THE SHAPE OF SUSTAINABLE STREET NETWORKS FOR NEIGHBORHOODS AND CITIES

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ABSTRACT

Although the New Urbanist approach to compact, connected street networks is gaining currency with mainstream planners and designers, there are a number of problems that have slowed their development. One such issue has to do with the fundamentals of measuring and defining street networks. A second is that the New Urbanist design effort has, largely by necessity, been focused on street networks of individual neighborhoods, thus ignoring issues related to street networks at larger scales.

This paper presents a nomenclature for characterizing street networks that works at the neighborhood level but also focuses on the citywide street network as a separate but equally important entity. We propose that this nomenclature be used in conjunction with simple street network measures to give a fuller characterization of street networks. We illustrate the applicability of this approach using 24 medium-sized California cities as a test case.

INTRODUCTION

One important tenet of Charter of the New Urbanism is that metropolitan areas should support a framework of transportation options including walking, biking, transit and private vehicles. It is often taken as an article of faith by New Urbanist designers that in order to achieve this goal, cities must be made up of neighborhoods consisting of a compact, connected network of streets. There is growing evidence to support the veracity of the belief that compact, connected street networks have many advantages in terms of community sustainability over contemporary street networks, which are often sparse and unconnected. In their book *Streets and the Shaping of Towns and Cities,* Southworth and Ben-Joseph praise New Urbanists and their return to more traditional street patterns as one of the few good alternatives to conventional suburban development and specifically mention the importance of the higher densities and increased street connectivity that characterizes New Urbanist designs. They go on to say

> "S*treet patterns contribute significantly to the quality and character of a community. The total amount of land devoted to streets relates directly to infrastructure costs. The number of blocks, intersections, access points, and loops or cul-de-sacs per unit area affects the number of route options and ease of moving about" (1).*

Although the New Urbanist approach to compact, connected street networks is gaining currency with mainstream planners and designers, there are a number of problems that have slowed its renewed development. The first problem has to do with definition. What exactly is a compact and connected street network? What are the parameters for measuring this type of network? And what are suitable cutoff points for these measures? For example, this is an issue being debated as part of the development of LEED-ND. A second problem that besets the New Urbanist goals for broader sustainability through better street network design is the fact that the New Urbanist design effort, for practical reasons, has been forced to focus on the street networks of individual neighborhoods and largely ignored two other important issues: i) the expansion or connection of the street networks between adjacent neighborhoods, and ii) the city and regional level street networks that facilitate longer distance travel in the region.

In this paper, we present a nomenclature for characterizing street networks that works at both the neighborhood and citywide levels, and we look at how this nomenclature can be used in conjunction with simple street network measures, so as to better characterize and define walkable neighborhoods and cities. We illustrate the applicability of this approach using 24 medium-sized California cities as a test case.

REVIEW OF TRADITIONAL MEASURES

Many New Urbanists point to increased street connectivity and network density as desirable qualities, and some cities and towns have adopted this premise in their ordinances (2). Networks come in a wide variety of shapes and sizes but can generally be characterized by their configuration, connectivity, and density. Network configuration is not amenable to being characterized by a simple parameter or two. On the other hand, a number of measures have been developed in an attempt to characterize network connectivity and density, respectively. Still, there is no one commonly accepted method of quantifying either network connectivity or density. And to further complicate the issue, some of the most basic measures are often calculated in multiple ways. This section will give a brief synopsis of some of the basic street network measures of connectivity and density and outline some common misapplications of these measures. The more complicated issue of network configuration will be addressed later in the paper.

The key variables in most of the traditional street network measures often include the number of intersections, the number of cul-de-sacs, the number of road links, the centerline miles of various street types, and average block size. The link to node ratio and the connected node ratio are some of the more common connectivity indices while intersection density, dead end density, centerline mile density, and average block size comprise some of the more common street network density indices.

