

Measuring Network Connectivity for Bicycling and Walking

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ABSTRACT

Advocates of New Urbanist and neo-traditional planning concepts include street connectivity as a key component for good neighborhood design. Street networks that are more grid-like are preferred over networks that include many cul-de-sacs and long blocks, thus increasing distances between destinations. The increased distances are thought to discourage walking and bicycling and, thus, physical activity. While intuitively attractive, there is limited empirical research at this time making this connection. There is also debate over how to measure connectivity and what levels of connectivity are appropriate. The objective of this research is to evaluate various measures of connectivity for the purpose of increasing walking and bicycling. Measures of connectivity can be useful in two arenas: (1) research linking travel behavior (and perhaps physical activity and health) to urban form; and (2) public policy establishing performance standards for new and/or existing development. This paper first defines and describes a wide range of measures of connectivity, drawn from multiple fields, including transportation, urban planning, geography, and landscape ecology. The paper then includes some preliminary results applying four measures of connectivity to the Portland, Oregon region.

INTRODUCTION

Advocates of New Urbanist and neo-traditional planning concepts include street connectivity as a key component for good neighborhood design. Street networks that are more grid-like are preferred over networks that include many cul-de-sacs and long blocks, thus increasing distances between destinations. The increased distances are thought to discourage walking and bicycling and, thus, physical activity. While intuitively attractive, there is limited empirical research at this time making this connection. There is also debate over how to measure connectivity and what levels of connectivity are appropriate. The current debate is particularly unclear because street connectivity is proposed to meet multiple, sometime conflicting objectives. In addition, most efforts to date have focused on the street network, which may differ from the pedestrian and bicycle network.

The New Oxford American Dictionary defines connect as "bring together or into contact so that a real or notional link is established...join together so as to provide access and communication." Connectivity is the primary purpose of any transportation network; it links locations people want to travel between. Travel is generally considered a "derived demand" – we travel mainly because we want access to other locations, not simply because we enjoy movement. Travel demand modeling generally assigns a cost to travel that includes the "cost" of time. All else being equal, shorter travel times are preferred. This is particularly true for bicycling and walking, which are usually slower than motorized travel. There are practical limits to how far a person will walk or bike. Increased network connectivity can reduce travel distances for all modes, including walking and bicycling. An additional benefit of increased connectivity for these modes is having a wider range of routes from which to choose. A cyclist, for example, might choose a slightly longer route if he or she can use a bicycle lane, a street with less traffic, or a less steep hill.

The objective of this research is to evaluate various measures of connectivity for the purpose of increasing walking and bicycling. Measures of connectivity can be useful in two arenas: (1) research linking travel behavior (and perhaps physical activity and health) to urban form; and (2) public policy establishing performance standards for new and/or existing development. This paper first defines and describes a wide range of measures of connectivity, drawn from multiple fields, including transportation, urban planning, geography, and landscape ecology. The paper then includes some preliminary results applying four measures of connectivity to the Portland, Oregon region.

MEASURES OF CONNECTIVITY: PLANNING LITERATURE

Transportation and urban planners – both practitioners and researchers – have focused more attention on the issue of street or network connectivity with the rise of concepts such as smart growth, New Urbanism, and neo-traditional development. A review of the planning and transportation literature found several measures of connectivity. Each measure is defined and described below. Table 1 (following the text) identifies which researchers have used each measure.

Block Length

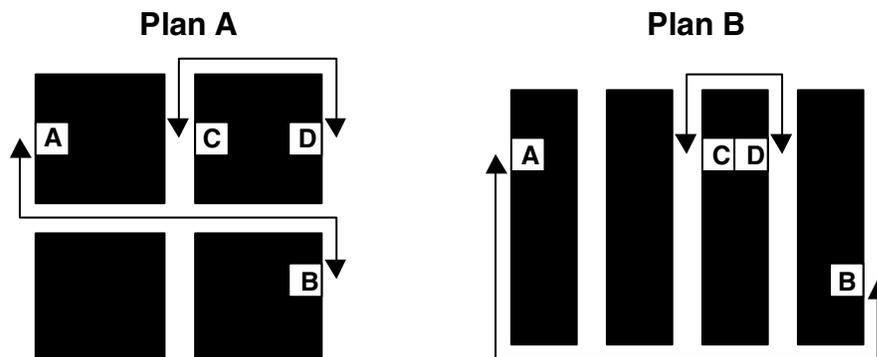
Block length is used in a number of ways to promote or measure connectivity. Several communities have adopted maximum block length standards for new development (Handy et al., 2003). Standards usually range from 300 to 600 feet and apply to every block, with some exceptions. Metro, the planning agency for the Portland, Oregon region, established maximum block length requirements of 530 feet, which were subsequently adopted by most local governments in the region. Shorter distances (330 feet) are recommended for pedestrian and bicycle connections.

Block lengths can be measured from the curb or from the centerline of the street intersection. The theory behind using block length as a standard is that shorter blocks mean more intersections and, therefore, shorter travel distances and a greater number of routes between locations. The concept of a maximum block length is attractive from a policy standpoint because it is easy to understand. As a tool for research or as an overall performance measure, rather than a new development standard, one could use the share of blocks meeting a minimum standard or the average block length for a defined area.

Block Size

A handful of communities have adopted standards setting maximum block sizes, which capture two dimensions of the block, rather than the individual length of each side (Handy et al., 2003). This can be measured by the width and length, the area (e.g. acres), or the perimeter. For example, Fort Collins, Colorado specifies a maximum block size of 7 to 12 acres, depending on the zoning. Using block size measured by area or perimeter as a standard may be more flexible than block length for each side. However, the impact on walking and cycling distances between two points is unclear. Consider two simple examples in Figure 1. Under Plan A, each block face is the same length. In Plan B, the same four blocks are half as wide, but twice as long. The perimeters and areas of the blocks are the same in each plan. The walking distance between points A and B, located on opposite sides of the development, for Plan A is shorter than Plan B. But, when the two points are located on the same block, near one end, the distance for Plan B is shorter.

Figure 1: Maximum Block Length vs. Block Size



As with block length, block size could be used as a research tool or performance measure by calculating the share of blocks meeting a standard or the average value.

Block Density

A few researchers have used block density as a proxy measure for connectivity. Frank et al. (2000) used the mean number of census blocks per square mile. The authors assert that census block density is a good proxy for street connectivity, since census blocks are typically defined as the smallest fully enclosed polygon bounded by features such as roads or streams on all sides. Cervero and Kockelman (1997) use blocks defined more traditionally – areas of land surrounded by streets. In either case, increased block density is thought to represent increased connectivity – more blocks means smaller blocks and more intersections.

Intersection Density

Intersection density is measured as the number of intersections per unit of area, e.g. square mile. A higher number would indicate more intersections and, presumably, higher connectivity.

