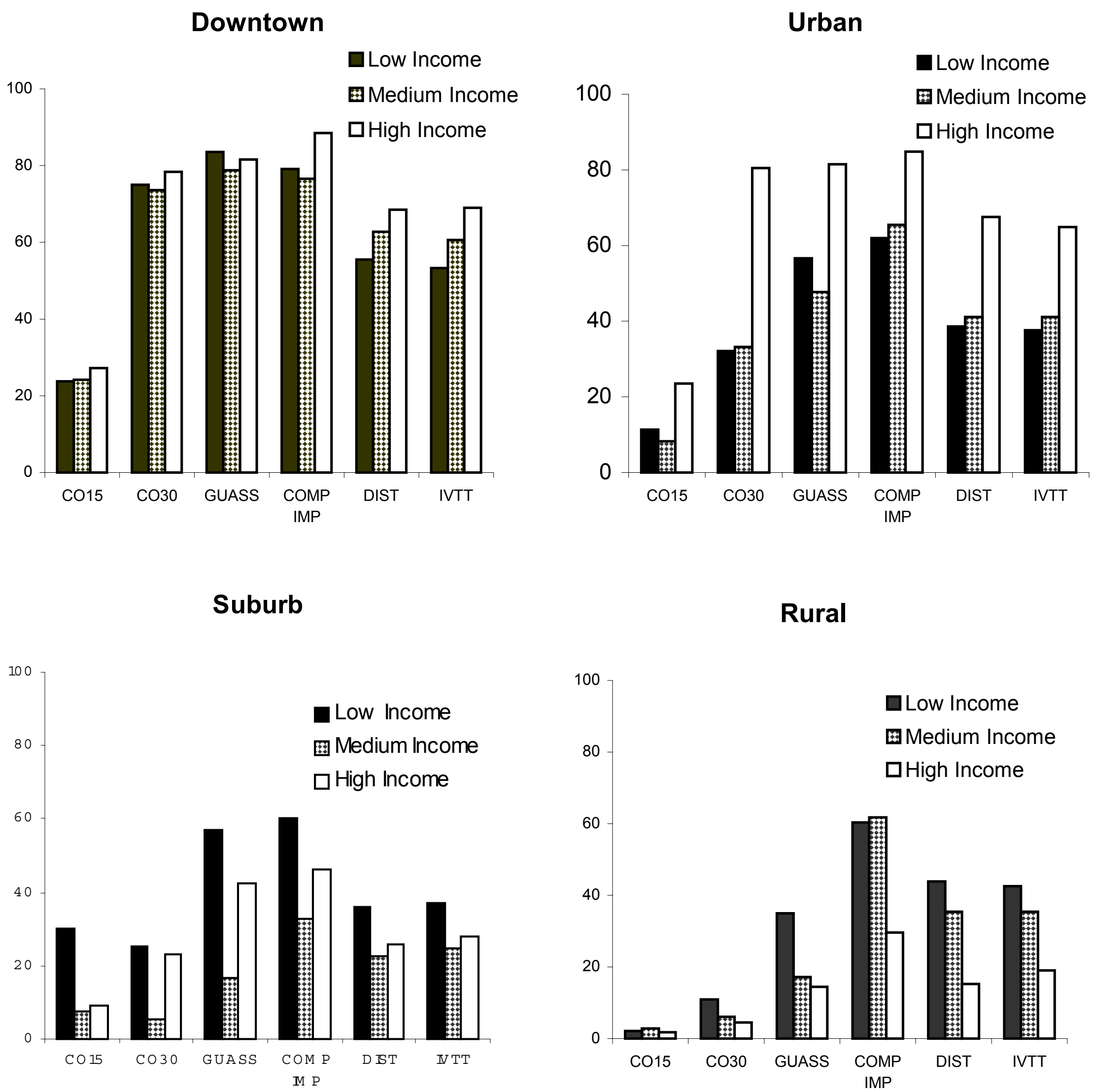

Figure 5.17 – Work Accessibility in the 12 Zone Clusters: Grouped by Land use

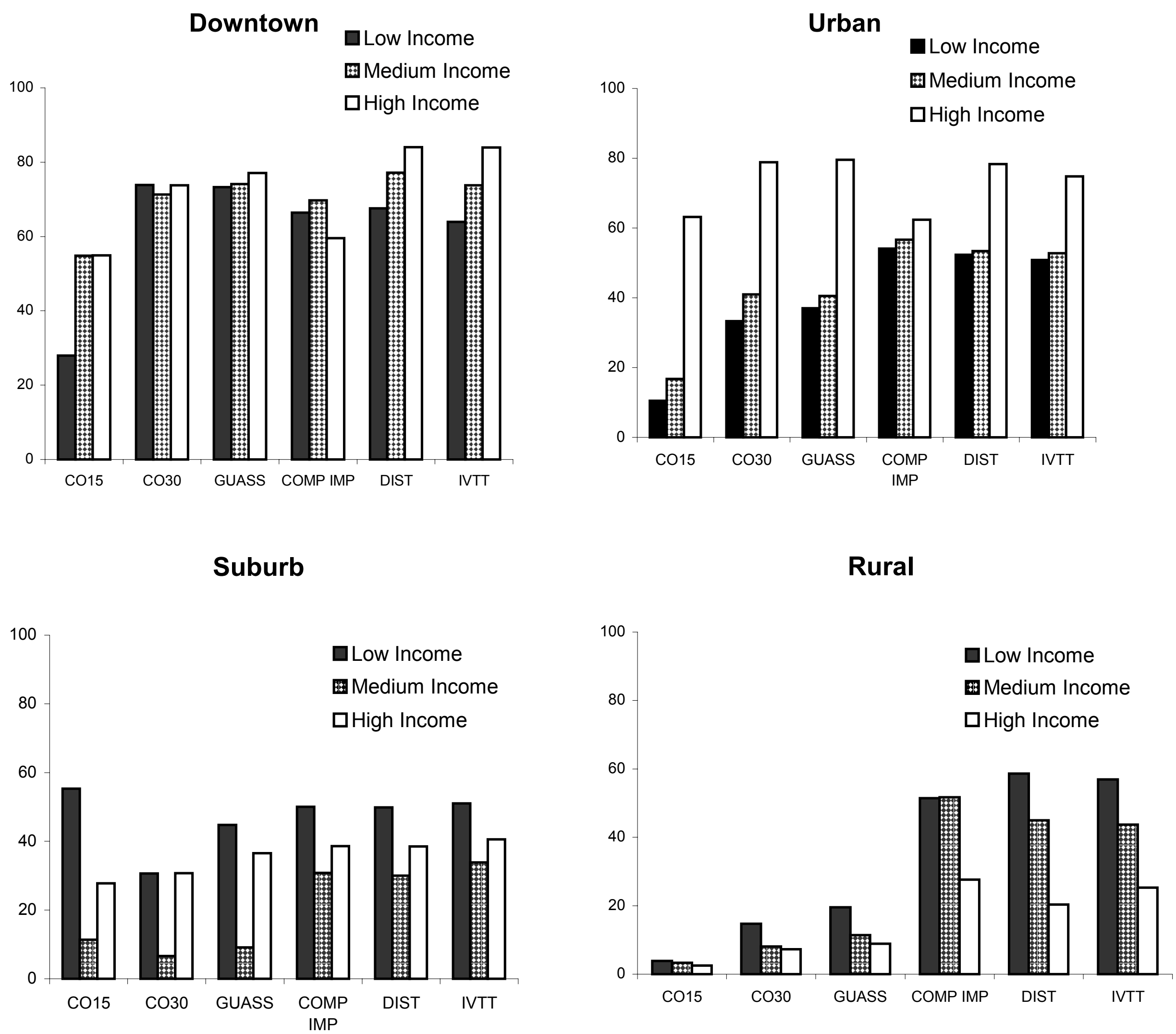