Connectivity Indices

The Link to Node Ratio

For the link to node ratio, the number of links (road segments between intersections) is divided by the number of nodes (or intersections) (3, 4). The node count in this case typically represents the total number of intersections, including the dead ends of cul-de-sacs. As a result, a higher number of dead ends effectively reduces the link to node ratio of the network; accordingly, the higher the link to node value, the more connected the street network.

Generally, a score of 1.4 or higher indicates a walkable community (4). San Antonio, Texas and Cary, North Carolina require a link to node ratio of 1.2 in their town regulations while Orlando, Florida and Middletown, Delaware require 1.4 (2). This is usually a fairly easy value to calculate with GIS; there is however some discrepancy in how this index is calculated. For example, some cities include the nearest arterial intersection as a node while others do not; in addition, some places also include the links connected to that nearest arterial intersection. Also, high connectivity can be achieved within a subdivision without any consideration of global connectivity. The result is often an inconsistent value that cannot be easily compared from place to place.

The Connected Node Ratio (CNR)

The connected node ratio is another measure of connectivity and represents the number of real (non-dead end) intersections divided by the total number of intersections including dead ends (2). The index is on a scale of zero to 1.0, and most literature uses a CNR value of 0.75 as the minimum connectivity required for a walkable community (2, 4). Like with the link to node ratio, CNR does not give any indication of street network compactness; so in reality, it is difficult to truly know anything about walkability based solely on a CNR value.

Network Density Indices

Intersection Density
Intersection density is a measure of street network density and is typically calculated by the number of intersections per unit area, typically a square mile. Overall intersection density includes the total number of nodes or intersections, including dead ends; alternatively, real intersection density only counts the "real" intersections and does not include dead ends in the calculation while the dead end density only includes cul-de-sacs. Intersection density can also be calculated separately for major roads and local roads in an attempt to give an indication of the type of intersections that make up a street network.

Similar to some of the issues with the link to node ratio, intersection density can be calculated in various ways. For example, the LEED-ND proposal subtracts the number of intersections serving cul-de-sacs from the number of real intersections, which does not include the cul-de-sacs to begin with. The result is a useful calculation as long as we understand what the number means. For instance, a street serving only dead ends, even if those dead ends are quite numerous, would have the same LEED-ND intersection density as no street network whatsoever. For this reason, it might be worthwhile to use both real intersection density and dead end density as separate measures, so that these types of distinctions can be made.

Average Block Size
Average block size, also a measure of street network density, is simply the average area of the street blocks within a specified area. Although seemingly straightforward, average block size can be somewhat problematic because blocks can be hard to define for some types of street pattern types. A variation of block size is average block length, which again can be tricky with some street patterns.

Misapplying the Basic Street Network Measures

As New Urbanists continue to advocate increased "street connectivity" as a tenet of good design and a way to improve sustainability, accessibility, reduce congestion, and increase walking and biking, there is a need for a better consensus with regard to what this means and how it can best be measured. One ongoing problem is with terminology; even though the most common phrasing cites increased street connectivity, in most cases this is meant also as shorthand for more a compact and denser overall street network. But the traditional street connectivity measures such as the link-to-node ratio give little indication as to the compactness of the streets. For instance, the gridded street network in Figure 1 is highly connected; however without more information, there is no way to tell whether the grid covers one square mile or one-hundred square miles.

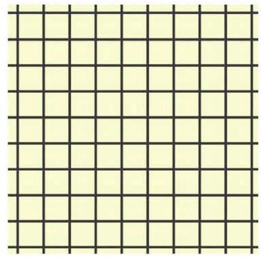


Figure 1 Highly Connected Grid Street Pattern

On the other hand, it is not uncommon to see street network density measures like intersection density used as a proxy for street connectivity. Figure 2 depicts the trouble using such measures interchangeably causes with three very different street networks all with the same intersection density. As a result, it is important to keep in mind that a connected street network is not necessarily a dense street network and vice versa.