Street Density

Street density is measured as the number of linear miles of streets per square mile of land (or kilometers per square kilometer). A higher number would indicate more streets and, presumably, higher connectivity. Street density, intersection density, and block density are likely highly and positively correlated with each other.

Connected Node Ratio

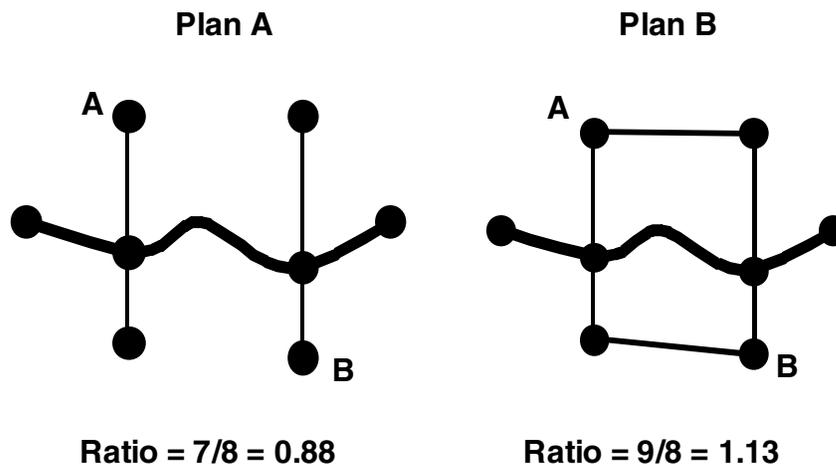
The Connected Node Ratio (CNR) is the number of street intersections divided by the number of intersections plus cul-de-sacs. The maximum value is 1.0. Higher numbers indicate that there are relatively few cul-de-sacs and, theoretically, a higher level of connectivity. The INDEX model calls this Internal Street Connectivity and recommends against networks with values less than 0.5. Values of 0.7 or higher are favored (Criterion Planners Engineers, October 2001).

Similar to CNR, some researchers have used the percentage of intersections that four-way to measure connectivity (see Table 1). A perfect grid would be 100%.

Link-Node Ratio

Link-Node Ratio is an index of connectivity equal to the number of links divided by the number of nodes within in a study area. Links are defined as roadway or pathway segments between two nodes. Nodes are intersections or the end of a cul-de-sac. A perfect grid has a ratio of 2.5. Ewing (1996) suggests that a link-node ratio of 1.4, about halfway between extremes, is a good target for network planning purposes. At least three cities have adopted the link-node ratio as a standard, with values of 1.2 and 1.4 (Handy et al., 2003). Figure 2 shows how increasing the link-node ratio increases connectivity. Both plans have the same number of nodes. Plan B has two additional links, resulting in a link-node ratio of 1.13 versus 0.88 for Plan A. Under Plan A there is only one route between points A and B. Under Plan B there are three potential routes. Intuitively, this represents increased connectivity. However, for walking and bicycling, minimizing trip distance is perhaps a more important objective. The additional routes under Plan B may or may not be shorter. Moreover, link-node ratio does not reflect the length of the links in any way. Therefore, a perfect grid of 1,000-foot blocks will have the same link-node ratio as a grid with 200-foot blocks. The latter would result in shorter network trip distances. For this reason, at least one city has combined link-node ratio with an intersection spacing standard (Handy et al., 2003). In addition, link-node ratio is less intuitive and, therefore, may be less attractive as a policy tool. Another issue with using link-node ratio as a performance standard is the need to clearly define which links and nodes are included in the calculation.

Figure 2: Link-Node Ratio



Grid Pattern

Many researchers have measured the street network based upon whether it is a grid or not. For example, Greenwald and Boarnet (2001) and Boarnet and Crane (2001) use the percentage of area in a one-quarter mile buffer zone that is covered by a grid street pattern, as measured by four-way intersections. Boarnet and Crane chose this measure based upon research that showed that the number of four-way intersections was a good predictor of whether a neighborhood reflected "neotraditional" design elements. Other researchers have simply categorized a neighborhood's street network as grid or not, or partially gridded and used dummy variables (e.g. 1=grid, 0=not grid) for models.

Pedestrian Route Directness

Pedestrian Route Directness (PRD) is the ratio of route distance to straight-line distance for two selected points. The lowest possible value is 1.00, where the route is the same distance as the "crow flies" distance. Numbers closer to

1.00 indicate a more direct route, theoretically representing a more connected network. PRD is the same as the "circuitry factor" sometimes applied in logistics to approximate travel distances between cities (Ballou et al., 2002).

Portland's Metro allows PRD to be used as an option to the maximum block length design standard, with 1.5 as the maximum (Handy et al., 2003). Randall and Baetz (2001) found that neighborhoods with grid street patterns and relatively short blocks had PRDs of 1.4-1.5. Neighborhoods with more curvilinear streets and cul-de-sacs had PRDs between 1.63 and 1.88. The INDEX model recommends PRDs of 1.2-1.5, with values of 1.6-1.8 characterized as indirect (Criterion Planners Engineers, October 2001).

Intuitively, PRD is perhaps a better measure for promoting bicycling and walking than those described above. Distance traveled for a trip is a primary factor in determining whether a person walks or bikes, and this measure directly reflects that factor. However, using PRD as a measure of performance or for research requires selecting pairs of points. This may add a degree of subjectivity and does add to the computational complexity. Therefore, it is less feasible to use as a measure when conducting research involving many units of analysis. It would be even more difficult to use for policy making or as a planning standard. No local governments in the Metro area have used the PRD option (Handy et al., 2003).

An even simpler (theoretically) measure is walking (or cycling) distance. Aultman-Hall et al. (1997) calculated mean walking distance, maximum walking distance, and the share of homes with minimum walking distances above a 400 meter standard. The analysis chose three destinations (a school, the nearest open space, and the nearest transit stop) and calculated the shortest path distance for each home using GIS software.

Effective Walking Area

Effective Walking Area (EWA) is used by the INDEX model for Tampa, Florida. EWA is a ratio of the number of parcels within a one-quarter mile walking distance of a node to the total number of parcels within a one-quarter mile radius of that node. Values range between 0 and 1. A higher value indicates that more parcels are within walking distance of the pre-defined point, reflecting a more connected network. As with PRD, the researcher or planner must select nodes from which to measure EWA. In addition, parcel boundary and location information is necessary.