Figure 5.18 – Shopping Accessibility in the 12 Zone Clusters: Grouped by Land Use

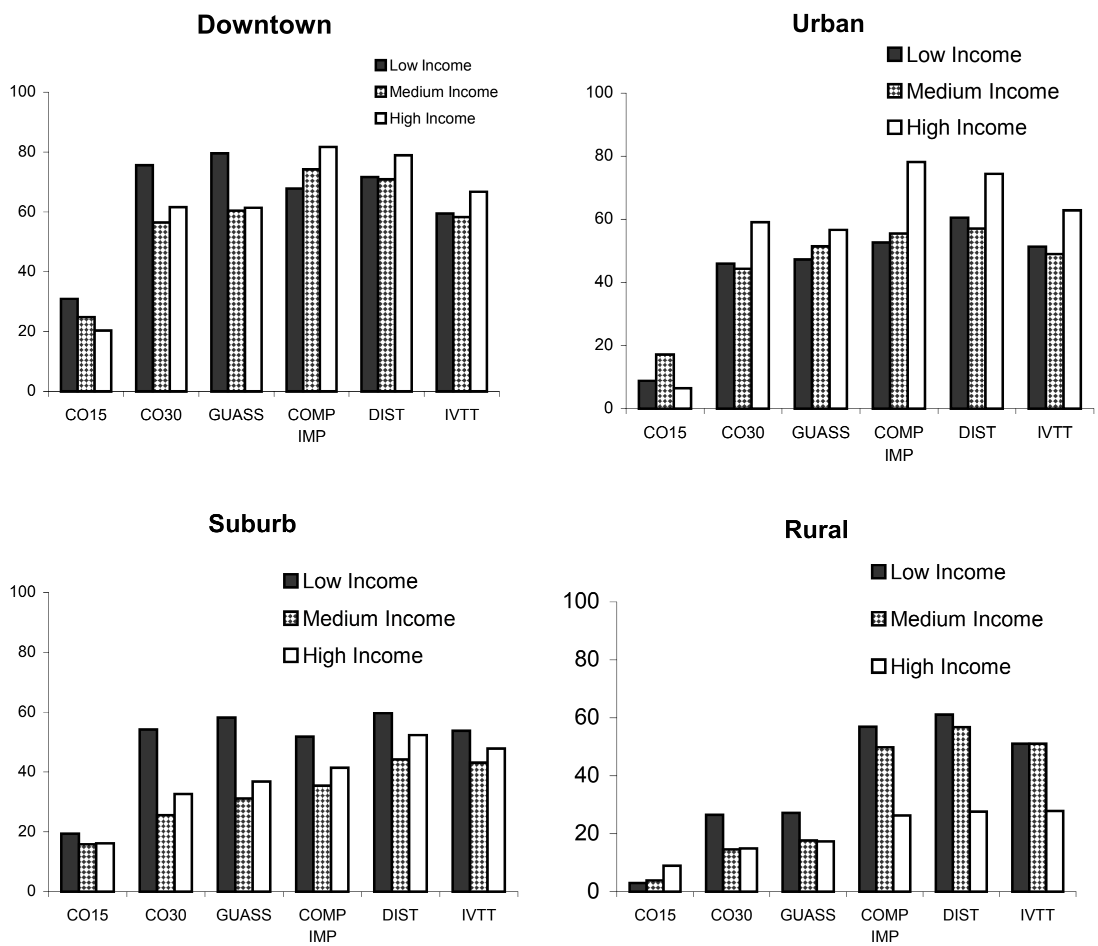

Figure 5.19 - Recreation Accessibility in the 12 Zone Clusters: Grouped by Land use