Intersection Density	**144**	**144**	**144**
Links	119	87	73
Nodes	74	77	63
Link to Node Ratio	**1.61**	**1.13**	**1.16**
Real Intersections	74	60	46
Dead Ends	1	17	17
Connected Node Ratio	**0.99**	**0.78**	**0.73**

Figure 2 Three Street Networks with Equal Intersection Densities

The seemingly obvious solution is to present one measure that represents street connectivity and another one to represent street network density. For instance, we can safely say that a neighborhood with a link to node ratio of 1.4 and an intersection density of 200 per square mile is likely walkable. However, it is also important to recognize that connectivity and density together are incomplete descriptors of street networks. To get a more complete characterization, we need to know about network configuration. In other words, what are the actual street patterns? And how porous is a given neighborhood with respect to the surroundings?

SIMPLYFYING STREET NETWORK CLASSIFCATION

We need to know three fundamental things in characterizing a street network: what is the configuration of the street pattern, how connected are the streets, and how compact is the network. One problem that we have seen with traditional measures is that they do not given any sense of the configuration. Secondly, street connectivity and street network density, although separate concepts, are regularly treated as if they are interchangeable entities. A third problem is that the numbers produced with the traditional indices, even if used correctly, are difficult to convey and visualize. More advanced techniques such as space syntax or Stephen Marshall's routegram provide some additional information about the street network, but they are often difficult to calculate, difficult to interpret, and usually overlook network density altogether.

In this section we present a straightforward methodology for classifying street patterns based upon Stephen Marshall concept of macroscopic and microscopic street networks, which differs from the conventional concept of major and local roads. While major roads are based upon the functional classification system and generally differ from local roads in terms of variables such as the number of lanes, lane widths, and traffic volumes, the macroscopic network is classified strictly based upon street network structure. Figure 3 displays a chart, adapted from Stephen Marshall, which emphasizes the structure of the Macro-level street network – or Citywide network – separately from the Micro-level street network – or Neighborhood network (5). Overall, this system not only conveys common street patterns, but it also helps us recognize the differences between neighborhood and citywide connectivity. When combined with a basic street network density measure like intersection density, we are able to achieve a fuller understanding of the street network than can conventionally be achieved. We illustrate the applicability of this approach using 24 medium-sized California cities as a test case. We also show how the network structure of these cities is associated with basic sustainability measures such as mode choice and road safety.

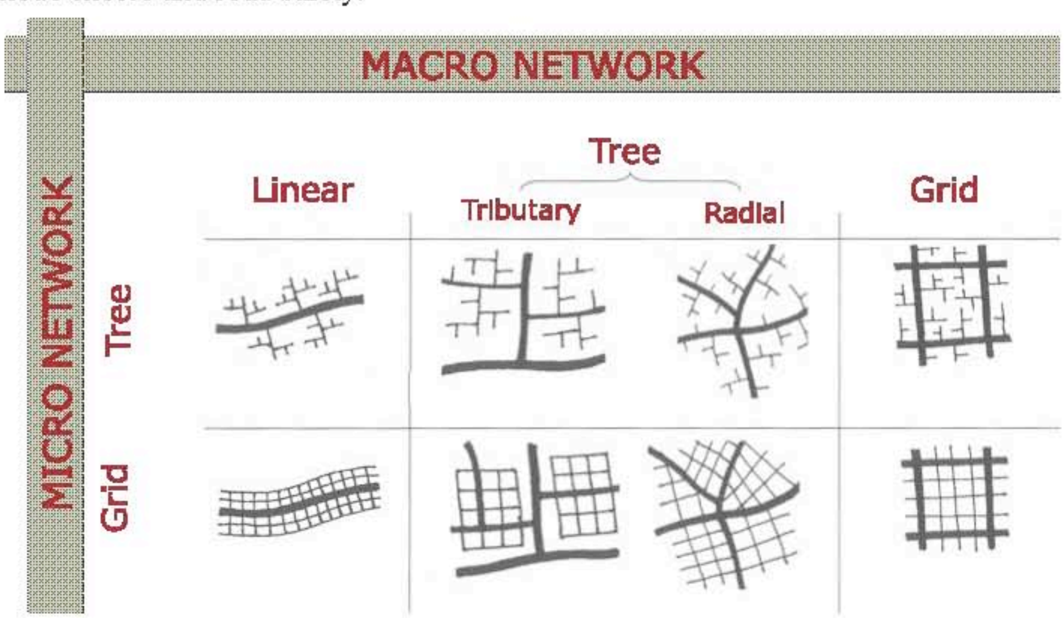


Figure 3 Macroscopic-Microscopic Street Pattern Classification System (5)