Table 1: Measures of Connectivity used in Research Literature

Measure	Literature
Block length (mean)	Cervero and Kockelman (1997)
Block size (mean area)	Hess et al. (1999) Reilly (2002)
Block size (median perimeter)	Song (2003)
Block density	Cervero and Kockelman (1997) Cervero and Radisch (1995) Frank et al. (2000) (census block density)
Intersection density	Cervero and Radisch (1995) Cervero and Kockelman (1997) (# dead ends and cul-de-sacs per developed acre) Reilly (2002)
Percent four-way intersections	Cervero and Kockelman (1997) Boarnet and Sarmiento (1998)
Street density	Handy (1996) Mately et al. (2001)
Connected Intersection Ratio	Allen (1997) Song (2003)
Link-Node Ratio	Ewing (1996)

Percent Grid	Boarnet and Crane (2001) Greenwald and Boarnet (2001)
Grid dummy variables	Crane and Crepeau (1998) Messenger and Ewing (1996)
Percent quadrilateral blocks	Cervero and Kockelman (1997)
Pedestrian Route Directness	Hess (1997) Randall and Baetz (2001)
Walking distance	Aultman-Hall et al. (1997) (mean, maximum, percent of homes meeting minimum standard)

MEASURES OF CONNECTIVITY FROM OTHER FIELDS

Planners are not the only profession concerned with connectivity. Searching on the word connectivity in any electronic database of journals will find citations in numerous fields, including medicine, geology, geography, ecology, computer science, and urban studies.

Geographers have developed the **gamma index** and **alpha index** as measures of connectivity. The gamma index is a ratio of the number of links in the network to the maximum possible number of links between nodes. The maximum possible number of links is expressed as $3 * (\# \text{ nodes} - 2)$ because the network is abstracted as a planar graph. In a planar graph, no links intersect, except by nodes (Taaffe and Gautheir Jr., 1973). This feature represents a transportation network well. Values for the gamma index range from 0 to 1 and are often expressed as a percentage of connectivity, e.g. a gamma index of 0.54 means that the network is 54 percent connected.

The alpha index uses the concept of a circuit – a finite, closed path starting and ending at a single node. The alpha index is the ratio of the number of actual circuits to the maximum number of circuits and is equal to:

$$\text{Alpha index} = \frac{\# \text{ links} - \# \text{ nodes} + 1}{2(\# \text{ nodes}) - 5}$$

As with the gamma index, values for the alpha index range from 0 to 1, with higher values representing a more connected network. Both indices could be applied as measures of connectivity for bicycling and walking.

Landscape ecologists are concerned about habitat connectivity. Tischendorf and Fahrig (2000) cite two definitions of connectivity that focus on the relationship and movement between habitat or resource patches. They explain that in simulation studies connectivity is often measured by the number of immigrants (dispersal success) or the number of movement steps between pairs of patches (search time). Empirical studies sometimes measure connectivity based upon actual animal movements. They evaluate three connectivity measures using simulation models:

1. **Dispersal success:** Total number of immigration events into all habitat patches divided by the initial number of individuals
2. **Search time:** Average number of movement steps between all pairs of habitat patches
3. **Cell immigration:** Total number of immigration events into all habitat grid cells (equal sized cells, rather than patches) divided by the initial number of individuals

The authors found that the three measures were weakly correlated with each other. Moreover, dispersal success and search time predicted that landscape connectivity increased with increasing habitat fragmentation – a counter-intuitive result. They concluded that cell immigration works better because it does not depend on the number of habitat patches and incorporates within and between patch movement. Two other ecologists, Moilanen and Nieminen (2002) also examine several measures of connectivity between patches of habitat. The simplest measure is **nearest neighbor** (NN). NN can be measured as the straight-line distance from one patch to its nearest neighbor. More complex NN measures scale the distance to the size of the patch. **Buffer measures** sum the area of all patches

within a predetermined distance of the patch in question. A third category of measures takes into account the distances to all possible source populations, scaled by the average migration distance. With all of these measures, distances were measured from center to center. Moilanen and Nieminen reviewed the research literature and found that NN measures are the most common, but concluded that they are inferior to the other two types of measures.

One limitation in applying the measures of connectivity derived from the landscape ecology field directly to transportation and urban planning is that the measures described above do not rely on a network. Many of the studies involve birds and insects that can fly between patches. However, the focus on locations of interest (habitats) is useful. When planning for bicycling and walking, ideally we want to connect locations that matter the most to cyclists and pedestrians. Being able to walk to Home Depot or Costco may not be a priority, but connectivity to parks and schools should be.

In an attempt to measure the global network connectivity of cities, Taylor et al. (2002) developed a ranking of cities based upon the service value provided by major service firms (e.g. banking) and how connected those firms are to other cities. They developed a gross measure of global connectivity and a proportional measure – that city's portion of the sum of the gross connectivity for all cities. As with the landscape ecology measures, this measure does not rely on a physical network. Finally, Silva (2000) measured the connectivity of neighborhoods to infrastructure, including sewer, water, and electricity. He defined connectivity as the percentage of households connected to the service. This simple measure could be applied, in particular, to bicycling. One could measure the share of parcels (all or by land use type) that abut or are within a certain distance of the bicycle network, defined by paths, lanes, and bicycle boulevards. Such a measure defines the bicycle network as the most important for cyclists, which may not be the case. Therefore, it might best be used in conjunction with measures that apply to the larger street network that is accessible to cyclists.

APPLYING CONNECTIVITY MEASURES

Four measures of connectivity were applied to the Portland, Oregon regional network:

- Street Network Density (miles per square mile)
- Connected Node Ratio
- Intersection Density
- Link-Node Ratio

These four were chosen to examine first because they rely on similar data and tools within GIS. The research will continue by applying many of the additional measures described above. The unit of analysis chosen is census tract. Census tract was chosen for several reasons. First, the median size of census tracts in the region resembles the probable walking and cycling area for an individual. Existing travel surveys show that most walking trips are well under one mile and most bicycle trips are under five miles. The median size of a census tract in the Portland region is 1.16 square miles and the mean is 9.39 square miles. Traffic analysis zones (TAZs) for the region are generally smaller, with a median size of 0.37 square miles. Therefore, it is likely that a person's walking or cycling trip would extend beyond one TAZ. Second, census tract boundaries are relatively stable over time and can be used in any area of the U.S. Third, there is a reasonable number of census tracts (under 400), compared with 1,247 TAZs. An alternative is to calculate connectivity measures specific to a point in space, such as a parcel or home. For example, the measure could be calculated for a one-mile radius for walking and a five-mile radius for bicycling. At this stage of the research, however, census tracts are adequate.

