Seeing the Elephant:
Multi-disciplinary Measures of Urban Sprawl

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Abstract

In this paper we review and discuss multiple approaches of measuring urban sprawl. Our intent is not to propose new measures or methods but to present in a single paper an overview of approaches to measuring sprawl taken by scholars trained in a variety of disciplines. Our intent instead is to describe general approaches and to provide references to key sources for further examination. Based on our review, we draw two conclusions. First, over the last two decades we have made substantial progress in our ability to measure and analyze spatial patterns that constitute the problem known as urban sprawl. Second, because of the disciplinary boundaries in which this progress has been made, we understand parts of the problem better than we understand the problem as a whole.

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Because urban sprawl is notoriously ill defined it is often defined by analogy. To some, for example, sprawl is like beauty—in the eye of the beholder. To others sprawl is like pornography—you know it when you see it. In the paper, however, we offer a new analogy—sprawl is like an elephant, as in the old Indian proverb.[1] In the proverb, six blind men characterize an elephant after exploring different parts of the elephant's body. One, who touches the ear, thinks the elephant is like a fan. Another, who touches a leg, likens the elephant to a tree. A third, who touches its side, claims it resembles a wall. The fourth, who touches the trunk, view it as a snake. The fifth, who touches its tusk, sees a spear. And the sixth, who touches the tail, thinks the elephant is like a rope. The moral of the story, is expressed by John Saxe (2004) as follows:

So oft in theologic wars,
     The disputants, I ween,
Rail on in utter ignorance
     Of what each other mean,
And prate about an Elephant
     Not one of them has seen!
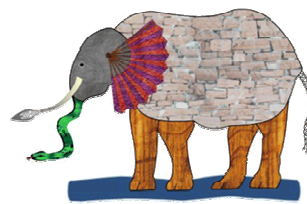
In this paper we review and discuss multiple approaches of measuring urban sprawl. Our intent is not to propose new measures or methods but to present in a single paper an overview of approaches to measuring sprawl taken by scholars trained in a variety of disciplines. Our review is far from comprehensive. In such a broad and diffuse literature we could not possibly review every pertinent paper. Our intent instead is to describe general approaches and to provide references to key sources for further examination. Based on our review, we draw two conclusions. First, over the last two decades we have made substantial progress in our ability to measure and analyze spatial patterns that constitute the problem known as urban sprawl. Second, because of the disciplinary boundaries in which this progress has been made, we understand parts of the problem better than we understand the problem as a whole.

Introduction

Three recent trends have combined to increase interest in sprawl while at the same time expanding the means to study it. First, rising concern over its presumed consequences—traffic congestion, loss of open space, increases in property taxes--has made urban sprawl a topic of widespread popular interest. Whereas research on the spatial structure of cities was once of interest only to German geographers, today the latest sprawl index makes the front page of USA Today (February 21, 2001). Second, GIS technology has made analysis of spatial patterns a simple exercise on a laptop computer and as engaging as a video game. Several software packages are now available for analyzing spatial development patterns and for predicting the consequences. Finally, the quality of spatially referenced data has reached levels unimaginable a few years ago. Today, one can download from local government websites detailed tax lot records and data layers that contain comprehensive planning designations, zoning regulations, land cover information, and much more. From federal sources one can obtain aerial photos that not only reveal natural features such as wetlands, topography, or forest cover, but also the pool in your backyard, the car in your driveway, and the newspaper on the front step.

Our review focuses on work that is empirical in orientation and pertinent to the current debate on urban sprawl. Thus we exclude, for example, conceptual work on urban fractals, systems of cities, and models of urban growth (For more on these, see Torrens and Albert 2000). We do not attempt to review every study on the subject. Instead, we rely on key studies that represent a particular approach. Thus we leave plenty of material for future, more comprehensive reviews.

To impose some structure on our review, we classify approaches to measuring urban form into five categories.

- Metropolitan structure
- Sub-metropolitan structure
- Community design
- Urban design, and
- Landscape ecology

We do not assert that these classifications are mutually exclusive or ideal. They do, however, provide structure for our discussion of a large, diffuse, and rapidly growing literature.

Metropolitan Structure

The *Metropolitan Structure* approach to measuring urban form is perhaps the oldest and focuses on spatial patterns at the metropolitan scale. Measures in this approach are based primarily on census data available for all metropolitan areas in the United States. Most of these approaches predate geographic information system (GIS) technology. For this

reason, many social scientists—especially economists--have used these measures to test varieties theories of urban form.   Common and longstanding measures in this category include measures of population density, population density gradients, and the shape of metropolitan areas; more recent measures include employment density and employment distributions. These measures have frequently been used to examine the effects of urban form on transportation behavior and other urban performance measures.

Measures of Metropolitan Density

The simplest measure of urban form is population density. It is impossible to determine who first described urban form with such a simple measure, but urban population density is still closely watched and regularly analyzed. Sprawl from this perspective is simply a decline in population density. Newman and Kenworthy (1989) stimulated considerable discussion about when they argued that gasoline consumption in European and Asian cities was much lower than in US cities largely because they are more dense. (More about this below). And to date, the only ex-post empirical study of the fiscal impacts of sprawl (Ladd 1992) also focused on aggregate density. Many popular sprawl indicators and periodic assessments in the press (Sierra Club 2004, U.S. News and World Report 1999, Fulton et al 2001) compare changes in population and changes in urban areas— what amounts to changes in aggregate urban density.

The data for examinations of density usually come from the census. Thus it is possible to characterize metropolitan density by the density of particular census tracts. Besides measuring total population density, for example, Malpezzi (1999) ranks census tracts within a metropolitan area by population and identifies the density of the census tract in a particular place in the ranking. Measures of metropolitan density include:

- Population density: total metropolitan population divided by total metropolitan area;
- Minimum density: density of census tract with the lowest density;
- Maximum density: density of the census tract with the highest density;
- Weighted median density: density of the census tract that contains the median person;
- Percentile density: density of the census tract in the xth percentile;

Measures of Density Variation

Besides measuring total density or the density of particular tracts, it is possible to measure variation in density among census tracts. Again using census tracts as units of analysis, Malpezzi (1999) computes several measures of variation in population density. As with any set of data, a number of measures of variation are possible.[1] Measures of variation in population density include:

- Coefficient of variation: measure of density variation from the mean;

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[1] See, e.g., Theil (1967).

- Density entropy: measure of proportionate density variation;
- Density Gini: measure of difference in density from uniform distribution.

Measures of Distribution

Most of the interest in urban form by economists is focused on density gradients. To scholars trained in urban economics, cities are shaped by urban rent gradients that peak in the city center and fall exponentially to the urban edge, where urban rents equal agricultural rents. Sprawl in this model simply reflects a flattening of the rent gradient, an expansion of the urban area, and a decrease in overall density. Brueckner and Fansler (1983), among the first urban economists to formally address the problem of urban sprawl, showed that urban densities fall when incomes rise and when agricultural rents fall, just as predicted by the monocentric urban model.

Clark (1951), an urban geographer, is generally credited as the first to estimate urban population density gradients. But many urban economists have followed suit—again, largely to test the monocentric theory of urban form. McDonald (1989) provides a comprehensive review. Density gradients can be expressed using the following equation,

$$\text{Density Gradient } D(u) = D_0 e^{-rue}$$

Where, D_0 = density in the urban center
  u = distance from the city center
  r = an exponential decay parameter
  e = an error term.

Taking the log of both sides of the equation yields the linear equation,

$$\text{Ln } (D) = a + b \ln (u) + e$$

Two parameters of the density gradient, a and b, are all that is needed in this model to characterize urban form. A fall b represents in increase in sprawl.

In his review of studies, McDonald finds that a and b vary extensively across cities of the United States, but in general central densities are higher and density gradients are steeper in older eastern cities. Perhaps more importantly, however, the empirical results suggest that both central densities and density gradients have fallen over time in nearly every city. The reasons for this pervasive increase in sprawl, according to economic theory, include falling transportation costs and rising incomes. While most of these studies have focused on the US, Betaud and Renaud (1997) have shown similar trends around the world, with exceptions in socialist countries. (See Figure 1.)

In more recent years, economists have also begun to measure and explore the spatial pattern of employment. Glaeser and Kahn (2003) estimate population and employment density gradients for 150 US metropolitan areas and find negative exponential gradients

for both. Glaeser and Kahn also report several other density-related sprawl measures. These include proportions of populations and employees located within 3, 5, and 10 miles rings of the city center, average population and employment densities, and median person and employee distance from the city center. Measures of population density patterns include:

- Estimated central density: estimated value of intercept in density gradient;
- Estimated density decay parameter: estimated value of density gradient;
- Population and employment centrality: proportion within x mile rings of center;
- Density at median distance: density at median distance from center to edge.