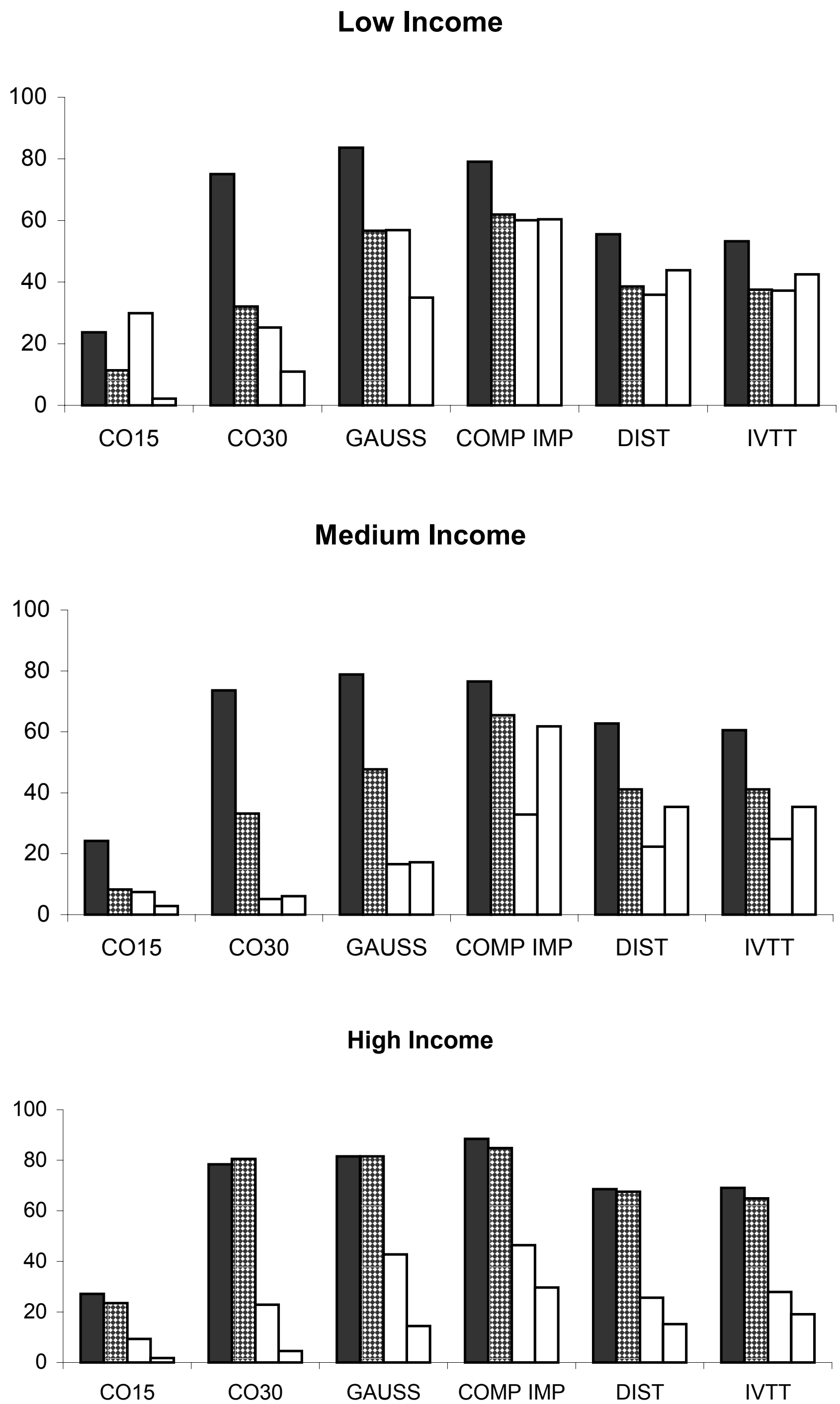

Figure 5.20 – Work Accessibility in the 12 Zone Clusters: Grouped by Socio-demographics