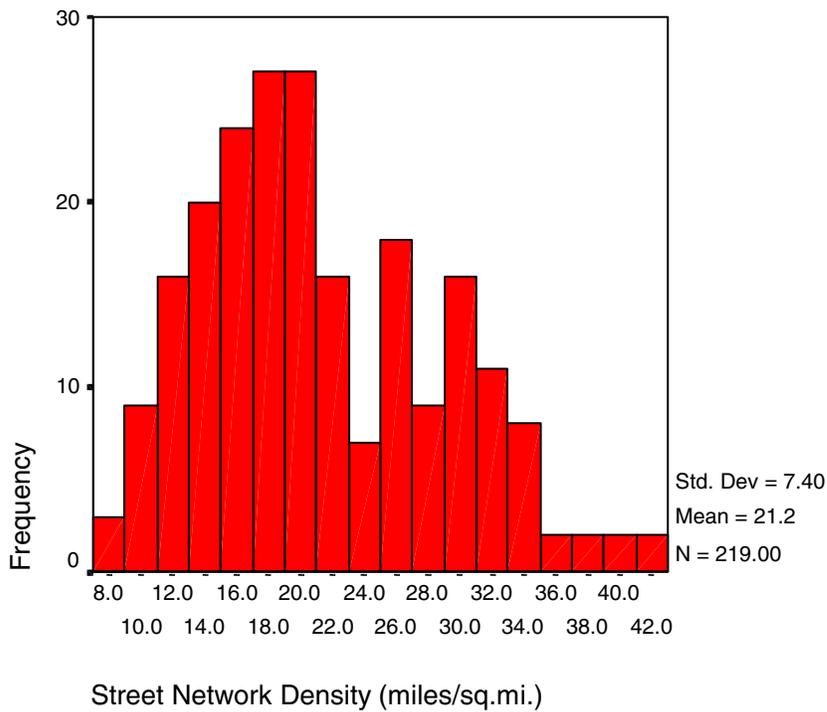
The connectivity measures were calculated for 219 census tracts that were entirely within the region's urban growth boundary (UGB). Tracts that run outside the UGB are not included at this time because the street network data is not complete outside the UGB. Descriptive statistics for the four measures are shown in Table 2. The distribution of census tracts for each measure is shown in Figure 3 through Figure 6. With the exception of Connected Node Ratio, the data follow a normal distribution fairly well.

Table 2: Descriptive Statistics of Connectivity Measures Applied to Portland

	Street Network Density (miles/sq. mi.)	Intersection Density (#/sq. mi.)	Connected Node Ratio	Link-Node Ratio¹
Minimum	8.61	51.49	0.61	0.15
Maximum	42.84	651.72	1.00	1.97
Mean	21.22	196.40	0.82	1.54
Standard deviation	7.40	91.90	0.11	0.24
Median	19.72	175.38	0.81	1.57

n = 219

Figure 3: Street Network Density Distribution



¹ Link-Node Ratio in this paper is calculated using only intersections as nodes, not the ends of cul-de-sacs.

Figure 4: Intersection Density Distribution

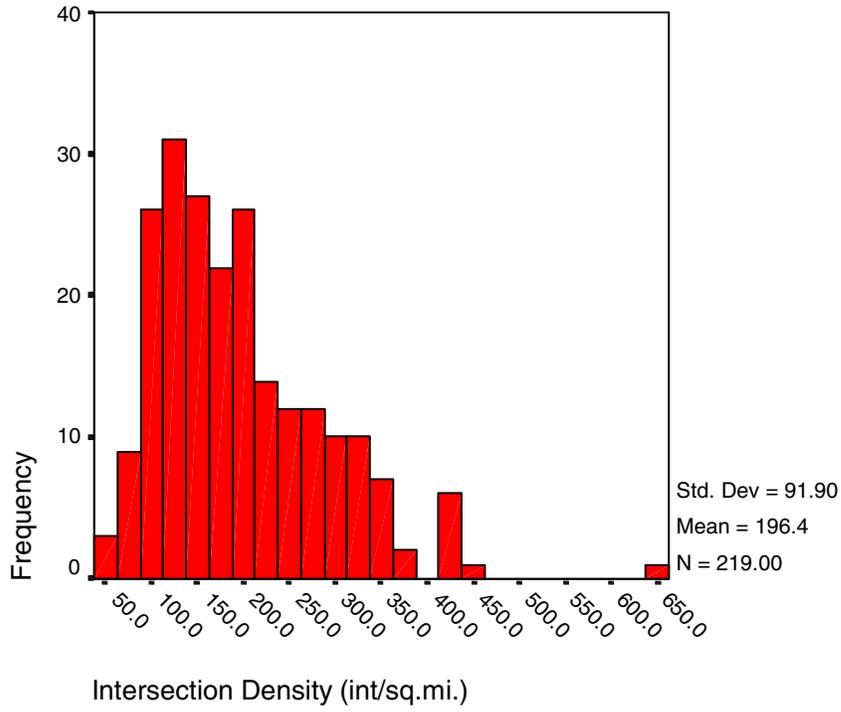


Figure 5: Connected Node Ratio Distribution

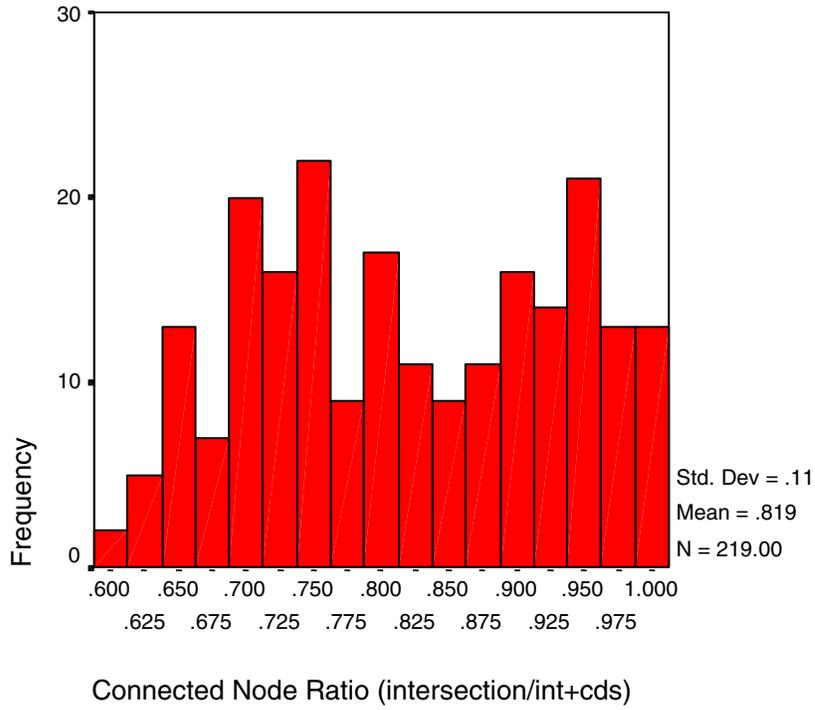
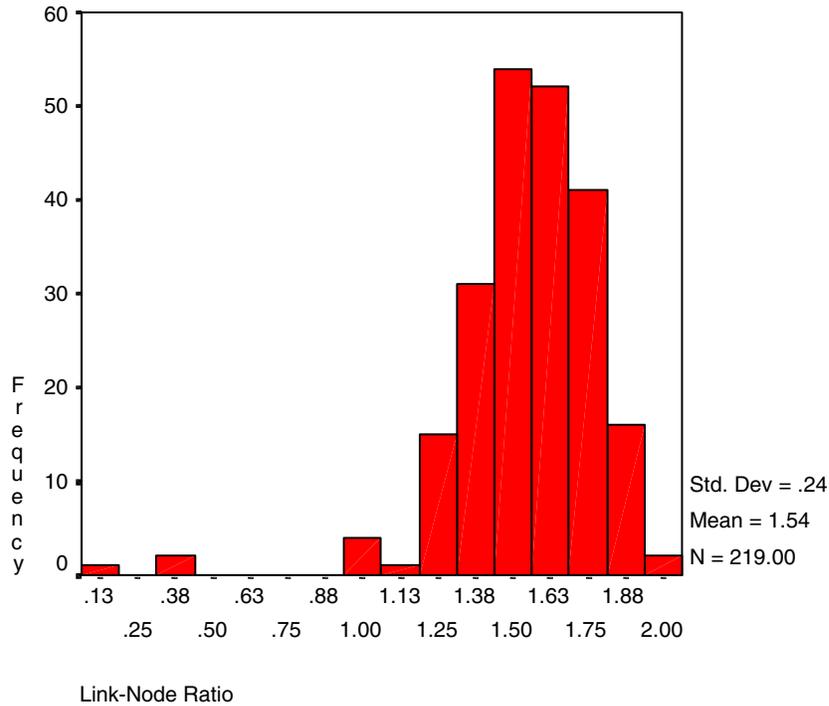