Measures of Shape

Researchers who have examined travel behavior at the metropolitan level have also developed measures of metropolitan shape. Intuition suggests more compact and circular cities should have shorter travel distances. For this reason, Bertaud and Malpezzi (1999) compute a compactness index and a measure of discontiguity. Bento et al (2002) compute a measure of city shape that uses a circle as a reference. Measures of metropolitan shape include:

- Oblong ratio: ratio of diameters between the shortest and longest diameters as if the city was an oblong ellipse;
- Compactness: ratio between the average distance per person to the city center and the average distance to the center of gravity of a cylindrical city whose circular base would be equal to the build up area and whose height will be the average population density;
- Contiguity: R^2 statistic from density regression.

Other Measures of Metropolitan Structure

Because much of the research on urban sprawl at the metropolitan level has focused on transportation behavior, researchers have developed several other metropolitan measures that potentially influence travel behavior. Bento et al (2002), for example, include measures of jobs-housing balance, road network density, and transit service supply. Other measures of metropolitan structure include:

- Jobs-housing Gini coefficient: measure of difference in job-housing ratio from even distribution;
- Road density: total miles of road network per square mile;
- Transit supply: total miles of rail transit service.

Composite Indexes of Metropolitan Sprawl

In the last five years there have been developed two widely cited composite indexes of metropolitan sprawl. The first was developed by Galster et al. (2001) using data primarily from the US Census. Galster et al. begin by assigning all land in the

metropolitan area into one of three types: residential, non-residential, and undevelopable due to natural or environmental constraints. Next they overlay a grid of ¼ square mile blocks over the area to use as units of analysis. Finally, by analyzing the composition of and spatial relationships among these grids, Galster et al. define and measure eight dimensions of metropolitan structure; from these compute an overall measure of sprawl. The eight dimensions include:

- Development density: residential units and employment divided by developed land area;
- Continuity: developed area divided by total metropolitan area;
- Concentration: measured in three ways: the percentage of very high density grids among all grids with developable land, the coefficient of variation in the density of grids, and the Delta index of dissimilarity—a formula that captures the extent to which the existing distribution of housing units or employees among the grids constitutes a uniform distribution.
- Clustering: measured by first calculating the density of each one square mile block of the grid and of each of the ¼ square mile blocks within it. The standard deviations of density of each ¼ mile square block from their associated one square mile block density are then averaged and standardized using the average density of all one square mile grid blocks;
- Centrality: measured in two ways: the average distance of housing units or employees from the CBD, and through a centralization index measuring the cumulative percentage of the total housing units or employees falling within concentric rings from the CBD;
- Nuclearity: is measured in two ways: the number of nodes, and the number of housing units in the highest density nucleus as a percentage of the number in all nuclei.
- Mixed Use: measured using a version of an exposure index that shows the average density of one land use in the area of a separate land use.
- Proximity: measured using an index value that is made up of weighted average distances between the same and between different land uses.

Galster et al. convert the values obtained for these eight measures into standardized Z-scores, and then add up each urban area's Z-scores for the eight dimensions. This aggregate number is then offered as a sprawl index. Higher Z-scores reflect lower levels of sprawl.

Another composite index of urban sprawl was developed by Reid Ewing, Rolf Pendall, and Don Chen (2002). Ewing et al. rely primarily on three sources of data: the Census of Population and Housing, the Annual Housing Survey, and the Census Transportation Planning Package (CTPP). Like Galster et al., Ewing et al. work toward a single overall sprawl index for U.S. metropolitan areas and counties. Unlike Galster et al., however, they proceed in two steps: first, using principal components analysis, they develop indices of four subcomponents of urban form, then use these subcomponents develop an overall sprawl index. The four subcomponents include the following: density, mix, centrality, and streets.

Density

Ewing et al. use seven measures to capture the intensity of land use. These include:

- Gross population density: persons per square mile.
- Suburban density: percent of population living at densities less than 1500 persons per square mile.
- Urban density: percent of population living at densities greater than 12,500 persons per square mile.
- Density at center of a metropolitan area: derived from estimated population density gradient.
- Gross population density of urban lands: based on data from the USDA Natural Resources Inventory.
- Lot size: weighted average size of single family lots.
- Population center density: weighted density of population centers based on a grid system.

As expected, suburban density and lot size were negatively correlated with this factor while all the rest were positively associated.

Mix

Ewing et al. compute a mix index based on six measures. Three of these come from the Annual Housing Survey; three come from the CTPP.   These measures include:

- Percent of residents with businesses or institutions within ½ a block of their homes
- Percent of residents with "satisfactory" neighborhood shopping within one mile
- Percent of residents with a public elementary school within one mile
- Balance of jobs to residents
- Balance of population-serving jobs to residents. Population-serving jobs include retail, personal services, entertainment, health, education, and professional services.
- Mix of population-serving jobs

The first three measures are well-defined but limited to the responses given by a small sample. The two balance measures are based on differences in jobs-residents ratios in transportation analysis zones (TAZs) and the metropolitan job-residents ratio. The jobs mix measure is based on the concept of entropy. All are positively correlated with the overall mix index.

Centrality

Ewing et al. compute an index of centrality using six measures. These are:

- Coefficient of variation of population density across census tracts
- The rate of decline in density from the CBD (density gradient)
- Percent of population that lives less within 3 miles of the CBD
- Percent of population that lives more than 10 miles from the CBD
- Percent of population relating to centers within the same metropolitan area
- Ratio of density between the highest density portion of the metropolitan area and the entire metropolitan area

Ewing et al. find that centrality is largely independent of residential density, which means including these variables to the sprawl index provides unique measures not available through other data.

Street Network

Ewing et al. compute an index of street network accessibility using three measures. These are:

- Average block length in the urbanized portion of the metro area
- Average block size in square miles (excluding blocks greater than one square mile)
- Percent of small blocks (less than .01 square miles)

The composite approach by Ewing et al. offers several advantages. First, because they use multiple sources of data, they add new information on transportation infrastructure and provide richer measures of density, centrality, and mix. Further, by developing sub-indices and overall sprawl indices they provide measures that include a wealth of information while removing troublesome problems of multi-collinearity.

Research on Sprawl at the Metropolitan Scale

Much of the research on urban sprawl at the metropolitan scale has been performed by economists. The overwhelming work by economists has focused on density gradients of various types. With few exceptions, the results confirm economic theory. The rise of polycentric cities notwithstanding, land prices and rents, capital to land ratios, and population and employment densities fall with distance from the city center as predicted by urban economic theory. In the comfort of these results, many economists infer that markets therefore serve adequately to guide urban form and that government policies more often detract from, rather than improve, this result. Glaeser and Kahn (2003) offer a rare empirical analysis of those common presumptions. Subjecting these measures to a variety of econometric tests, they conclude that sprawl largely reflects the influence of the automobile—and for the most part the benefits of the automobile exceed the costs of sprawl.

The effects of urban sprawl on travel behavior at the metropolitan scale remain more controversial. Newman and Kenworthy's (1989) finding that gasoline consumption is lower in high density cities has been widely criticized, especially by economists.

Levinson and Kumar (1997) argue that metropolitan density actually captures the effects of city size and that the effect of density on travel time is ambiguous: higher densities shorten travel distance but lower travel speed. Using the predicted population of the census tract in the 10th percentile, Malpezzi (1999) finds that density lowers commute times. Bento et al (2002) find that jobs-housing balance, population centrality, and rail miles supplied lower the probability of travel to work by car and vehicle miles traveled, though the elasticities are small. Ewing et al. (2002, 2003), in work that received considerable exposure, used their metropolitan sprawl index to examine the relationship between sprawl, transportation behavior, obesity and environmental quality. They found that metropolitan sprawl was correlated with higher rates of driving and vehicle ownership, increased levels of ozone pollution, greater risks of fatal accidents, depressed rates of walking and transit ridership, and higher rates of obesity.

Sub-Metropolitan Structure

The *Sub-Metropolitan Structure* approach to measuring urban form uses relatively large submetropolitan units of analysis. The most common users of this approach are transportation planners and engineers. The focus of transportation planning is determining how best to provide access from one part of the metropolitan area to another. This work began long before the development of GIS technology, following a four-step transportation model. And, until recently, most of the work focused primarily on movement by car. As a result, the most common unit of analysis, the transportation analysis zone (TAZ), is built on census geography, is sized to distances pertinent to travel by car, and includes information about factors that affect transportation origins, destinations, mode choice, and route assignment. Transportation infrastructure is very costly; thus large investments have been made toward meeting the data needs of transportation planners.[2]

As described in a number of review articles, transportation planners and scholars generally use submetropolitan measures of urban form to examine transportation behavior—typically measured by the number of trips, the mode of trips, and total vehicles miles traveled (Boarnet and Crane 2001, Ewing and Cervero 2001, and Handy 2004). Further, because entire metropolitan areas contain regions with considerable variation in urban form, there are insights to be gained by measuring urban form at the submetropolitan level.