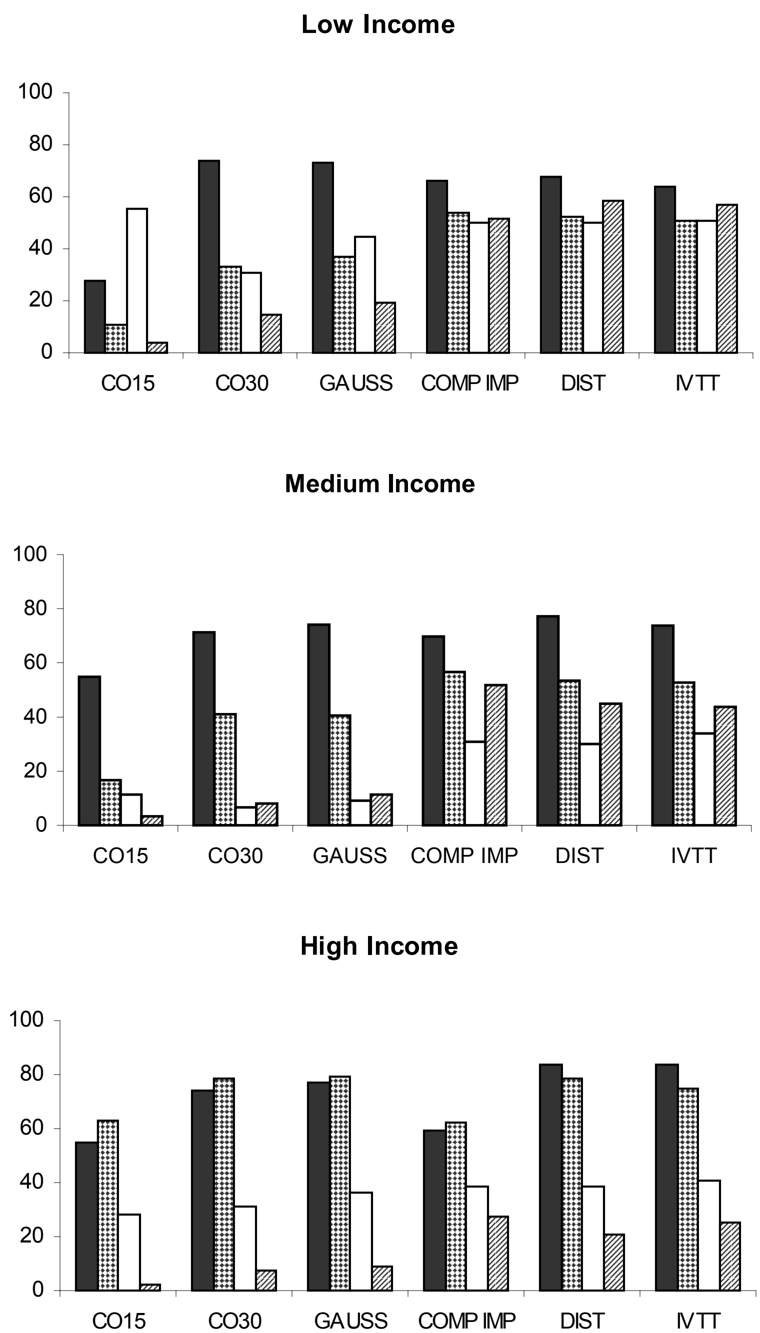

Figure 5.21 – Shopping Accessibility in the 12 Zone Cluster: Grouped by Socio-demographics

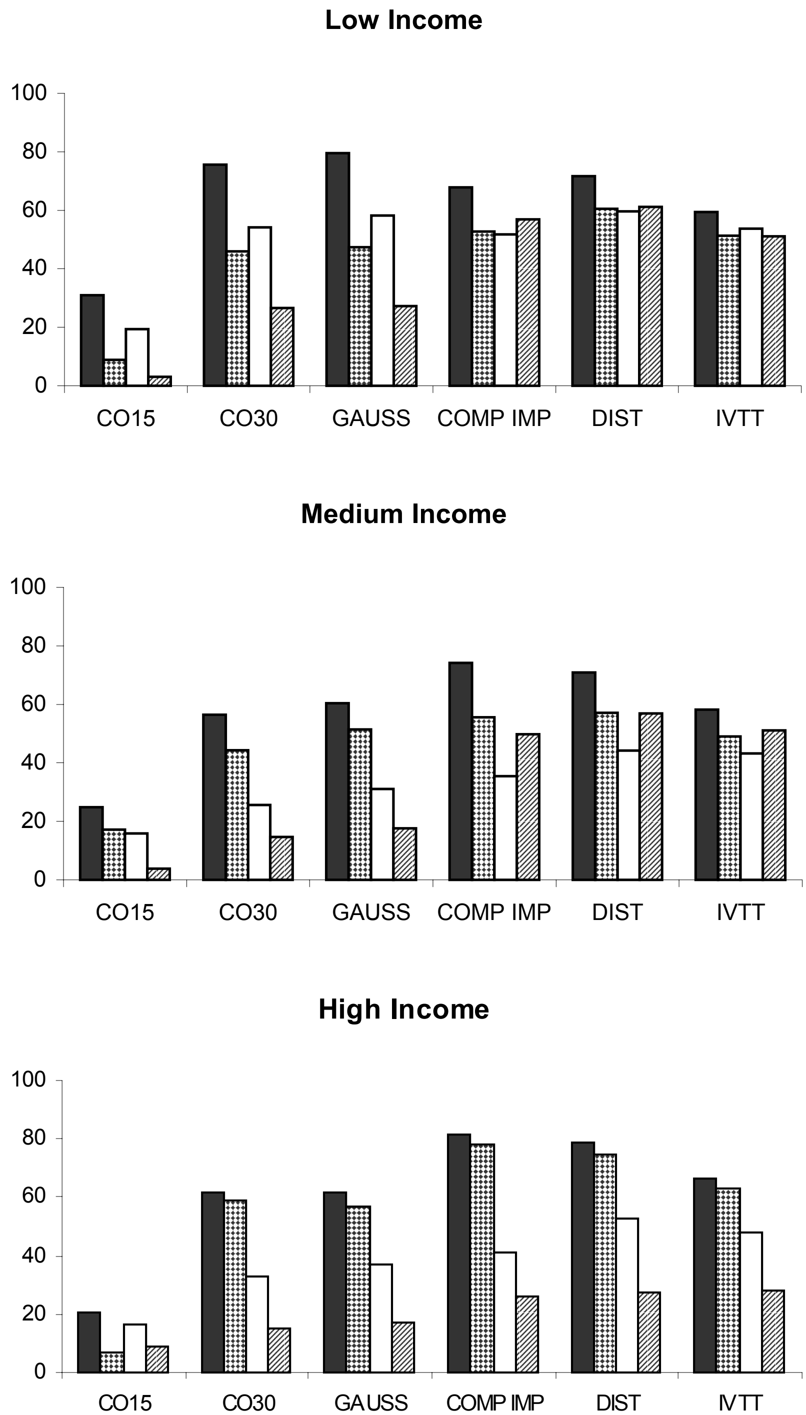

Figure 5.22 – Recreation Accessibility in the 12 Zone Clusters: Grouped by Socio-demographics

5.1 Summary

Table 5.1 summarizes the performance of the different measures as discussed in this section. Poor ratings indicate either a lack in variation across the study area, or lack of correlation with the results. Good ratings indicate generally good variation across the study area and good correlation with known results. The CO15 measure indicated generally low values for the 12 zones chosen for separate comparison and analysis. The composite impedance, activity/distance, and activity/IVTT measures often presented similar results. However, performance across all activity types should not be weighted equally. In order to address traffic and safety concerns due to peak-hour weekday traffic it might be appropriate to weigh work accessibility performance higher than the other activity types.