In the approach outlined here, we first focus on characterizing network structure with respect to both the Citywide and Neighborhood street networks. In general, the streets making up the Citywide network are generally continuous across a substantial portion of the city. On the other hand, the streets in the Neighborhood network generally serve neighborhood travel because they are not typically on routes that are continuous over a significant portion of the city.

Figure 4 shows this difference between roads classified as major and those that serve a Citywide network function in Carlsbad, California. With the new classification, we can better see the overall network structure and the connectivity of Citywide street network.

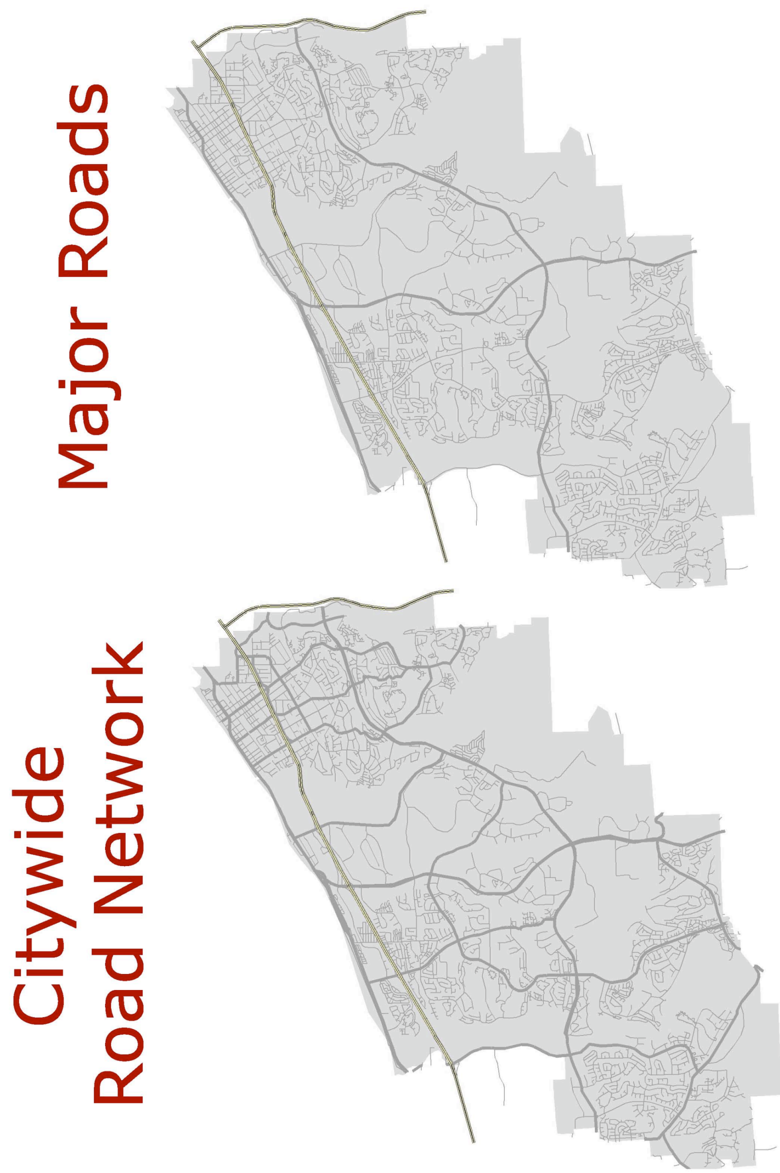


Figure 4 Major Road vs. Citywide Road Network Classification in Carlsbad, CA

Although the new classification system does not accommodate every street pattern possible, it does create a straightforward system for most street patterns. In fact, most actual street configurations tend to show one of the four characteristic Citywide network structures: linear, tributary, radial, or grid. The system is fairly intuitive to apply. By distinguishing between the Citywide and Neighborhood-level street patterns, this system helps us better understand overall network structure both within and between neighborhoods.