Measures of Density

Like density measures of entire metropolitan areas, density measures of submetropolitan areas are generally derived from the census data, which include information about populations, employment, and housing units. Unlike metropolitan measures of density, however, submetropolitan measures of density are not aggregated or analyzed as a set, but are used to characterize census tracts or TAZs themselves. For transportation planners, density measures provide information on the number of potential trip origins

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[2] The most important, perhaps, is the CTPP, which aggregates many types of census data to transportation analysis zones, including employment by place of work.

and destinations for submetropolitan areas. Often density is computed for TAZs, but most measures of density (population and housing but not employment) can be computed for areas as small as census blocks, the smallest unit of census geography. (See Figure 2.) Frank and Pivo (1994) for example, measure gross population densities in origin and destination census tracts. Cervero (1994) measures employment density around rail stations. Messinger and Ewing (1996) measure the sum of employment and population density of TAZs. Parsons Brinkerhoff Quade and Douglas (1994) measure household densities of TAZs. Submetropolitan measures of density include:

- Population density: persons per acre;
- Household density: households per acre;
- Employment density: jobs per acre;
- Housing density: housing units per acre;
- Total person density: residents plus jobs per acre.

Measures of Diversity

Measures of diversity capture the mix of activities. For transportation planners, measures of diversity offer approximations of the distance between origins and destinations. Greater jobs-housing balance, for example, suggests shorter commute distances, perhaps more nonmotorized travel, and perhaps less inter-zonal travel. Greater mix can also mean a more diverse urban environment and thus a more inviting route for walking or biking. Mix can be measured in many ways. The simplest involve ratios and proportions. Ewing et al (1996) for example, measure the ratio of jobs to houses. Boarnet and Sarmiento (1998) measure retail and service employment levels in census tracts and zip codes. Messinger and Ewing (1996) measure the proportion of commercial jobs within a TAZ. Proportions and ratios can also be aggregated into summary statistics, such as Gini coefficients and entropy measures. Again, most of these measures can be computed for census blocks, the lowest level of census geography, and for TAZs. Submetropolitan measures of diversity include:

- Jobs-housing ratio: jobs divided by housing units
- Single family-multiple family housing share: number of single family or multiple family housing units divided by total housing units
- Employment diversity: proportion of jobs of various types.

Measures of Accessibility

For transportation planning, location is key. Thus the location of a TAZ or census tracts, relative to other locations to which travel is likely, is a key feature in a transportation model. The most common measure of proximity is accessibility. This is typically measured using a gravity model, where distance to other TAZs is aggregated and weighted by the employment or households in the other TAZs. Kockelman (1997), for example, computes two measures of regional accessibility to jobs using a gravity model. Another common measure is cumulative accessibility: how many jobs or households are accessible from a given TAZ. Parsons, Brinkerhoff, Quade and Douglass (1993) measure

the total number of jobs accessible within 30 minutes by car or transit. The simplest measure is distance. Parsons Brinkerhoff Quade and Douglas (1996) also measure distance to the CBD. These measures, too, can be computed for any level of census geography. Submetropolitan measures of accessibility include:

- Employment or household accessibility: gravity measure of accessibility to employees or households;
- Cumulative employment or household accessibility: total number of households and jobs within a given distance;
- Distance to x: straight line distance to key geographic feature.

Measures of Transportation Networks

Getting from one place to another usually requires travel along some form of transportation infrastructure, such as roads and highways. Roads and highways, like other forms of transportation infrastructure, are part of networks, and the configuration of such networks is an important element of urban form. There are many ways to measure road network configuration. Simple measures involve total miles of roads or intersections. Loutzenheiser (1997), for example, measures the length of arterials around a transit station. Several measures involves an accounting of intersections (Ewing 1996), four-way intersections (Cervero and Kockelman 1997), and intersections per road kilometer (Pushkar et al 2000). Network measures are also often expressed as ratios—such as the ratio of intersections to cul-de-sacs or the percent of road networks that are grids (Messinger and Ewing 1996). Measures of transportation networks include:

- Internal connectivity: ratio of street intersections to the sum of street intersections plus cul-de-sac ends;
- External connectivity: distance between roads or highways that intersect the TAZ boundary;
- Street network density: centerline mileage of streets per square mile.
- Street miles (per capita): total street centerline distance (divided by total residents);
- Block size: average perimeter of block;
- Directness: ratio of distance between two points along road network and straight line distance;
- Intersection density: number of intersections per unit area.

Research on Sprawl at the Submetropolitan Scale

Overwhelmingly, research on urban sprawl at the submetropolitan scale has focused on transportation behavior. These effects have now been the subject of several review papers and more than one book. The results are mixed but reasonably consistent. According to a meta analysis by Ewing and Cervero (2001):

- Trip frequencies are primarily a function of socio economic characteristics of populations and secondarily a function of the built environment;

- Trip lengths are primarily a function of the built environment and secondarily a function of socio economic characteristics;
- Mode choices depend on both socio economic characteristics and the build environment;
- Vehicle miles traveled depend primarily on the built environment.

These findings are consistent with conclusions offered by Cervero (1991) who argues that travel behavior depends on the three Ds: density, diversity, and distance. From this he and many others argue that if the intent is to reduce automobile travel, land use policies should favor high-density, mixed use, and compact urban forms.

This perspective, however, is not universally held. Boarnet and Crane (2001) claim that the only land use strategy that reduces vehicle miles traveled by car is traffic calming— that is, road network designs that intentionally slow automobile speeds. Further, according to Boarnet and Crane, most of the research on the relationship between transportation behavior and urban form lacks a sound theoretical foundation. That is, if density, mixed use, and compact forms of development reduce automobility, we do not have a sufficiently clear understanding why. Such knowledge, they argue is the key to successful land use policy. They appear unconcerned, however, about extrapolating the results of studies that use submetropolitan data to entire metropolitan areas.

Community Design

The *Community Design* approach to measuring urban form is relatively new. These measures are based primarily on GIS data that did not exist for most places even ten years ago. Many local governments, for example, now have data layers that contain information on tax records, land cover, land use, zoning and plan designation, slope and floodplains, wetlands and other sensitive area, and much more. Further, these data allow analysts to focus on spatial patterns at very high levels of resolution, such as the tax-lot parcel. Finally, because the data are "object" oriented, the measures can be computed for nearly any self-defined geographic unit.

Measures of community design have been used for a variety of research and planning applications. As these more disaggregated data have become available, more detailed measures of community design have been used to explore transportation and other physical activity behaviors. Measures of community design have also been used by policy analysts to measure differences in community design between cities and changes in community design in a given city over time. Finally, measures of community design have been incorporated in planning support systems to help planners and policy makers design and evaluate alternative development designs.

Measures of Density

For geographic areas larger than census blocks, every metropolitan and submetropolitan measure of density described above—e.g., population, employment, and households--can be computed for any user-defined spatial unit. But because local GIS data include

information on many more urban attributes, densities can be computed for many different features—such as parking spaces, classrooms, recreation facilities, transit stops or any geocoded feature that can be counted. In their evaluation of growth management success in Portland, for example, Song and Knaap (2003) measure population density, housing unit density, and average lot size of single-family homes within ¼ mile of recently sold single-family homes. Further, because land areas can be identified for different uses, zones, or land covers, density measures can be computed based on areas defined by use, zone, or cover, not just area within a census polygon. Bush and Hickman (1999), for example, measure population density within one-quarter mile of a transit station. Community design measures of density include:

- Residential density: residents per residential acre
- Household density: households per residential acre
- Single family density: single family housing units divided by single family acres
- Multi-family density: single family housing units divided by multi-family acres
- Employment density: jobs per commercial and industrial acres
- Commercial floor area ratio: commercial floor space per commercial acre
- Housing density: housing units per residential acre.
- Residential floor area ratio: residential floor space per residential acre
- Lot size: average lot size in use x.

Measures of Composition

GIS data maintained by local governments are typically organized by tax lot parcel, and each parcel often has a current use, a zoned use, and a planned use. Further, local GIS data typically include political boundaries, such as municipal, county, school district, congressional district, and tax district boundaries. Finally, local governments often have designated service areas for particular public services. Thus measures of composition can be constructed as the intersection or unions of any of these spatially defined regions. To facilitate a build-out analysis in various communities, for example, The Massachusetts Office of Geographic and Environmental Information identifies the amount of land in each zoning class in each township in the state (Massachusetts, State of, 2004)). Measures of urban sprawl, however, typically focuses on uses, with particular emphasis on parks and green spaces, total area of developed land, and land in agricultural uses. A large body of research, for example, uses measures of agricultural areas and greenspaces to examine how such areas affect land values (Geoghegan 2002). Community design measures of composition include:

- Total area of development: area of land in urban uses;
- Area of land in use x: area of land in use x, where x = residential, commercial, industrial, institutional, or agricultural uses;
- Green space: amount of land in parks or conservation use

Measures of Diversity

Because local GIS systems contain information on so many urban features, the number of possible measures of diversity is limited only by the sets of variables that can be measured in the same units. Again, diversity can be computed in proportions and ratios or in summary measures such as Gini coefficients or entropy measures. As discussed above, measure of diversity are especially common in transportation research, based on the presumption that more diverse land uses facilitate more walking and biking. But local GIS data enable higher resolution measures of diversity. Cervero and Kockelman (1997), for example, measure the proportion of commercial parcels that are vertically mixed; Frank and Pivo (1994a, 1994b) compute an entropy measure of the mix using tax-lot parcels; Kockelman (1997) computes three entropy indices and a dissimilarity index. Common community design measures of mix include:

- Proportion of mixed land use: proportion of mixed or dissimilar land uses;
- Land use mix: entropy measure of land use mix.