Table 5.1 – Summary of Performance of Accessibility Measures

		Whole Area	Histograms	All 12 Zones	Income	Land Use
CO15	Work	Poor	Poor	Poor	Fair	Poor
	Shop	Poor	Poor	Fair	Fair	Poor
	Rec.	Poor	Poor	Poor	Fair	Poor
CO30	Work	Poor	Fair	Good	Fair	Fair
	Shop	Poor	Good	Good	Fair	Fair
	Rec.	Poor	Good	Good	Fair	Fair
Gaussian	Work	Fair	Good	Good	Fair	Fair
	Shop	Fair	Good	Good	Fair	Fair
	Rec.	Fair	Good	Good	Fair	Fair
Composite Impedance	Work	Good	Good	Good	Good	Good
	Shop	Good	Good	Good	Good	Good
	Rec.	Good	Good	Good	Good	Good
Activity/ Distance	Work	Good	Good	Good	Good	Good
	Shop	Good	Good	Good	Good	Good
	Rec.	Good	Good	Good	Good	Good
Activity/ IVTT	Work	Good	Good	Good	Good	Good
	Shop	Good	Good	Good	Good	Good
	Rec.	Good	Good	Good	Good	Good

CHAPTER 6 – CONCLUSIONS AND AGGREGATION ISSUES

The beginning of this paper outlined four considerations for the evaluation of alternative accessibility measures: a) the theoretical basis of the measure; b) the ease of aggregation over time; space, activity, mode and individual or household type; c) the data needed for estimation; and d) application and performance of the accessibility measure.

The measures chosen for evaluation all could be estimated with existing data sources. Therefore, they can all be considered to score Good on the consideration of data needs. The theoretical basis of the measures was discussed in chapter 3 and the performance of the measures was discussed in chapter 5. The results of these analyses are presented in Table 6.1.

Table 6.1 – Evaluation of Accessibility Measures

		Theory		Overall performance		Stratified performance	
			Rank		Rank		Rank
CO 15	Work	Fair	6	Poor	6	Poor	6
	Shop	Fair	5	Poor	6	Poor	6
	Rec.	Poor	6	Poor	6	Poor	6
CO 30	Work	Fair	5	Poor	5	Fair	5
	Shop	Fair	6	Poor	5	Fair	5
	Rec.	Poor	5	Poor	5	Fair	5
Gaussian	Work	Good	2	Fair	4	Fair	4
	Shop	Good	2	Fair	4	Fair	4
	Rec.	Good	2	Fair	4	Fair	4
Composite Impedance	Work	Good	1	Good	2	Good	3
	Shop	Good	1	Good	1	Good	3
	Rec.	Good	1	Good	3	Good	3
Activity/ Distance	Work	Good	4	Good	3	Good	2
	Shop	Good	4	Good	3	Good	2
	Rec.	Good	4	Good	2	Good	2
Activity/ IVTT	Work	Good	3	Good	1	Good	1
	Shop	Good	3	Good	2	Good	1
	Rec.	Good	3	Good	1	Good	1

Based on these three considerations the CO15 and CO30 measures are both outperformed by the other measures. They have the added disadvantages of not distinguishing the small towns in rural areas very well and the cut off times might not be appropriate for all activities. Although the Gaussian measure performed better than the cumulative opportunities measures, it clearly did not perform as well the other three gravity measures. The composite impedance, activity/distance, and activity/IVTT measures all performed reasonably well and similarly. The composite impedance measure has the advantage of being able to explicitly incorporate other modes into its calculations, without using a separate aggregation technique.

The final consideration in evaluating the accessibility measures under consideration is the ability to aggregate the values that are calculated for each zone across a variety of dimensions. The degree and type of disaggregation should be specified prior to the determination of accessibility measures (Wilson 1971). The suggested accessibility indices were computed at the most elemental spatial unit of Traffic Analysis Processing (TAP) zone, for each mode of transport, for each time of day, and for each trip purpose. Therefore, the dimensions of aggregation that were identified are as follows:

- spatial;
- intermodal and network level of service attributes;
- time of day; and,
- trip purposes.

Let the accessibility measure of zone z for purpose p by mode m and time of day t be represented by *Acc(z,m,t,p)*. This disaggregate level accessibility measure may be computed using one of the approaches discussed in the previous section. Assuming that the utilities of all combinations of zones, modes, times of day, and trip purposes are independently and identically distributed, aggregation could be performed across multiple dimensions at the same time as presented in the following set of equations:

Aggregation Over Times of Day

$$Acc(z,m,p) = \ln\left[\sum_{t=1}^{T} \exp\left(Acc(z,m,t,p)\right)\right] \qquad \text{Eq. 6.1}$$

where T is the number of time periods.

Aggregation Over Transport Modes

$$Acc(z,p,t) = \ln\left[\sum_{m=1}^{M} \exp\left(Acc(z,m,t,p)\right)\right] \quad \text{Eq. 6.2}$$

where M is the number of transport modes.

Aggregation Over Trip Purposes

$$Acc(z,m,t) = \ln\left[\sum_{p=1}^{P} \exp\left(Acc(z,m,t,p)\right)\right] \quad \text{Eq. 6.3}$$

where P is the number of trip purposes.

Aggregation Over Zones

$$Acc(m,t,p) = \ln\left[\sum_{z=1}^{Z} \exp\left(Acc(z,m,t,p)\right)\right] \quad \text{Eq. 6.4}$$

where Z is the number of TAP zones.

The same procedure could be applied for the aggregation of the different types of cumulative opportunities (CO) that were used in this study. The CO measures could be interpreted as the maximum utility of a TAP zone; and therefore, could be aggregated using the previously described procedure.

Finally, one could remove the IIA assumption behind MNL models by using a nested logit structure to describe the destination choice model. However, the use of nested structures limits the ability to aggregate across any and every dimension (and combination of dimensions) since it requires different nested structures for different aggregation schemes. For example, the use of a mode-destination-time of day choice model, with mode at the highest level, destination at the intermediate level, and time at the lowest level allows for the aggregation over different times of day for a certain zone; however, it does not permit the aggregation over different zones for the same time period. Therefore, one is required to use a different nesting structure, which leads to the proliferation of nesting structures for different aggregation schemes. Flexibility is another aspect of the ease of aggregation that is desirable for an accessibility measure.