Figure 6: Link-Node Ratio Distribution



Each of the measures is measuring something slightly (or more than slightly) different. However, if an objective is to recommend a single (or even two) measures, it is useful to see how correlated the measures are with each other. As expected, street network density and intersection density are highly and positively correlated (Table 3). In fact, all of the measures are positively correlated, though the correlations with link-node ratio are the weakest. This likely reflects the issue raised earlier that link-node ratio is unrelated to the size or spacing of the blocks or intersections; a grid with large blocks has the same ratio as one with small blocks, though the street network density and intersection density would be different.

Table 3: Pearson Correlation Coefficients for Connectivity Measures

	Intersection Density	Link-Node Ratio	Connected Node Ratio
Street Network Density	0.902 (0.00)	0.259 (0.00)	0.799 (0.00)
Connected Node Ratio	0.741 (0.00)	0.148 (0.03)	
Link-Node Ratio	0.186 (0.01)		

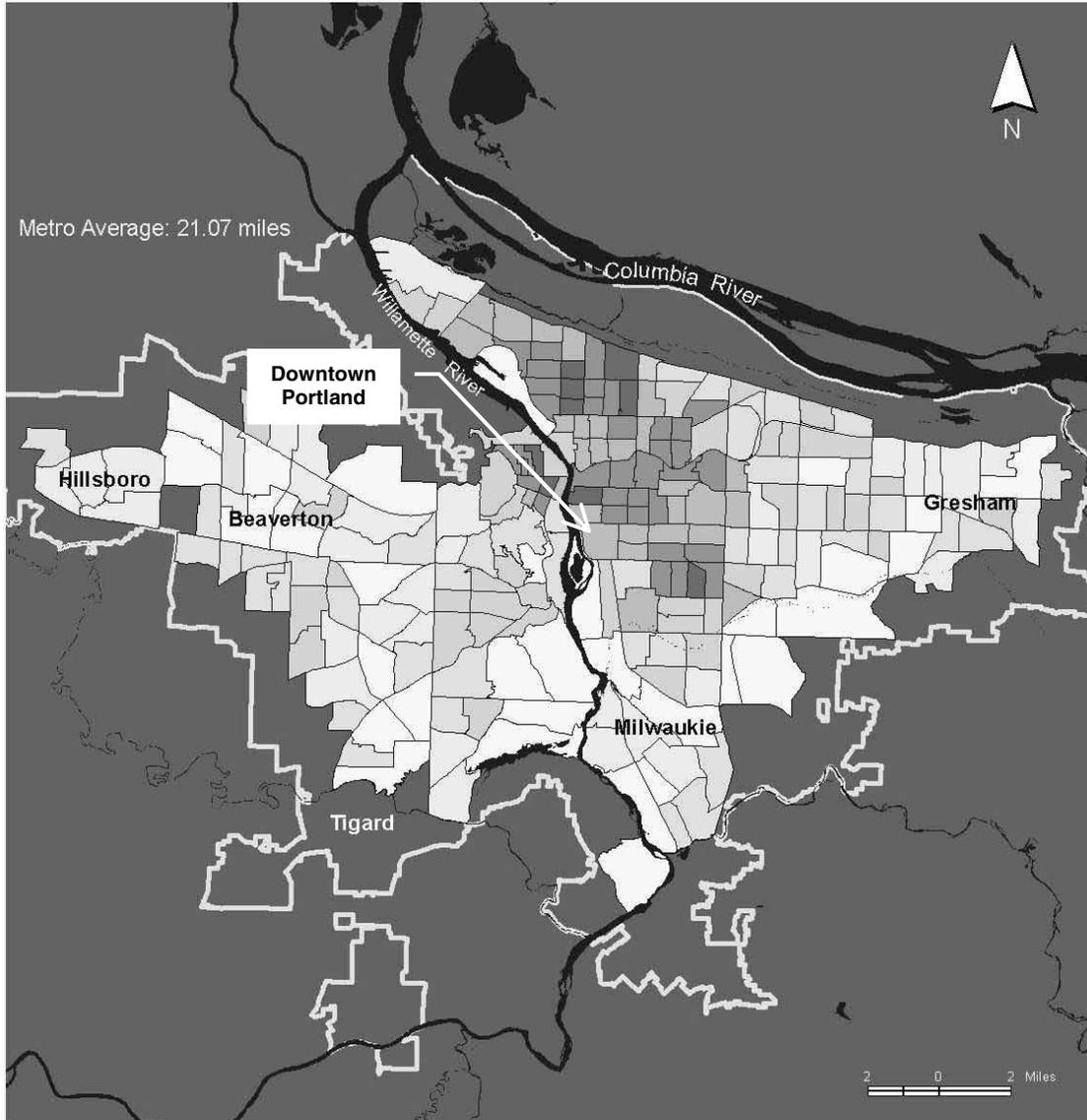
Values in parentheses are 2-tailed significance levels.

To examine the issue of consistency further, each census tract was assigned a quartile for each measure. Fourteen-percent of the census tracts were in the same quartile on all four measures and nearly half (47%) were in the same quartile for three of the four measures. Forty-two percent of the tracts that were in the same quartile for all four measures were in the highest, or most connected, quartile, and 19% were in the least connected quartile.

The maps in Figure 7 through Figure 10 show the some of the variation between the measures. In general, the most connected tracts are found in downtown Portland and in the inner eastside (east of the Willamette River, which runs north-south through the middle of the region). These are areas that developed largely before 1950 and are dominated by a grid street pattern.