Measures of Accessibility

As at the submetropolitan level, proximity between places to and from which people want to travel is a critical feature of urban form. Once again, however, the breadth of GIS data available at the local level makes the number of proximity measures virtually limitless. More importantly, however, because the locations of households and jobs can be identified to a particular point, it is possible for accessibility to be measured for individual households and jobs rather than for polygons that contain aggregates of households and jobs. As a result, accessibility can be measures as a gravity measure to all potential attractors (weighted by distance), as distance to the nearest attractor, or as the number of attractors within a given distance. Cambridge Systematics (1994), for example, measures the availability of convenience services within ¼ mile of a transit station; Cervero (1996) measures the number of commercial and nonresidential buildings within 300 feet of a residence; Holdsclaw (1994) measures the fraction of population with neighborhood shopping within ¼ mile. Individual measures of accessibility can then be aggregated for all those contained within a specific area. Song and Knaap (2003) for example, measure the proportion of single family housing units within a TAZ that are located within ¼ mile of a commercial use. Krizek (2003) reviews commonly used operational measures of neighborhood design, which contribute to overall "neighborhood accessibility". For his application to travel behavior research, a composite index of five of these measures (population and housing densities, land use mix, street intersection density, and average block size) was computed at the 150-meter grid cells across the entire Seattle region. Community design measures of accessibility not listed above include:

- Amenities accessibility: gravity, distance, or cumulative measure of accessibility to amenities, including schools, parks, or shopping.
- Transit proximity: walking distance to the closest transit stop.

- Transit-oriented residential density: number of housing units that are within a ¼ mile walk of a transit stop.
- Transit-oriented employment density: average number of employees per net non-residential acre that is within a ¼ mile walk of a transit stop.

Measures of Transportation Networks

Because community design measures can be computed for any geographic unit, and because a street network is almost always among the sets of data maintained by local governments, it is possible to compute all the measures of transportation networks as those for submetropolitan areas but for self-defined regions. But again, because local GIS data may contain more information than the census or through the use of orthophotos and other remote sensing technology, it is possible to compute measures of additional transportation networks, such as pedestrian and bicycle transportation networks. Rodriguez and Joo (2004) measure the presence of sidewalks. Recent attempts have been made to calculate the directness and distance of nonmotorized transportation facilities. Randall and Baetz (2001) and Dill (2004) present measures of the connectivity of sidewalk and bicycle networks to capture these characteristics. Nelson and Allen (1997) compute per capita miles of bicycle facility infrastructure. Community design measures of transportation networks not listed above include:

- Transit service density: number of miles of transit routes multiplied by number of transit vehicles traveling those routes each day, divided by total acres;
- Sidewalk network coverage: percent of total street frontage with sidewalks on both sides;
- Lane miles of non-motorized infrastructure: total distance devoted to bicycle or pedestrian facilities (on or off road);
- Pedestrian route directness: ratio of the shortest walkable route distance to the straight-line distance between the same points. Points chosen usually include a central node and an outlying residential area;
- Bicycle network coverage: percent of total street centerline distance with a designated bike route.

Categorical Measures of Neighborhood Design

Some studies do not compute any of the above measures of urban form but examine differences between neighborhoods that differ categorically. In some cases, the categorical difference between neighborhoods are quantitatively defined using principal components analysis (Song and Knaap 2004b), in others the distinction is more general. Friedman et al. (1994), for example, compare how travel behaviors differ between auto-oriented neighborhoods (areas developed after the 1950s, with little transit service, separated uses, and a well-defined hierarchy of roads) and transit-oriented neighborhoods (areas developed before WWII, with a mixed use commercial district, and an interconnected street grid). Similar analyses have been conducted between other neighborhood types (Handy and Clifton, 1998). Some categorical measures of neighborhood design include:

- Traditional: Built before WWII;
- Conventional suburban: Built after 1950;
- Planned unit development: Built as a planned unit development;
- New Urbanist: built following principles of new urbanism;
- Neighborhood type: type defined by principal components analysis.

Research on Sprawl at the Community Design Scale

Research that uses measures of urban sprawl at the community scale has largely been used in three ways: to analyze transportation behavior, for policy analysis, and to assist in the planning process. As in the case of submetropolitan measures, studies examine the effects of community design on transportation behavior have produced mixed results. According to Handy (2004), several studies have found walking and biking positively related to population and employment density, not related to street network structure or the presence of sidewalks, and positively related to accessible destinations. Thus for walking and biking, community measures of urban form seems to matter.

In a series of papers, Song and Knaap have used measures of community design to evaluate effects on property values and to assess differences in urban form between metropolitan areas and in changes of urban form within metropolitan areas over time. Using measures of community design for Washington County, Oregon, Song and Knaap (2004a) showed that property values were higher for single family homes located in neighborhoods with better internal connectivity but lower external connectivity. They also found that single family home prices were higher in low density, homogenous. neighborhoods and for homes located on cul-de-sacs. In another paper, Song and Knaap (2004c) showed that single family densities and internal connectivity has been increasing over time in several metropolitan areas, but that external connectivity has been decreasing and there has been almost no change in the mixture of land uses. (See Figure 3.)

To assist in the planning process, Eliot Allen and his colleagues at Criterion Consultants developed the Smart Growth Index with support from the U.S. EPA (Allen 2001). The Smart Growth Index requires a number of GIS data inputs which characterize an existing or proposed development. The Index produces seven sets of indicators: demographics, land use and community form, housing, employment, recreation, environment, and travel. Unlike the indices by Galster et al. and Ewing et al., the Smart Growth Index does not compute an overall sprawl index, though with user-defined weights it has the capacity to do so.

Allen's Index tool allows users to weigh each factor according to its importance in the study area. This flexibility enhances analysis options. Alternatively, if data are available, planners may hold factor weights constant and apply them to a variety of study areas to see if some dependent variable, such as vehicle miles traveled, mode choice, or physical activity level of residents is influenced by the urban form.

Urban Design

Urban design measures capture urban form at the highest level of resolution and are drawn from a rich and well developed body of theory. According to Lynch (1960), good urban designs offer a sense of imagability, coherence, closure, legibility, and edge. Developing measures of these properties, however, is difficult. The urban design approach is the most disaggregate approach. For this reason, these measures cannot be obtained, or computed, from secondary sources but must be collected through field observation or interviews. Measures of urban design have been used to explain variation in a number of urban phenomena, such as crime, social capital, residential satisfaction, and transportation behavior (Hess et al. 1999, Project for Public Spaces 2001). Most recently considerable work toward measuring urban design, however, has been directed toward explaining variation in physical activity, in part a form of transportation behavior.

Urban design characteristics have an important impact on how people perceive and experience space. With the advent of the automobile, most design elements became focused on experiencing urban space from the inside of a car. Signs are large, buildings are set back from the street, and trees are trimmed to allow traffic signals to be easily viewed. Other design elements are influenced by the need to create adequate space for automobiles: parking lots line many roads, turning angles create wide pedestrian crossings, and garages, rather than windows, are the dominant element in many residential neighborhoods. At a pedestrian scale, different elements rise to importance. These include the need for complex buildings to capture the attention of the eye, shade for walking comfort, and a sense of enclosure from building facades.

Measures of urban design are both objective and subjective and can be collected by members of a research team (often students) or by interviewing residents or employees. Objective measures include, for example, the existence of a sidewalk and its width, the heights of buildings, or the presence of afternoon shade. Subjective measures include safety, coherence, pedestrian friendliness, or beauty. The distinction between objective and subjective, however, is not precise, since measurement usually involves some degree of interpretation. In part for this reason, measurements of urban design often vary between researchers and survey respondents.

Much work has been directed toward objective measures or urban design in recent years, due in part to the growing interest in the determinants of walking and biking. The prevailing wisdom is that walking and biking activity is affected by characteristics of the urban environment that are highly detailed, not observable from the car, and not routinely collected by local governments. Hence, they must be collected through fieldwork.

Because nearly every measure must be collected directly, researchers have paid considerable attention to the problem of validity—does the information collected accurately portray the physical environment? The typical approach is to have more than one individual collect data for a particular site. A high level of agreement suggests a high degree of validity. In some cases, this approach has been used to validate survey instruments. In this approach, the responses to a survey about a particular site are

validated by a member of the research team. Once again, a high level of agreement suggests that the survey instrument is valid. As in any data-collection effort, auditors must be trained and the results must be checked for inter-auditor validity. Elements of the audit instrument include transportation infrastructure design and quality, building design, environmental features, and more.