Our study of 24 medium-sized California cities of similar populations – twelve cities with good road safety records and twelve with poorer road safety records – classified each of more than 1,000 Census Block Groups into one of the eight network configurations. The process included designating all of the Citywide networks manually. We tried to use space syntax to automate this effort, but the results for street networks with even a moderate number of curvilinear roads were less than satisfactory; we still plan to test some graph theory techniques for finding the citywide network roads as developed by Jiang and Claramunt (6).

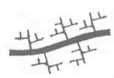
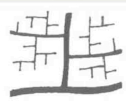
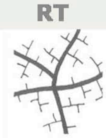
Table 1 displays the overall differences between the two sets of cities. The safer cities have a greater population density, much less driving, and a much denser street network. However, the two sets of cities average similar levels of street connectivity.

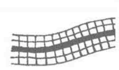
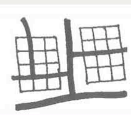
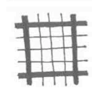
Table 1 City Level Results

	Safer Cities	Less Safe Cities
Population	65,719	59,845
Population Density	5,736 per sq. mi.	2,673 per sq. mi.
Mode Share		
Driving	84.1%	95.8%
Walking	5.4%	1.7%
Biking	4.1%	0.7%
Transit	6.6%	1.7%
Real Int. Density	106 per sq. mi.	63 per sq. mi.
Dead End Node Density	32 per sq. mi.	23 per sq mi.
% Dead Ends	23.2%	26.7%
Macro Node Density	6.9 per sq. mi.	5.2 per sq. mi.
% Major Nodes	6.3%	8.2%
Link to Node Ratio	1.34	1.29
Connected Node Ratio	0.76	0.73
Fatal Crashes per 100,000 pop.	3.2 per year	10.5 per year
Severe Crashes per 100,000 pop.	16.0 per year	18.0 per year
% Fatal or Severe	1.6%	3.1%
Macro Road Fatal or Severe per 100,000 population	13.9 per year	22.9 per year
% Fatal or Severe	1.8%	3.3%
Micro Road Fatal or Severe per 100,000 population	3.0 per year	2.8 per year
% Fatal or Severe	1.7%	2.7%

At the smaller Block Group level of analysis, we calculated the traditional connectivity and network density measures, such as the link to node ratio and intersection density. Overall, we looked at how the various street connectivity and network density indices as well as the different street patterns correlated with each other in addition to other variables such as mode choice, road safety outcomes, and the year that the street network was developed. The results, as shown in Table 2, indicate that outcomes such as mode choice and safety are much more closely associated with differences in street network density as opposed to street connectivity.

Table 2 Block Group Results based upon Citywide and Neighborhood Network Classification

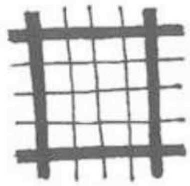
MACRO-MICRO CLASSIFICATION	LT	TT	RT	GT
				
Avg. Year of Development	1966	1965	1974	1966
SAFER CITIES				
Real Int. Density	105	155	185	195
Dead End Density	42	42	32	39
Link to Node Ratio	1.08	1.14	1.24	1.22
CNR	0.69	0.76	0.84	0.84
Vehicle Mode Share	87.8%	86.1%	88.9%	87.5%
% Fatal or Severe (Non-HW Crashes)	2.9%	2.8%	1.7%	2.0%
LESS SAFE CITIES				
Real Int. Density	65	88	111	116
Dead End Density	28	31	41	25
Link to Node Ratio	1.11	1.17	1.17	1.25
CNR	0.71	0.73	0.73	0.83
Vehicle Mode Share	95.5%	94.5%	95.5%	94.9%
% Fatal or Severe (Non-HW Crashes)	11.9%	4.4%	3.9%	3.8%