One way to evaluate the appropriateness of each measure for the objective of promoting bicycling and walking is to compare the measures using a performance measure, such as PRD. If one major objective of increasing connectivity for cycling and walking is to create shorter, more direct routes, PRD is a way to measure that objective. But, as discussed earlier, it is probably too cumbersome and subjective to use as a policy standard or large-scale research. An example of PRD is shown in Figure 11. The origin is a household and the destination is the nearest light rail station. This census tract contains many cul-de-sacs and was in the lowest quartile for three of the four connectivity measures. In addition, the light rail tracks pose a barrier. In this example the PRD is 2.46, meaning that the household member must walk nearly two-and-one-half times further than the straight-line distance to get to the station. At the other extreme is a census tract that was in the highest quartile for all four measures (Figure 12). The origin is a household and the destination is a light rail station scheduled to open in 2004. The straight-line distance (0.39 miles) for this trip is virtually the same as in Figure 11 (0.37 miles), but the walking trip using the shortest path is only half as long (0.43 versus 0.91 miles). The PRD is 1.10.

Figure 7: Street Network Density by Census Tract



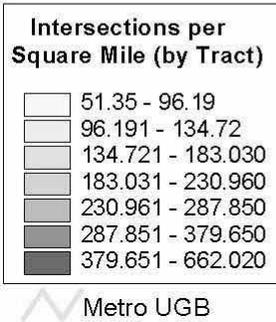
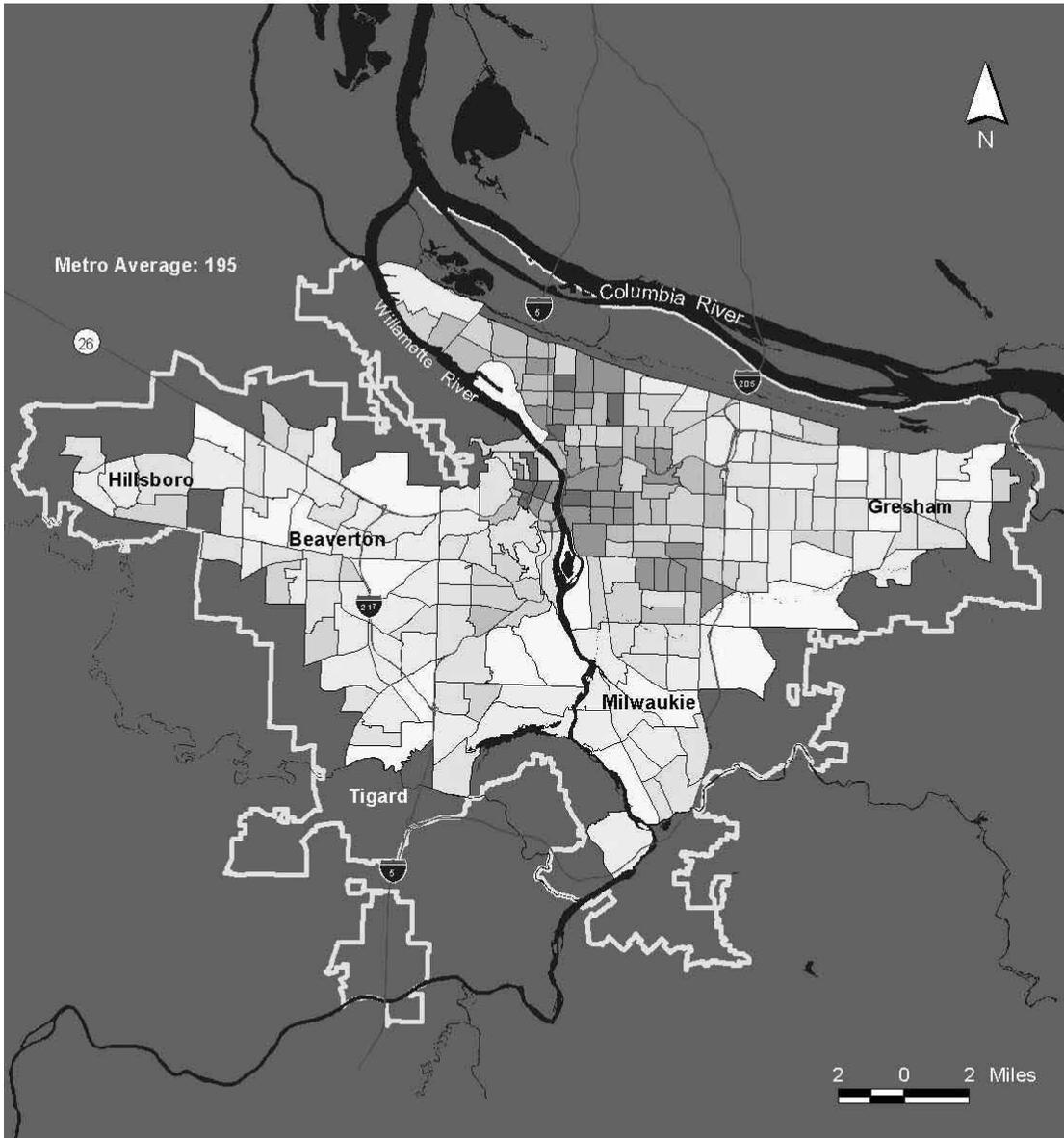
Aggregate Street Length per Square Mile (by Tract)

8.61 - 13.13
13.131 - 16.360
16.361 - 19.430
19.431 - 23.570
23.571 - 28.450
28.451 - 34.140
34.141 - 42.840