Measures of Transportation infrastructure

At the micro scale, the mere presence of a street or street network is a clearly inadequate measure of transportation infrastructure. At this scale, not only is infrastructure for the pedestrian or the bike of greater interest, but of greatest interest are the micro scale features of infrastructure that serves pedestrians and bicyclists. Urban design measures of transportation infrastructure, therefore, include walking trails, sidewalk widths and quality, cross walks and signals, and curb cuts. For bicycles, there needs to be a presence of dedicated lanes or off-road facilities, bicycle parking, intersection treatments, and parking facilities. Transit options and parking spaces are important as well. Urban design measures of transportation infrastructure not listed above include:

- Sidewalk width: width of sidewalk;
- Cross walks: presence of crosswalks;
- Pedestrian traffic signals: presence of pedestrian traffic signals;
- Traffic volumes: vehicular traffic volume over specific period;
- Speed limit; posted speed limit;
- Sidewalk quality: sidewalk quality rating;
- Parking spaces: number of parking spaces
- Transit options: transit service options in particular area;
- Trails: number, length, and characteristics of trails

Measures of Building design

The design of buildings is thought to have a significant effect on the quality of the urban environment. Building heights provide a measure of the sense of scale. Ewing (undated) for example, offers a range of ideal building height and height-to-width standards. Consistency of building heights provides a measure of design coherence. Building spacing provides a measure of enclosure. Measures of building design can be measured for any geographic regions, but are most commonly measured by block face.

- Building height: average height of buildings;
- Building width: average width of buildings;
- Building height uniformity: coefficient of variation in building height;
- Set backs: average set back of building from street;
- Historic building design: number of buildings with historic façade;
- Building mix: number of building types;
- Enclosure: percent of block face that has no building façade.

Measures of Environmental Context

Other features of the local environment can be considered part of the urban design. The extent of tree canopy and the shade it provides, for example creates a sense of enclosure and comport in warm climates. The presence and type of street lights can provide a sense of safety and pedestrian friendliness. Similarly, the presence of parked cars can provide a barrier from street traffic.

- Tree canopy: percent of block face covered with trees;
- Shade: the percent of block face shaded at specific time;
- Streetlights: presence of street lights, by type of light;
- Parked cars: number of parked cars on block face;
- Public art: number and quality of public art;
- Street furniture: number and type of street furniture;
- Slope or topography: degree of incline in the local environment;
- Signage: number and types of signs.

Measures of Accessibility

Location matters at every scale. And because much of the interest in this area is focused on walking and physical activity, proximity to opportunities for physical activity is particularly important. Again, at the micro scale, detail and precision matter. Thus at this scale, the mere location of commercial uses an insufficient measure. Instead what is needed is the type of commercial activity—e.g., a candy store—the scale of the activity, the number of adjacent automobile and bicycle parking spaces, and an indicator of whether the entrance to the store faces the street (Ewing, undated). In the physical activity literature, of interest is what is termed physical activity supports (Giles-Corti et al 2002). These include parks, gyms, pools, tennis courts, etc. As at other scales, accessibility at the urban design scale can be measured as a gravity measure, as distance to the nearest opportunity, or as the sum of opportunities within a given distance. Urban design measures of accessibility not listed above include:

- Street orientation: number of doors facing the street;
- Entry accessibility: number of entrances to facility;
- Handicap friendliness: presence of handicap facilities;
- Physical activity supports: gravity, distance, or cumulative measure of accessibility to physical activity opportunities.

Measures of Perceptions

Not every quality of urban form can be measured directly. What's more, perceptions—they way humans interpret the qualities of the environment—matter as well. Recent studies of the relationship between land use and behavior (Clifton and Livi 2004b, Kitamura et al. 1997, Targa and Clifton 2004) have recognized that travel-related choices are not expected to depend exclusively on objective measures of the transportation and land use system, but also on their perceived attributes or qualities. Important perceptions

about the qualities of places, for example, are traffic safety, safety from crime, cleanliness, attractiveness, and pedestrian friendliness. The only way to collect information about perceptions is to ask—e.g., do you feel the neighborhood in which you live is safe? In a study of neighborhood perceptions and walking behavior, Clifton and Livi (2004b) asked residents about their subjective interpretation of the overall walking conditions as well as specific attributes of the environment, including traffic safety, personal security, attractiveness, sidewalks and pedestrian accommodations. An alternative is a visual preference survey. In a visual preference survey, individuals are shown images of neighborhoods and asked to reveal whether they view the place as safe, attractive, clean, etc.

- Safety: rating of perceived safety;
- Pedestrian friendly: rating of perceived safety for walking;
- Cleanliness; rating of perceived cleanliness;
- Attractiveness: rating of perceived attractiveness.

Integrated Measures of Urban Design and Urban Perceptions

Recently a number of researchers have sought to develop quantitative links between objective measures of urban design with traditional subjective measures like transparency, imagability, coherence, etc. In this approach subjects are asked to rate an image or a place based on a subjective measure—like coherence. The image or place is then also subjected to an audit in which objective measures of urban design—such as building heights, street widths, number of windows, etc., are collected. Finally, the subjective measure is regressed on the objective measures to determine how subjective measures like coherence are shaped by objective qualities like street widths, building heights, etx.. Ewing et al (forthcoming a), for example, explored which design features led residents to view a highway as a "main" street. They found that residents viewed main streets as having high proportions of street frontage with parked cars at the curbside, high proportions of street frontage covered by trees, high proportions of buildings with commercial uses, wide sidewalks, and few travel lanes. In a subsequent study, Ewing et al (forthcoming b) identified the factors that cause residents to view urban landscapes as having eight qualities: imagability, legibility, enclosure, human scale, transparency, linkage, complexity and coherence. The results suggest that many subjective characteristics of good urban design can be attributed to specific and quantifiable design elements—elements that can then be incorporated into urban design guidelines. (See Figure 4.)

Research on Sprawl at the Urban Design Scale

Measures of urban design have been used to explore a number of issues, such as crime, social interaction, transportation behavior, and physical activity. Traditional urban design research, based in large on the work of Kevin Lynch, focused on perceptions and how those perceptions affect human behavior. Recent extensions of this work have used visual preference surveys to identify the kinds of urban environments citizens prefer (Nelessen 1994 Malizia and Exline 2000). Not surprisingly, the results reveal a distaste

for urban sprawl and strong preferences for principles of smart growth—e.g., preserved open spaces, high density development, and town centers with a strong sense of place. The results of these preference surveys have since found their way into regional plans and subdivision design standards (Ewing et al, forthcoming a). Yet these studies are subject to confounding effects and often cannot provide the specific needed for sound standards of urban design.

To over come these limitations considerable work has focused on objective measures of urban design. Many of these measures are collected using environmental audits. As a result, recent work has been directed toward assuring reliability of the audit instrument. In fact, a significant subset of the literature addresses this issue (Brownson et al. 2004, Pikora 2002, Clifton and Livi 2004a). As a result, several audit instruments are now considered standards for use in this kind of work. A recent paper (Hoehner et al. forthcoming) compared the results of an audit instrument with the results of a resident survey. While the results of the survey and audit were relatively consistent, the correlation between physical activity and perceived and objectively measures of the urban environment were not the same. No explanation was given for these results

In general, the research suggest that urban design can have an effect on a variety of human behaviors, though what may be good for reducing crime, for example, may not be good for social interaction. Of particular recent interest is the effect of urban design on walking and physical activity. In a recent comprehensive review, Handy (2004) divides the literature into two parts: research on active travel (walking and biking) and research on total physical activity (regardless of activity). For active travel, Handy reports strong correlations with measures of density and accessibility but weak correlations with measures of urban design and street networks. For physical activity, Handy reports strong correlations with measures of accessibility and neighborhood aesthetics and weak correlations with other neighborhood characteristics.

Landscape Ecology

The final approach to measuring urban form we call the *Landscape Ecology* approach. Landscape measures of urban form focus primarily on areas not developed for urban use. That is, from a landscape ecology point of view, the focus of interest is usually on the patch of land not developed for urban use, not the urban uses that surround the undeveloped patch. Landscape ecologists are interested in spatial patterns at variable scales and measures vary accordingly. Further, because landscape ecologists are primarily interested in "natural" landscapes, landscape measures are based primarily on types of land cover, not types of land uses. The form and structure of a landscape affects its capability to provide suitable habitats for plants and animals. Landscape heterogeneity over space and time affects ecological processes; as such studying its form and structure is an important step in understanding ecological outcomes. Common uses for landscape analysis include: natural resources inventories, coastal zone monitoring, soil classification, drainage patterns, crop yield estimation, or assessment of forest conditions (Quattrochi and Pelletier 1991).