This is only the beginning of the process for the development of an aggregation scheme for an accessibility measure. Therefore, the accessibility measures being evaluated here cannot be evaluated against this last consideration.

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APPENDIX A – ESTIMATION OF PARAMETERS

Preparation of the Data Set

Current Dallas-Fort Worth Regional Travel Model (DFWRTM), like any other conventional Urban Transportation Planning System, relies on activity survey, socioeconomic survey, land use, and level-of-service data for model estimation. The original data sets used to develop the model are:

(1) 1996 activity survey data, including the information of all the activities conducted by household members who are above five years old during a mid-week day.
(2) Household socioeconomic data, including the information of birthday, gender, race, education level, employment status, etc. for each member of the households participating in the activity survey.
(3) Land use demographic data, including the information of median income, number of households, population, number of basic employment, service employment, and retail employment for each Traffic Survey Zone (TSZ).
(4) Land use type data in GIS format, including a shape file that shows the polygons with unique land use type and a dBase file that shows the land use type for each polygon.
(5) TSZ structure in GIS format, also including a shape file that shows the polygons with unique TSZ number and a dBase file that provides the information of higher zone classification, such as Transportation Analysis Process (TAP) zone number, for each polygon.
(6) Level-of-service data, including distance, cost, in-vehicle travel time, etc. between each TAP zone pair during different time-of-day (peak or off-peak), for different modes (highway, HOV, and transit).

The 1996 activity survey data provides all the information about activities that were made by individuals during the survey day. The travel information, including origin/destination TAP zone number, origin/destination activity category, travel time, mode, and the time when the trip was made, are available from the survey data. Based on activity code, all trips are selected and the Trip File is generated. Based on origin/destination activity category the trips are classified into different trip purposes. Each trip is then aggregated into individual level in terms of person ID number, producing the Person-Trip File. The Household-Trip File is generated after aggregating person trips into household level. The households with missing data are deleted and the households with zero trips are added into the Household-Trip File.

In original household socioeconomic data, each household member is classified into one of five age categories based on birthday information. Along with the information of race, gender, etc. these person socioeconomic characteristics are aggregated into household level and appended to the Household-Trip File. There are 4641 households in the Household-Trip File. The households with inconsistent demographic data are deleted, leaving 3708. Household socioeconomic variables are used to cross check the total number of members of the household. After this process 3561 households remain in the Household-Trip File. The household socioeconomic variables can be used as exogenous variables to estimate trip productions. At the same time, the removed households are removed from the Trip File and the person socioeconomic characteristics are appended to the Trip File. The final Trip Files consist of 4561 work observations, 1206 shopping observations, and 1817 recreational observations.

To get the information of zonal land use acreage, the land use type shape file and TSZ structure shape file are intersected and a table is generated which provides the acreage of different land use types for each TSZ. Both TSZ acreage table and land use demographic file are aggregated into TAP zones because the model estimation will be based on TAP zonal level. In terms of attraction-end zone number, these two files are appended. These land use variables, such as acreage of retail area or number of retail employees, can be used as independent variables in the trip distribution model to represent the zonal attractiveness.

The level-of-service data are used to calculate the composite impedance. The composite impedance, along with land use data, is used in the trip distribution model to represent the accessibility measures.

Parameter Estimation

A generic Hansen-type (Hansen 1959) gravity accessibility measure takes the following form:

$$A^{\text{Activity}}{}_i = \frac{1}{N}\sum_{j=1}^{N}\left(\frac{(\text{Activity Measure}_j)^{\gamma_{\text{Activity}}}}{(Impedance_{ij})^{\beta\ Activity}}\right)$$

where A^{Activity} represents the accessibility to an activity (i.e. work, shopping, etc.), i is the zone index, and N is the total number of zones in the study region. $Impedance_{ij}$ is the composite impedance measure of travel between zone i and a destination zone j. γ_{Activity} and β_{Activity} are parameters that are estimated using a destination choice model of the form given below:

$$V_{ij}^{Activity} = \gamma^{Activity} \times \ln\left(ActivityMeasure\right)_j - \beta^{Activity} \times \ln\left(\text{Impedance}\right)_{ij}$$

where $V_{ij}^{Activity}$ is the utility presented by zone *j* for an activity to an individual in zone *i*. Assuming a multinomial logit form for destination choice then leads to an accessibility index for zone *i* that is equal to $(1/N)\times\sum_j \exp\left(V_{ij}^{Activity}\right)$. The functional form of $V_{ij}^{Activity}$ used above results in a Hansen-type accessibility measure.

The impedance expression used in the accessibility computations takes the form of a parallel conductance formula that accommodates multiple level-of-service measures and multiple modes (see Bhat et al, 1998 for a discussion of this formula). However, in the current empirical context, only highway auto level-of-service measures are used because of the lack of adequate transit observations in the destination choice model estimation. The highway auto impedance measure is in effective in-vehicle time units (in minutes) and is expressed as follows:

$$Impedance\,(\text{in IVTT minutes}) = IVTT + \delta \times OVTT\ (\text{in minutes}) + \eta \times COST\ (\text{in cents})\,.$$

The estimated values of the δ and η scalar parameters, and the γ and β vector parameters, are provided in Table 4.1. As can be observed, the only level-of-service variable that is relevant for recreational destination choice is in-vehicle time, while cost is not significant for employment destination choice. These results are perhaps a consequence of the strong multicollinearity in time and cost measures.