Street Network Density: Portland Metro Area

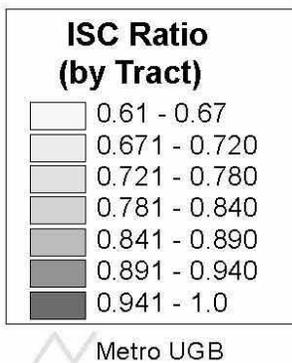
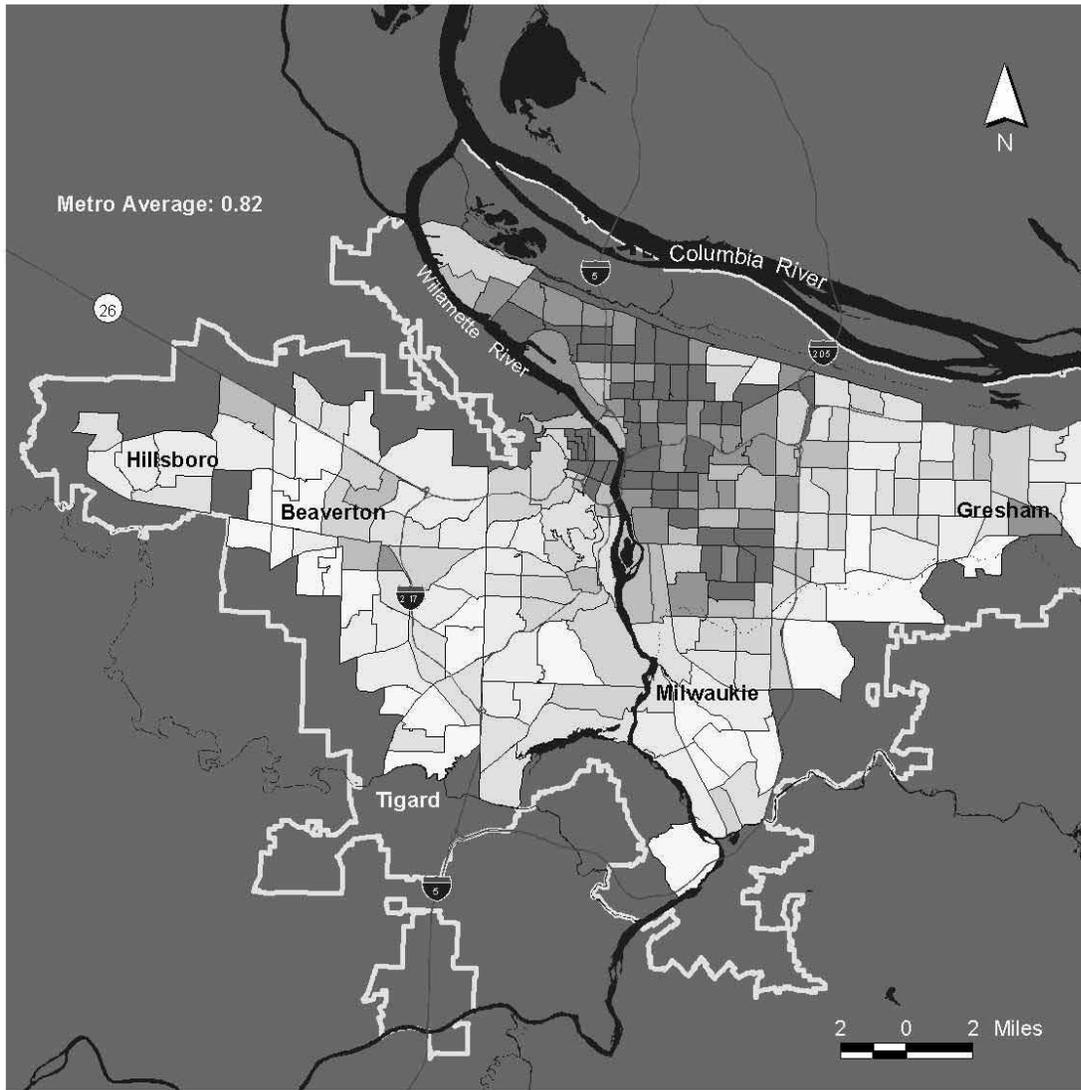
 Metro UGB

Figure 8: Intersection Density by Census Tract



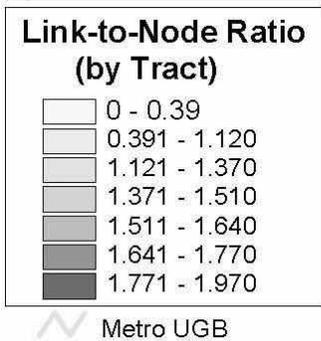
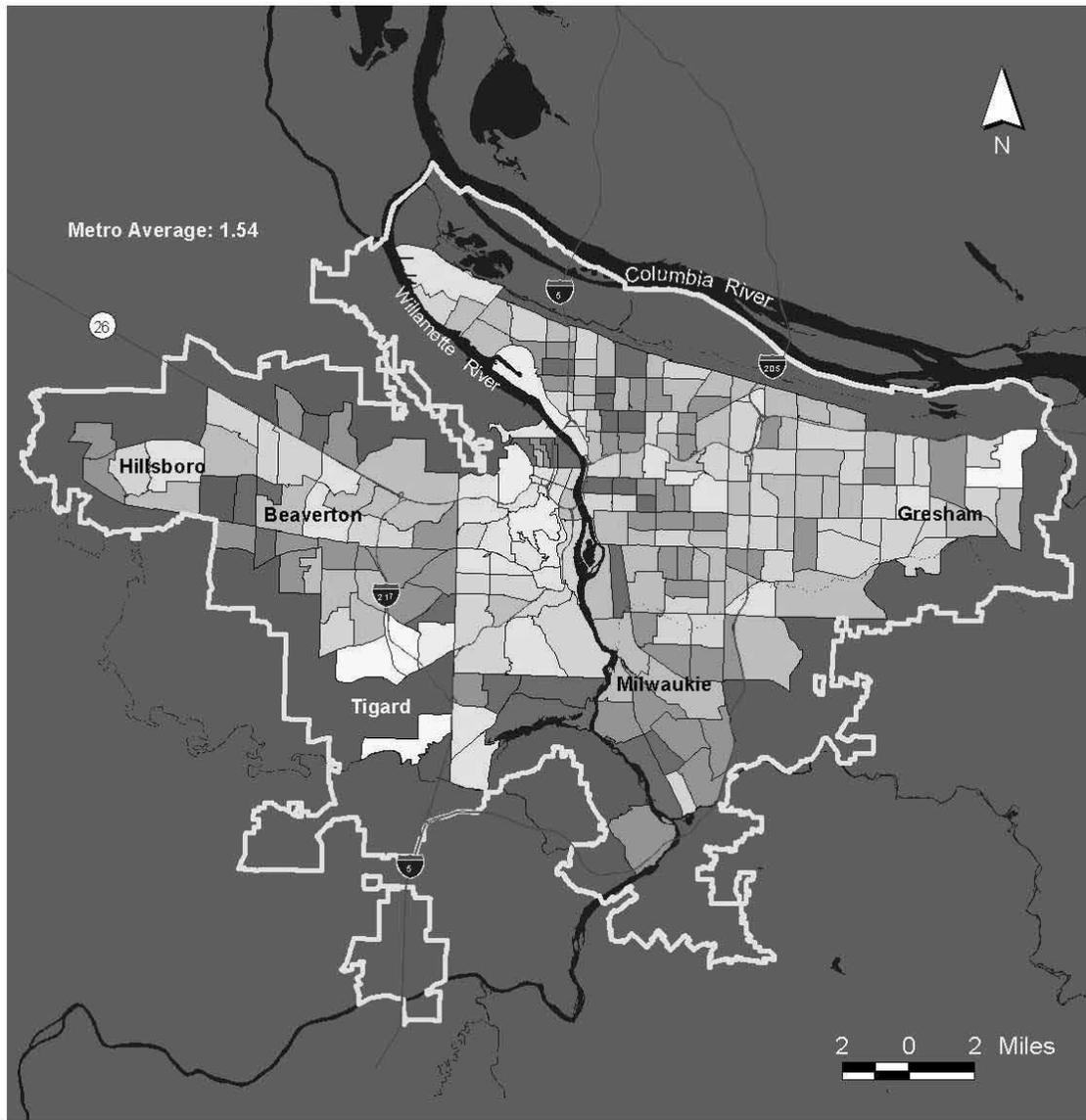
Intersection Density: Portland Metro Area