The data for ecological measures of urban form differ from the others described above in significant ways. First, the data often come from satellite imagery and air photogrammetry. As a result, landscape ecologists largely create their own data through photo interpretation. That said, considerable data on land cover and interpreted land use is available from the USGS (2004). Second, the basic unit of study for a landscape is a patch. McGarigal (2004) defines patches as discrete areas of homogeneous environmental conditions. Unlike a census tract or tax lot parcel, and more like entire metropolitan areas, the shape and size of the patch is of particular interest. Two other landscape elements build on the concept of a patch: classes represent sets of similar patches and landscapes represent the sum of all patches in a given area.

Patches are classified by land use based on the type of habitat or the extent of human development. A common classification system is the Land Use/Land Cover Classification System (LULC) developed by the US Geological Service (Anderson et al 1976). LULC includes 9 broad land use categories with subsets for each type. The nine broad categories are: urban land, agricultural land, rangelands, forest land, water, wetland, barren land, tundra, and perennial snow/ice (as cited in Dunn et al. 1991). These patch-based data are then used to derive measure of the patches themselves or the landscapes in which they are located. Patches can also be classified along a continuum. Clapham (2003), for example, examines the effects of urban sprawl in Ohio watersheds by classifying patches along continua of impermeability and canopy cover.

Measures of Patches

Because plant and animal species require suitable habitats, landscape ecologists are interested in the characteristics of patches themselves as well as the landscapes in which they are located. Further, the suitability of a patch of habitat may depend not only on its size but also on its shape. Soule (1991), for example, demonstrates how bird species are affected by edge effects in San Diego. To birds and other wildlife, it matters that its patches of habitat are not excessively thin and contains a significantly large area free from the edge effects of urban encroachment. The characteristics of patches can be aggregated to compute totals, averages, medians, and standard deviations to develop measures of landscapes. (See Figure 5.) Novak and Wang (2004) for example, compute for the entire state of Rhode Island the number of forest patches, average patch size patch size, standard deviation of patch size, and patch density. Hasse et al. (2003) measure changes in 'core' forests in New Jersey by aggregating the area of forest patches that are buffered by 90 meters from human-altered land use classes. Measures of patches include:

- Patch area: area in a particular patch;
- Patch edge length (perimeter); perimeter of a patch;
- Patch shape: patch area divided by patch perimeter;
- Patch shape index: comparison of patch shape to a standard shape such as circle;
- Core area: area of patch greater than some distance from the patch edge.

Measures of Composition

Characteristics of landscapes are in some sense also an aggregation of the characteristics of patches. The most common and widely used landscape measure is total land area (or proportion of the landscape) of a particular type of patch. Using satellite imagery, for example, Yang and Lo (2002) measure proportionate changes in high-density urban use, low density urban use, cultivated land, cropland, forest land, and water in the Atlanta metropolitan area. Similar inventories of farm and forest lands, wetlands, or wildlife habitats, or losses thereof, are also common landscape measures (American Farmland Trust 2004, Dahl 2000, Noss and Peters 1995). The amount and proportion of impervious surface is another common measure of urban composition. This measure, however, is usually estimated from aerial photography or satellite imagery and is not directly identified as the aggregation of patches (Arnold and Gibbons 1996).

- Landscape share: share of landscape in any particular class of patch;
- Richness: number of different patches in a landscape;
- Patchiness: number of patches in a class.

Measures of Diversity

Landscape ecologists are also interested in the mixture of patches. Thus, like those interested in submetropolitan structure and community design, landscape ecologist compute mixture using measures of diversity. Yeh and Li (2001), for example, use entropy measures of diversity to identify the degree to which new urban developments are scattered along concentric rings and highway corridors in China.

- Diversity: entropy measure of mix of patches in the landscape;
- Dominance: proportion of landscape in the largest type of patch.

Measures of Configuration

Though plants and animals don't drive cars or ride transit, the spatial relationships among their habitat patches are also potentially important and often disrupted by urban sprawl. Evidence suggests that changes in local plant and animal populations in a patch are influenced by their distance from other populations of the same or competing species. For example, McGarigal and Marks (1995) cite several studies showing that isolated patches have fewer bird species than those that have nearby patches of the same type. Organisms that need two or more habitats to survive are affected by the juxtaposition of patches because they require close proximity of different patch types to survive. This can be measured using contagion metrics. Contagion measures both patch type interspersion (the intermixing of units of different patch types) as well as patch dispersion (the spatial distribution of a patch type). In most cases, a landscape with well-interspersed patch types will have lower contagion than those without. Area-weighted patch size is a measure of the aggregation or clumping of land uses. This measure helps to differentiate between landscapes with a few large, contiguous patches and those with many small patches.

- Contagion: probability that adjacent patches are of the same type;
- Proximity: distance to a patch of a particular type;
- Connectivity: average distance to nearest patch of same type;
- Nearest neighbor: distance to nearest patch of the same type.

Research on Urban Sprawl Based on Measures of Landscape Ecology

Protecting the environment is often identified as one of the primary reasons for controlling urban sprawl. But in many respects, the relationships between environmental processes and urban form are the least understood (Alberti 2002). Traditional research on the effect of urban sprawl focused on urban growth per se and the effects of urban growth on farmland, wildlife habitat, air pollution, and water quality. From these perspectives, spread of urbanized areas is unambiguously harmful, as it consumes farmland, disrupts habitat, increases vehicle miles traveled (thus degrades air quality), and increases impervious surfaces (thus degraded water quality) (Gordon and Forman 1982, Chen et al. 1992, Randolph 2004). Discontinuous urban growth is even more harmful, as discontiguity further fragments farmland and wildlife habitat (Randolph 2004). But recent developments in remote sensing and in landscape measurement facilitate far more complex research on the relationships between urban form and ecological function.

According to Alberti (1999), research on the effects of urban development patterns on the use of energy, the flow of materials and ecosystem functions remains highly underdeveloped. Towards this end, Alberti (2002) has attempted to fuse community design measures of urban form with landscape measures of ecological conditions to examine the effects of alternative development papers on water quality and avian species abundance. The results suggest that single-family residential parcels have measurably lower levels of impervious surfaces than multifamily parcels or parcels currently in mixed uses. Also, and perhaps more importantly, different land uses have different levels of landscape fragmentation and natural covers that can be preserved under different land use scenarios. These results raise serious questions about prescriptions for high density, multifamily development based purely on ecological grounds. Further, Alberti finds that the spatial pattern of impervious surfaces as well as their percentage levels can affect fish species in sensitive watersheds. Bird species, on the other hand, are more strongly affected by the total availability of forested cover than its spatial configuration.

Several software programs have been developed to facilitate the computation of these more complex measures of landscape structure. (Turner 1989, University of Massachusetts 2004). A widely used package is FRAGSTATS developed by Kevin McGarigal and Barbara Marks (1995). Originally developed for the forest service, FRAGSTATS has recently been integrated with ARC/Info and made widely accessible. FRAGSTATS and similar packages have been used for a variety of landscape and ecological analyses. The potential of these tools is extremely high. But as noted by Berry (1999): "In the case of landscape structure analysis, we have the technological cart ahead of the horse—we can calculate the metrics, but haven't completed the research to translate them into management action."

Conclusions

Although interest in urban form is not new, our review suggests that scholars have made considerable progress in developing and computing measures of urban sprawl. These measures capture spatial arrangements at varying scales, use data from a variety of sources, and address concerns that confront multiple disciplines. Social scientists—especially economists--use census data to analyze spatial patterns at the metropolitan scale. Transportation planners use census and TAZ data to explore transportation behavior at the submetropolitan scale. Land use planners use local GIS data to analyze spatial patterns at the community scale Architects and urban designers conduct audits and visual preference surveys to analyze environments at the neighborhood and building scale. And landscape ecologists use land cover data to analyze landscapes at varying scales.

Any attempt to summarize the results of literally hundreds of papers is hazardous, but not impossible. In our view, economists have generally found that density gradients behave as predicted by economic theory, and conclude that markets provide adequate discipline on urban form. Transportation planners find less automobile use among residents of high-density mixed use census tracts or TAZs; they therefore recommend that public policies that favor high density and mixed land use. Land use planners, using the findings of transportation planners, evaluate the merits of plans by their levels of density and mixtures of use. Urban designers find preferences for intricately textured urban environments, and recommend that all environments be so textured regardless of cost. And landscape ecologists find that urban growth causes habitat and farmland fragmentation, greater impervious surfaces and thus recommend that urban growth be contained.

All of these conclusions and policy recommendations have merit. Still, most all problems of urban form are scale dependent, place specific, and highly interdependent with other similarly scale dependent and place specific problems. Thus, much progress remains to be made. And like the blind East Asians and the elephant, no one seems to have the big picture, yet policies (like the principles of smart growth, new urbanism, and sustainable development) offer universal prescriptions. Like the wise man that views the elephant as a snake, and prescribes a mouse, unfortunately, universal prescriptions are likely to fail. Of all the disciplinary approaches to the measurement of urban sprawl, landscape ecologists are perhaps the most careful to exercise caution with respect to definition and scale. McGarigal and Marks (McGarigal et al 1995), for example, state:

> The importance of fully understanding each landscape metric before it is used cannot be emphasized enough. Specifically, these questions should be asked of each metric before it is used: does it represent landscape composition, configuration, or both; what aspect of configuration does it represent; what scale, if any, is it spatially explicit; how is it affected by the designation of a matrix element? Based on the answers to these questions, does the metric represent landscape structure in a manner ecologically meaningful to the phenomenon

under consideration? Only after answering these questions should one attempt to draw conclusions about the structure of the landscape.