APPENDIX B – QUANTILE VERSION OF WORK ACCESSIBILITY MAPS

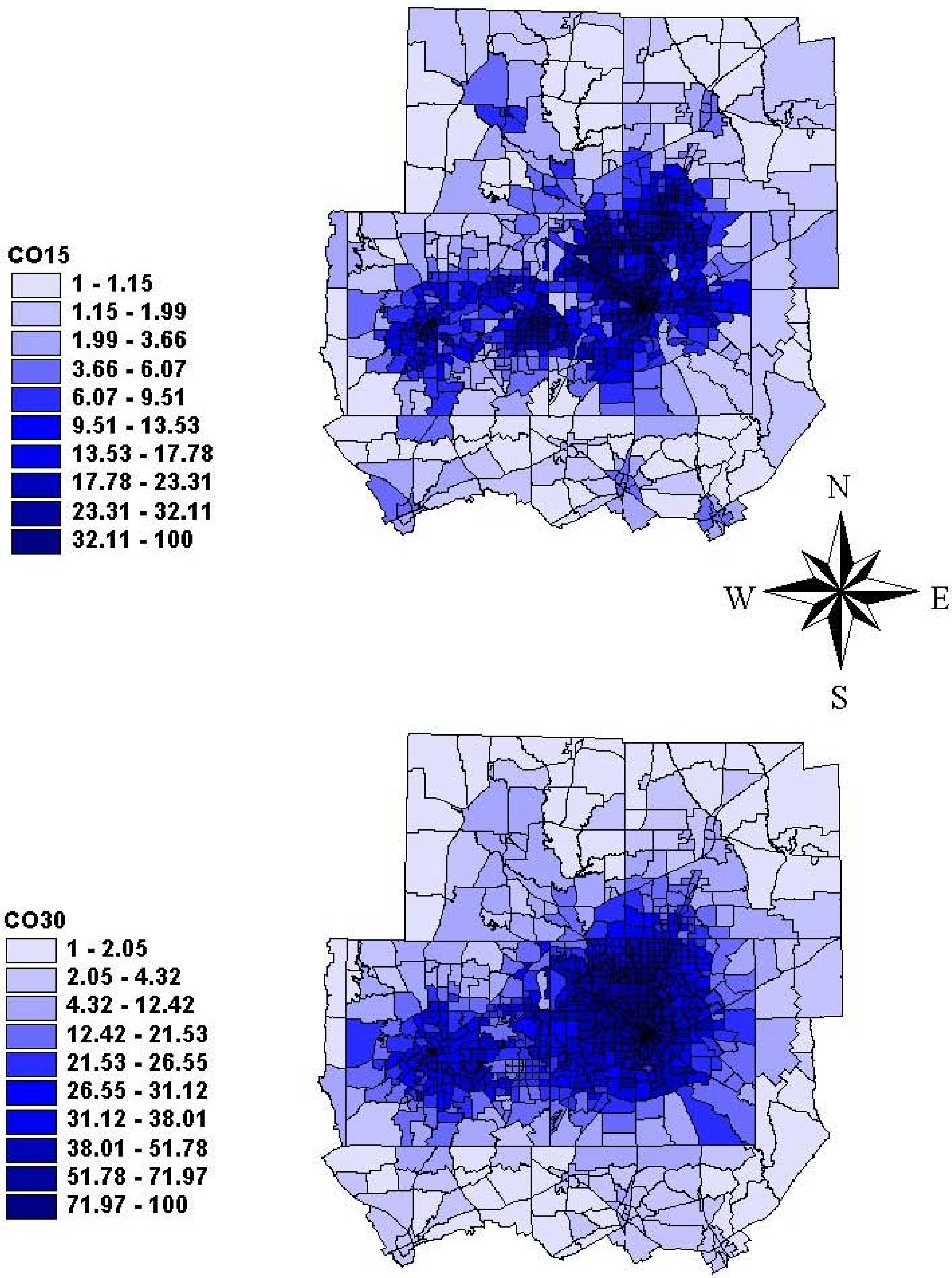

Figure B1 – Quantile Representation of Cumulative Opportunities Accessibility to Work