Figure 9: Connected Node Ratio by Census Tract



Connected Node Ratio: Portland Metro Area

Figure 10: Link-Node Ratio by Census Tract



Link/Node Ratio: Portland Metro Area

Figure 11: Example of Pedestrian Route Directness - Poor Connectivity

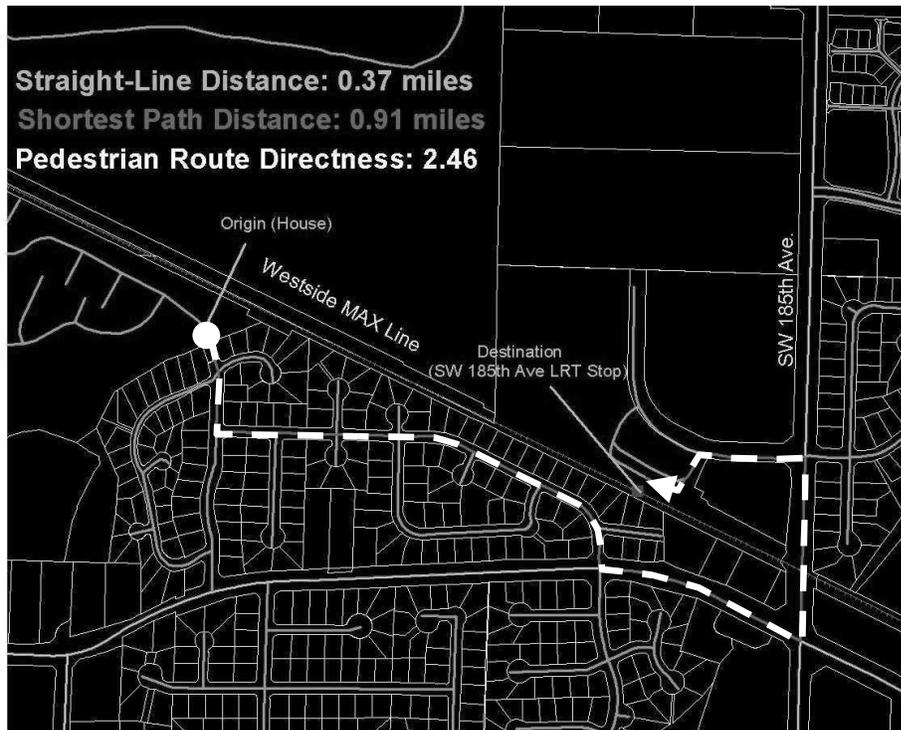
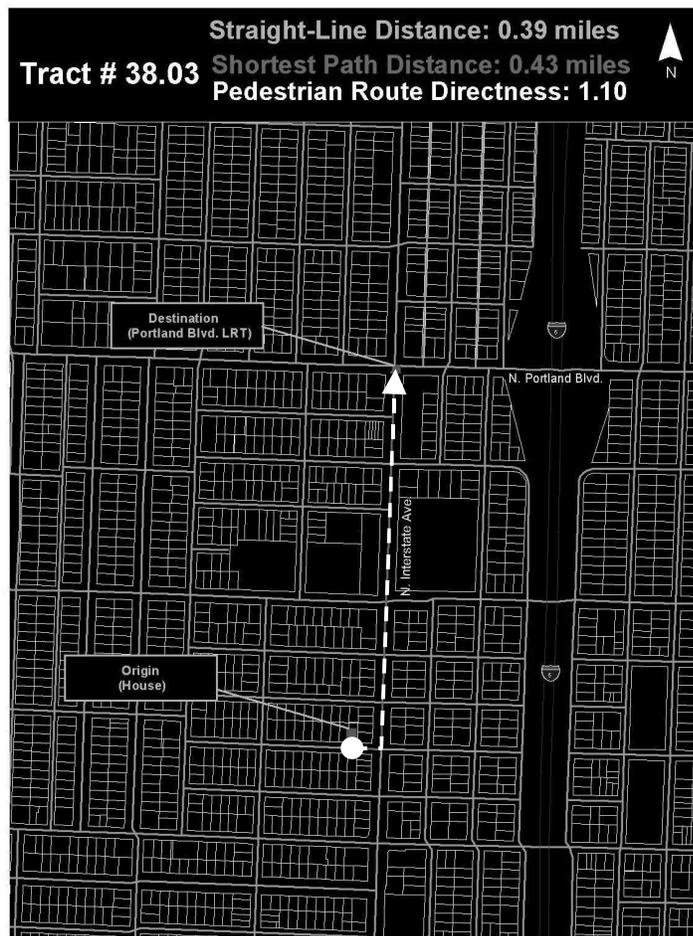


Figure 12: Example of Pedestrian Route Directness - High Connectivity



Conclusions and Future Research

This paper presented some preliminary results from an evaluation of measures of connectivity for bicycling and walking. Four measures were applied to census tracts in the Portland metropolitan region. Though positively correlated, the measures did not consistently assign the same level of connectivity for a tract. The next step in this research is to apply some of the other measures of connectivity from the literature described in the first half of the paper. Then, the measures will be evaluated for their potential to promote bicycling and walking. One evaluation measure will be pedestrian route directness (PRD). To do so, we propose to randomly select pairs of origins and destinations within several census tracts and calculate PRDs. The mean and median PRDs for each tract will then be compared to each connectivity measure to see which is most consistent with the PRD results. PRD captures one objective of increasing connectivity for cycling and walking – reducing travel distances. Another objective is to provide multiple, alternative routes. The alpha index might be an appropriate measure of this objective. A measure similar to PRD could also be developed by counting the number of routes between two points that are below a certain distance.

Multiple routes and shortest distances are not the only factors that influence the attractiveness of walking or bicycling on a network. Other factors that are related to the network include slope, the presence of sidewalks, bike lanes, and bike paths, the amount of motorized vehicle traffic, aesthetics, and pavement or sidewalk quality. Some factors, such as stop signs, may be attractive to pedestrians but annoying to some cyclists. This research will explore the possibility of including some of these factors in a measure of connectivity. However, it may be most appropriate

to develop separate measures of these factors to clearly show the trade-offs and variation between the factors. A review of existing research on factors influencing the decision to bike or walk will aid this evaluation.

In the end, this project will recommend which measure or measures are most appropriate for planners and researchers to use when promoting or evaluating a network's potential to increase cycling and walking. A final step will be an evaluation of local government's capability to use or support the use of the recommended measures. Some measures, such as street density, require less and more easily accessible data and require fewer calculations or manipulations. Calculating link-node ratio or effective walking area requires more data and GIS knowledge. We propose to contact a diverse sample of cities and counties to determine whether the GIS data necessary to calculate the measures are available.

ACKNOWLEDGEMENT

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