These questions are pertinent to nearly every aspect of urban sprawl. Yet most often, these questions are not addressed. And though we have developed and computed an impressive set of measures, we still don't know the beast very well.

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Figures

Figure 1: Density Gradients of Cities in Europe, Asia, and the United States.
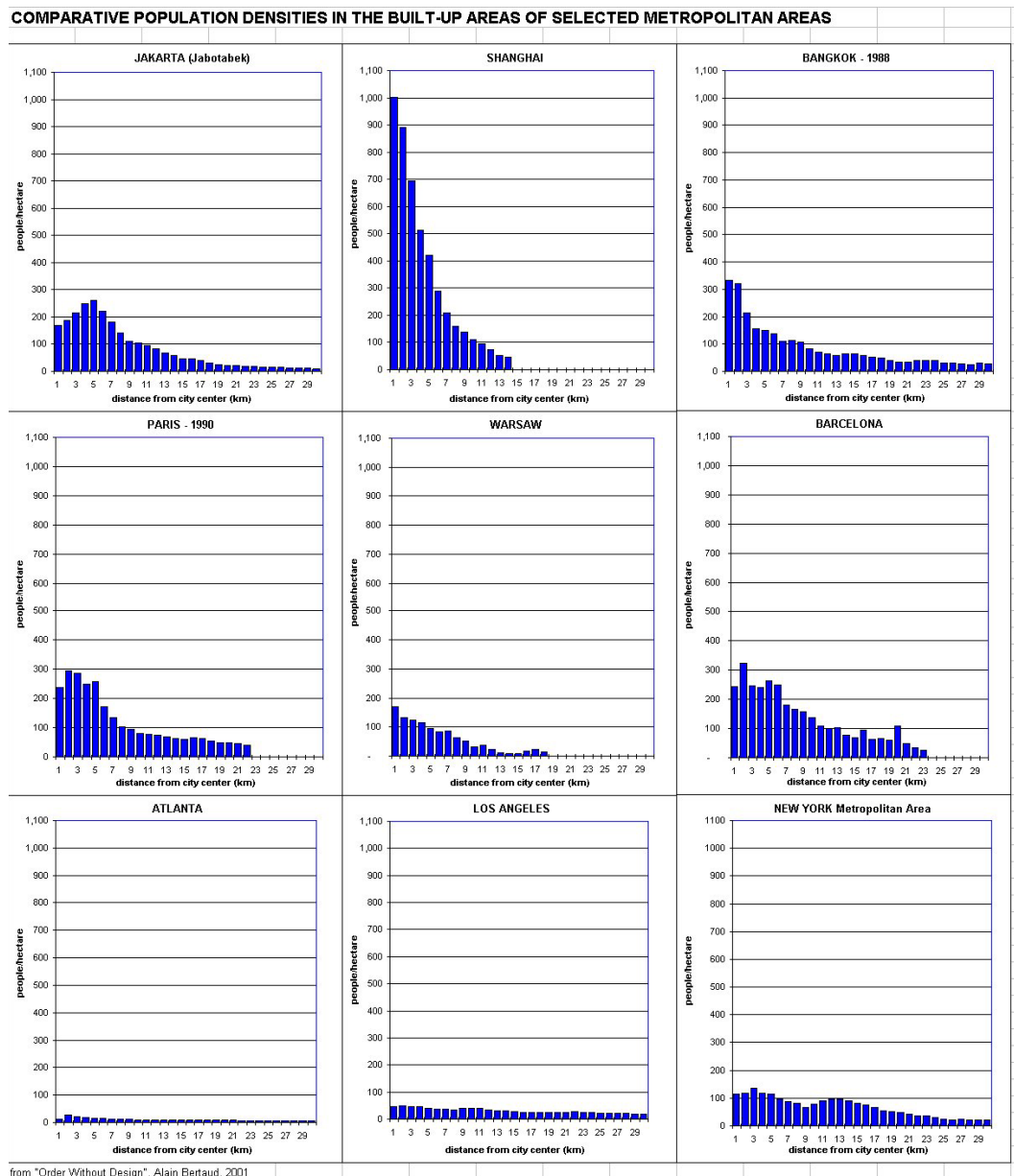

COMPARATIVE POPULATION DENSITIES IN THE BUILT-UP AREAS OF SELECTED METROPOLITAN AREAS

from "Order Without Design", Alain Bertaud, 2001

Figure 1 illustrates the variation in population density with distance from the city center in European, Asian, and U.S. cities. Betraud (2000) argues that the patterns illustrated above are consistent with urban economic theory. By comparing the rows in the figure, it is clear that aggregate density is the highest and density gradients are steepest in Asian cities where the dominant mode choice is walking and bicycling. Aggregate density is lower and density gradients are less steep in European cities where public transportation is most common. Aggregate density is the lowest and density gradients are the least steep in U.S. cities where travel is dominated by the automobile.
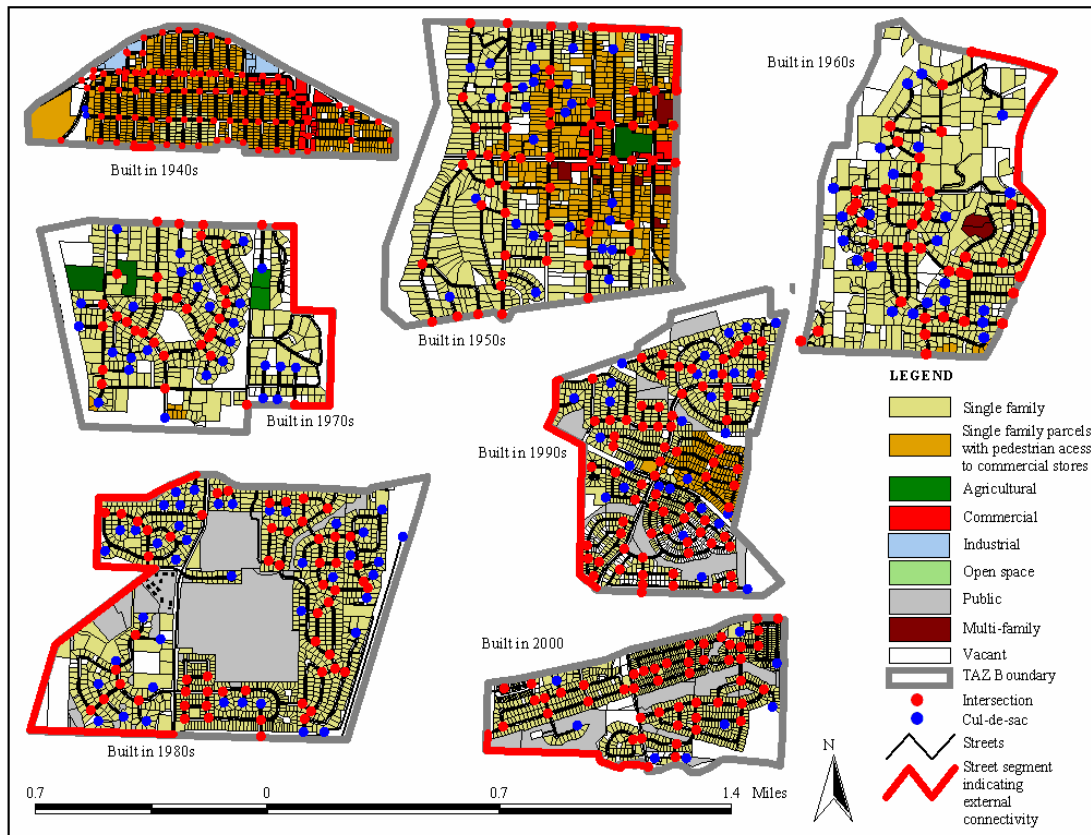
Figure 2