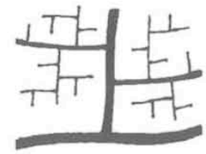
MACRO-MICRO CLASSIFICATION	LG	TG	RG	GG
				
Avg. Year of Development	N/A	1950	Pre 1940	Pre 1940
SAFER CITIES				
Real Int. Density	N/A	250	279	256
Dead End Density	N/A	26	16	13
Link to Node Ratio	N/A	1.31	1.36	1.40
CNR	N/A	0.89	0.94	0.94
Vehicle Mode Share	N/A	84.9%	79.4%	70.8%
% Fatal or Severe (Non-HW Crashes)	N/A	2.0%	1.6%	1.5%
LESS SAFE CITIES				
Real Int. Density	N/A	158	N/A	201
Dead End Density	N/A	12	N/A	10
Link to Node Ratio	N/A	1.39	1.45	1.44
CNR	N/A	0.92	0.94	0.94
Vehicle Mode Share	N/A	90.2%	N/A	89.2%
% Fatal or Severe (Non-HW Crashes)	N/A	2.6%	N/A	2.4%

The data in Table 2 begins to illustrate the fact that configuration, compactness, and connectivity are separate entities. For example in terms of configuration, the three gridded Neighborhood-level street networks – 'TG', 'RG', and 'GG' – all show very similar levels of connectivity and intersection density; however, basic sustainability outcomes like vehicle mode share and risk of a crash resulting in a severe injury or fatality are quite different, especially for the safer set of cities. And without a system that looks individually at the Citywide street network from the Neighborhood street network, patterns like 'TG' and 'GG', which are very different in terms of the basic sustainability outcomes, would be almost indistinguishable based solely on the common connectivity and street network density indices.

In terms of further refining the system, we would want to better understand the roles that connectivity and network density play. As the next step, these two factors – connectivity and street network density – can be broken out further Table 3 is an example of this effort that shows the differences in basic sustainability outcomes for two network configurations in the safer set of cities across four levels of connectivity as well as across four street network density levels. In this analysis, increased connectivity is associated with both less driving and increased safety, with these differences being much greater in the 'TT' network than in the 'GG' network. At the same time, increased network density (with similar levels of connectivity) seems be associated more with less driving than with increased safety in the 'GG' network, and more with increased safety than with less driving in the 'TT' networks. The key idea here is that all three factors – configuration, compactness, and connectivity – play a role in better understanding the performance of street networks.

Table 2 Comparison of Connectivity & Street Network Density for 2 Networks





	'GG' NETWORK 12 SAFER CITIES LINK TO NODE RATIO (links / total nodes)				'TT' NETWORK 12 SAFER CITIES LINK TO NODE RATIO (links / total nodes)			
	0 to 1.1	1.1 to 1.25	1.25 to 1.4	1.4+	0 to 1.1	1.1 to 1.25	1.25 to 1.4	1.4+
Block Groups (total number)	-	18	136	34	29	154	38	3
Avg. Block Group Year of Development	-	1943	1941	1942	1966	1964	1949	1946
Avg. Block Group Population (2000)	-	1,132	1,162	1,146	740	1,493	1,022	835
Population Density (block group avg. in people / sq. mi.)	-	12,529	13,890	9,198	7,598	5,543	7,884	3,913
Avg. Dist. from City Center (block group avg. in miles)	-	1.34	0.94	0.77	1.72	1.95	1.63	2.67
Vehicle Mode Share (block group avg.)	-	77.3%	69.3%	72.8%	87.1%	87.7%	79.8%	72.8%
Real Intersection Density (block group avg. per sq. mi.)	-	203.1	184.4	267.7	144.5	142.2	218.7	138.0
Dead End Density (block group avg. per sq. mi.)	-	37.2	11.8	3.3	56.4	46.3	14.1	42.8
Link to Node Ratio (L2N: block group average)	-	1.20	1.39	1.56	0.90	1.13	1.33	1.53
Connected Node Ratio (CNR: block group average)	-	0.82	0.95	0.98	0.67	0.74	0.92	0.87
Risk of Severe Injury: Avg. Chance of a Non-Highway Crash Resulting in a Fatality or Severe Injury (block group avg.)	-	1.64%	1.52%	1.30%	3.83%	2.43%	1.88%	0.96%