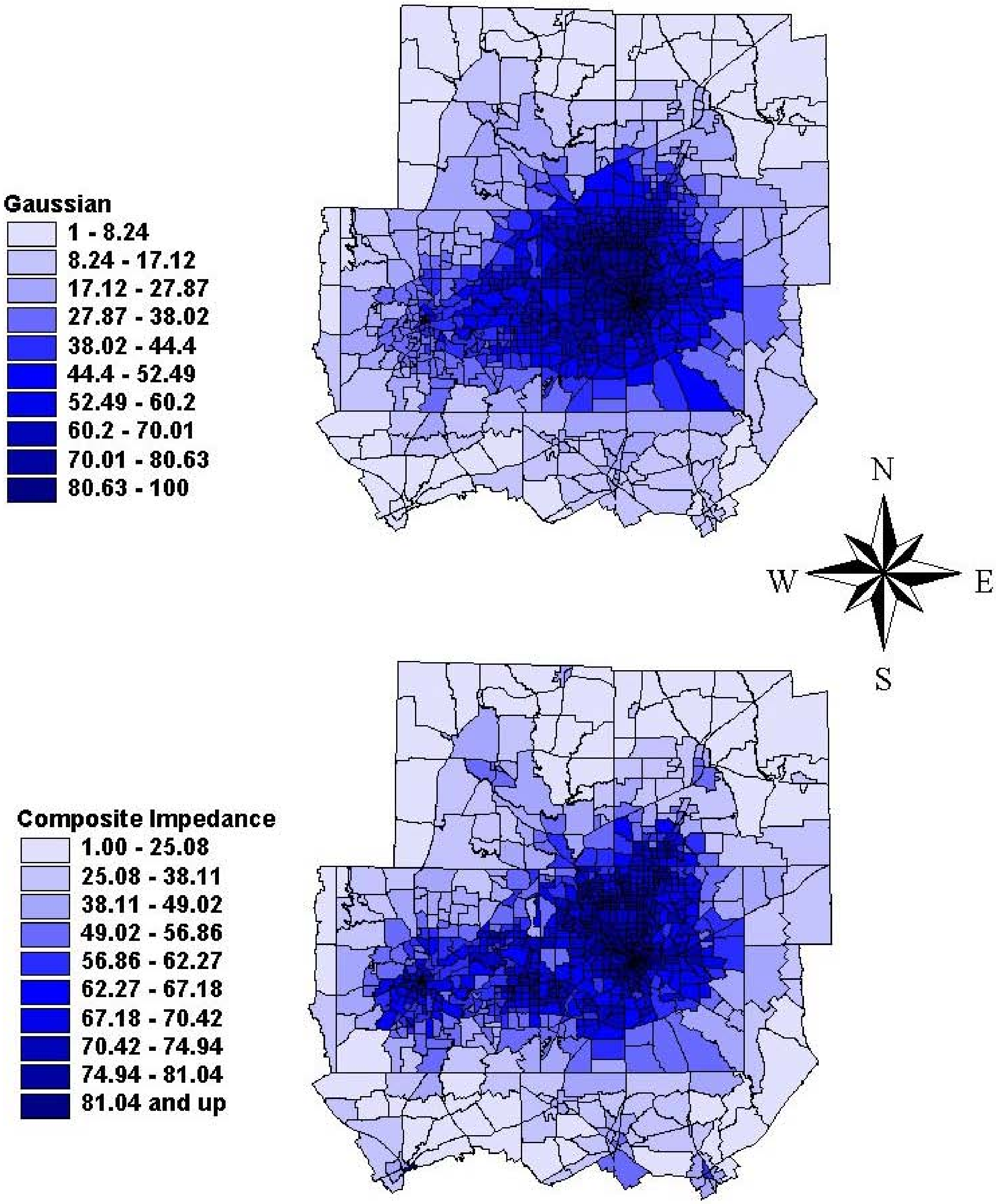

Figure B2 – Quantile Representation of Gaussian and Composite Impedance Accessibility to Work

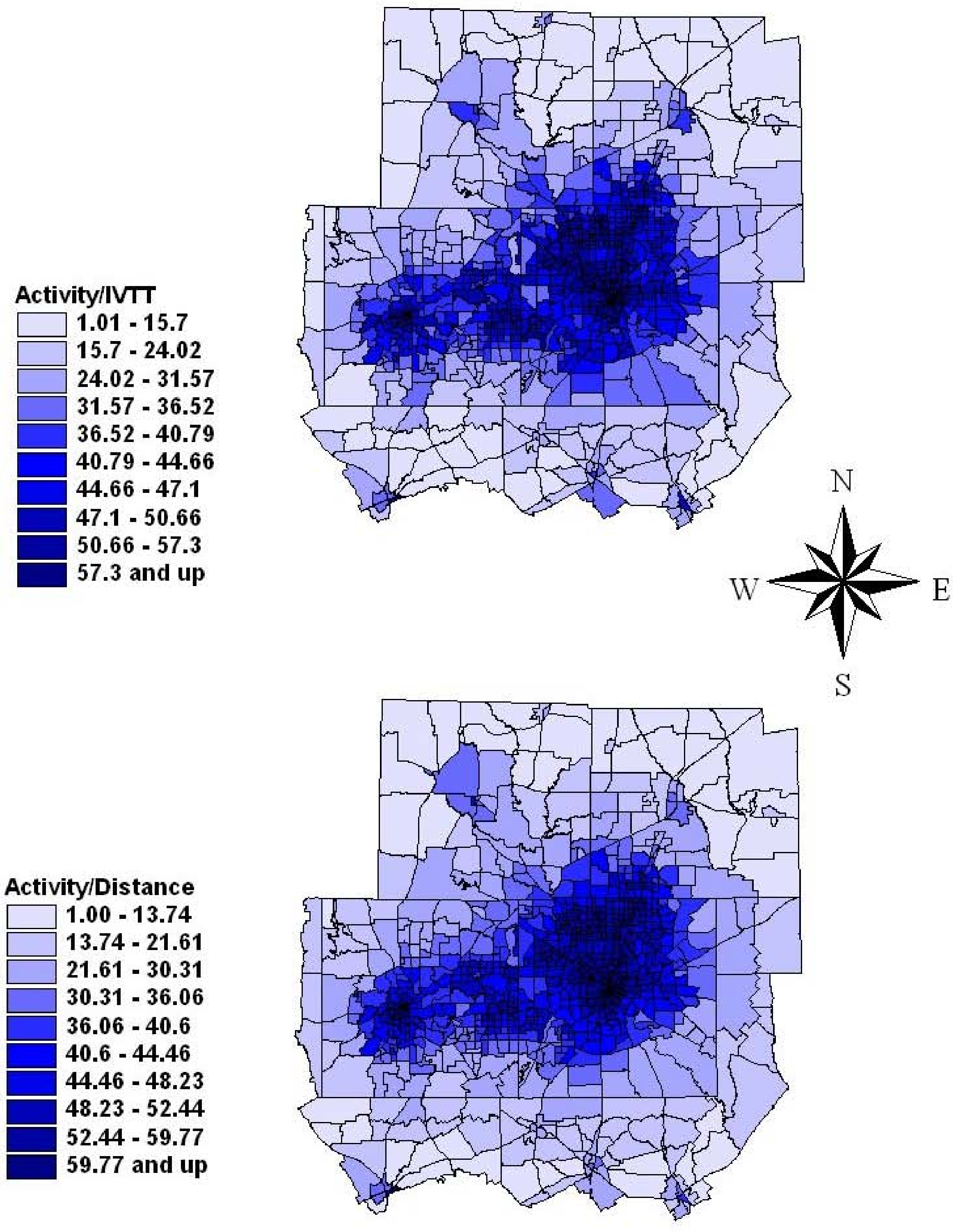

Figure B3 – Quantile Representation of Activity/IVTT and Activity/Distance Accessibility to Work