The Map of Average Transportation Distance in Portland Region
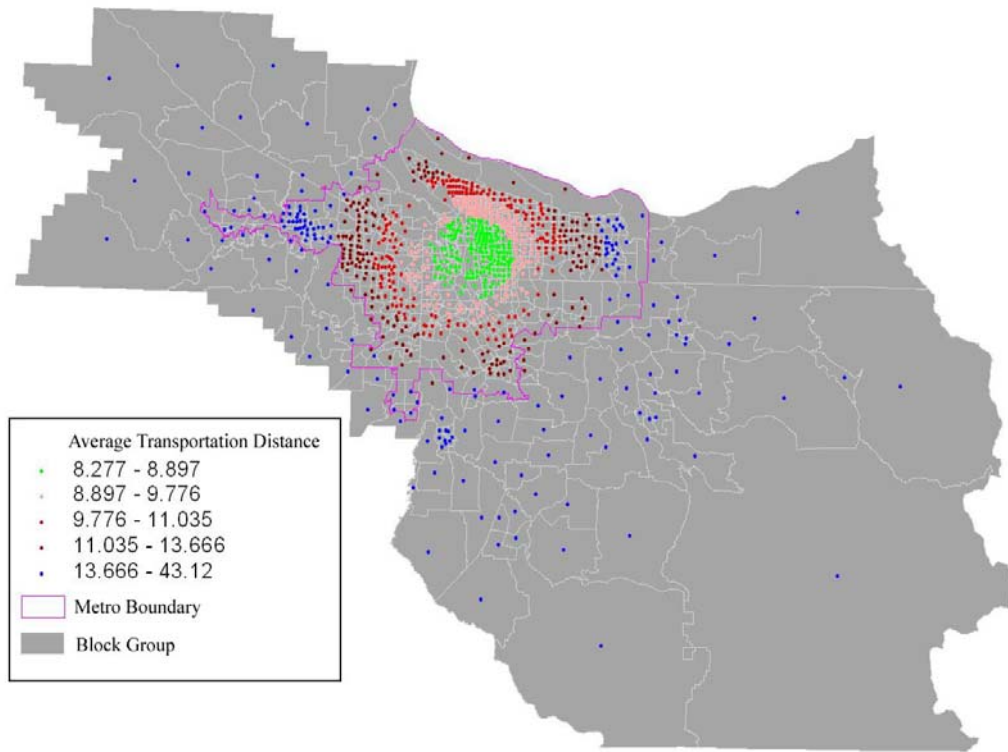
The above map illustrates accessibility to jobs in the Transportation Analysis Zones in the Portland metropolitan area. To compute average distance, the distance from each TAZ to every other TAZ is computed and divided by the number of TAZs. As shown average distance is greatest in the center of the metropolitan area and declines with distance from the center.

Figure 3: "Typical" pattern of neighborhood development in the Portland metropolitan area by decade.

Song and Knaap (forthcoming) use the above figure to illustrate how development patterns can be measured and how those measurements have changed in the Portland metropolitan area over time. Toward that end, they compute three sets of measures: Street Network Design; Land Use Intensity; and Land Use Pattern.

Street Network Design. Measures of street network design include internal and external connectivity.

o *Int_Connectivity* – number of intersections divided by the sum of cul-de-sacs (or dead ends) and intersections; the higher the ratio, the greater the internal connectivity. In Figure 3, internal connectivity is illustrated by the ratio of red dots (intersections) to the sum of red dots plus blue dots (intersections plus cul-de-sacs).

o *Ext_Connectivity* – median distance between Ingress/Egress (access) points in feet; the greater the distance, the poorer the external connectivity. In Figure 3, external connectivity is illustrated by the length of the red line segment around the perimeter of the neighborhood; this line represents the median length of the distance between points of access into or out of the neighborhood.

Land Use Intensity. Measures of development intensity include single family lot size and single family floor space.

o *Lot_Size* – median lot size of single-family dwelling units in the neighborhood; the smaller the lot size, the higher the intensity. In Figure 2, lot size is illustrated by the size of the parcel polygons.

o *Floor space* – median floor space of single-family dwelling units in the neighborhood; the larger the floor space, the higher the intensity. Median floor space is not illustrated in Figure 2.

Land Use Pattern. Measures of pattern include land use mix and two measures of accessibility.

o *LU_Mix* – A diversity index $H_1 = \dfrac{-\sum\limits_{i=1}^{s}(p_i)\ln(p_i)}{\ln(s)}$ where H_1 = diversity, p_i = proportions of each of the five land use types such as SFR, MFR, Industrial, Public and Commercial uses, and s = the number of land uses, in this case s equals to five. The higher the value, the more evenly distribution of land uses. In Figure 3, the mix of land uses is illustrated by the variety in the color of the parcels.

o *Comdis* – median distance to the nearest commercial use; the greater the distance, the lower the accessibility. This measure is not illustrated in Figure 3.

o *Ped_Com* – percentage of SFR units within one quarter mile of commercial uses; the greater the percentage, the greater the pedestrian accessibility. In Figure 3, single family parcels within one quarter mile of a commercial use are colored orange.
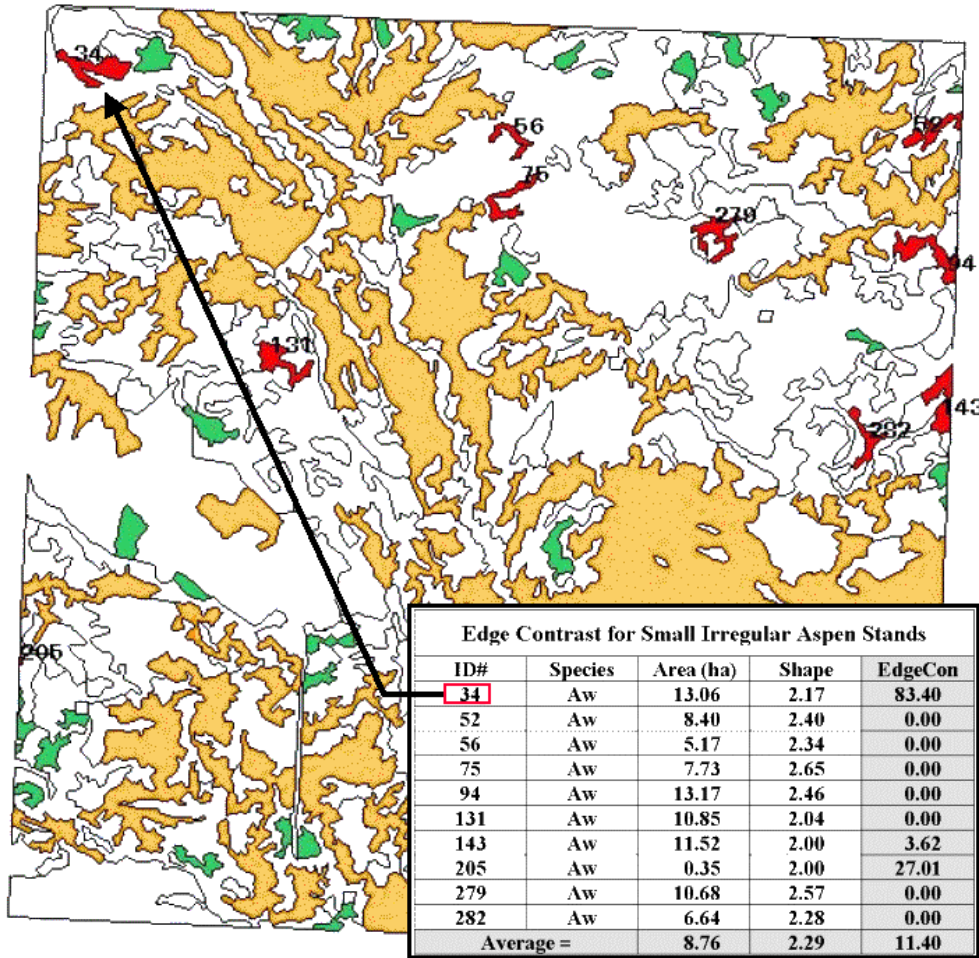
Figure 4: Street Scene

In a recent study by Ewing et al (forthcoming b), this image scored high in all eight subjective measures of urban form: imageability, legibility, enclosure, human scale, transparency, linkage, complexity, coherence, and tidiness. Using regression analysis, Ewing et al demonstrated that these high subjective scores reflect the fact that this image also ranked high on many objective urban design measures, including: number of landmarks, number of small planters, memorable architecture, uniform building height, number of moving pedestrians, sidewalk width, ratio of buildings heights to street width, common window proportions, textured sidewalk surface, proportions of parked cars, and more.

Figure 5: Hardwood landscape in northern Alberta, Canada

Small Irregular Aspen Stands

Edge Contrast for Small Irregular Aspen Stands				
ID#	Species	Area (ha)	Shape	EdgeCon
34	Aw	13.06	2.17	83.40
52	Aw	8.40	2.40	0.00
56	Aw	5.17	2.34	0.00
75	Aw	7.73	2.65	0.00
94	Aw	13.17	2.46	0.00
131	Aw	10.85	2.04	0.00
143	Aw	11.52	2.00	3.62
205	Aw	0.35	2.00	27.01
279	Aw	10.68	2.57	0.00
282	Aw	6.64	2.28	0.00
Average =		8.76	2.29	11.40

Berry (1999) uses the above map to illustrate several types of landscape measures. The colored polygons represent patches of land forested with Aspen trees. The green polygons represent aspen patches smaller than 15 hectares. The red polygons represent Aspen patches that are irregularly shaped—that is the perimeter of the polygon is greater than twice its area.

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[1] This proverb was brought to our attention by Hopkins (1984).