	REAL INTERSECTION DENSITY (real intersections / square mile)				REAL INTERSECTION DENSITY (real intersections / square mile)			
	0 to 81	81 to 144	144 to 225	225+	0 to 81	81 to 144	144 to 225	225+
Block Groups (total number)	-	6	69	114	38	71	81	34
Avg. Block Group Year of Development	-	1944	1942	1941	1967	1966	1959	1953
Avg. Block Group Population (2000)	-	2,071	1,205	1,076	1,431	1,532	1,245	847
Population Density (block group avg. in people / sq. mi.)	-	14,203	11,029	1,062	2,323	5,674	7,326	8,846
Avg. Dist. from City Center (block group avg. in miles)	-	0.93	0.98	0.93	2.13	2.02	1.72	1.67
Vehicle Mode Share (block group avg.)	-	82.4%	71.4%	69.8%	86.9%	86.3%	87.4%	81.5%
Real Intersection Density (block group avg. per sq. mi.)	-	121.1	193.2	301.5	50.2	113.6	184.9	290.0
Dead End Density (block group avg. per sq. mi.)	-	6.9	16.6	11.3	23.8	40.3	52.4	40.3
Link to Node Ratio (L2N: block group average)	-	1.37	1.39	1.40	1.03	1.12	1.17	1.23
Connected Node Ratio (CNR: block group average)	-	0.92	0.92	0.96	0.68	0.73	0.78	0.88
Risk of Severe Injury: Avg. Chance of a Non-Highway Crash Resulting in a Fatality or Severe Injury (block group avg.)	-	1.82%	1.34%	1.58%	4.11%	2.53%	1.89%	2.07%

CONCLUSION

The street network is a critical component of New Urbanist design, even if we neither have a universal system to measure it, nor much consensus on what variables are actually important in achieving the desired result of a safe and livable place. Moreover, most of the existing street network measures are either misunderstood and misused, or tough to interpret and difficult to explain to the general public.

Our system of categorizing street patterns based upon Citywide and Neighborhood network structure visually conveys easily understandable street patterns. One major advantage of this classification system is the ability to differentiate between street patterns at the neighborhood level versus those at the city or even the regional level. Combined with a measure of street network compactness such as intersection density, these measures were, based upon an empirical study of 24 medium-sized California cities, the most highly correlated with fundamental sustainability outcomes such as mode choice and road safety. By focusing on actual outcomes and understanding what the various street network indices are actually measuring, we have started on the path toward a streamlined and easily understandable system of street network measurement and classification at the neighborhood and citywide scales.

REFERENCES

1. Southworth, M. and E. Ben-Joseph, *Street and the Shaping of Towns and Cities*. 1997, New York: McGraw-Hill.
2. Handy, S., R. Paterson, and K. Butler, *Planning for Street Connectivity: Getting from Here to There*, in *Planning Advisory Service Report 515*. 2003, American Planning Association.
3. Ewing, R., *Best Development Practices: Doing the Right Thing and Making Money at the Same Time*. 1996, Washington, D.C.: APA Planners Press.
4. Litman, T. *Roadway Connectivity: Creating More Connected Roadway and Pathway Networks*. 2005 [cited 2005 October 25]; Available from: http://www.vtpi.org/tdm/tdm116.htm.
5. Marshall, S., *Streets & Patterns*. 2005, New York: Spon Press.
6. Jiang, B. and C. Claramunt, *A Structural Approach to the Model Generalization of an Urban Street Network*. GeoInformatica, 2004. **8**(2): p. 157-171.