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Measuring Non-motorized Accessibility and Connectivity in a Robust Pedestrian Network

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DISCLAIMER

Measuring Non-motorized Accessibility and Connectivity in a Robust Pedestrian Network

1. INTRODUCTION

Walkability has many important benefits. Higher walkability is associated with healthier communities mostly as a result of higher levels of physical activity (Frank et al. 2006, 2005; Boer et al 2007; Evanson et al 2009; Frank and Kavage 2009; Gebel et al 2009; Grow et al. 2008; McCormack et al. 2009b; Michael and Carlson 2009; Moudon et al. 2007; Owen et al. 2007; Van Dyck et al. 2009). Walkability is also associated with walking as a mode of transportation, whether as access to final destinations or as access to transit (Frank et al. 2006; Cerin et al. 2007; Canepa 1992; Cervero & Kockelman 1997). Walkability, as an essential complement to transit access, mixed land uses, and higher densities, is a major component of efforts in urban planning to reduce auto dependence (Canepa 1992; Leyden 2003; Al-Hagla 2009; Carnoske et al. 2010).

Walkability has been defined in many different ways. One important aspect of walkability is the quality of the environment, including the safety, comfort, and pleasure it instills in pedestrians. Another important aspect of walkability is the ability of pedestrians to access their destinations.. This is aspect of walkability is called pedestrian accessibility. Accessibility is a function of proximity to destinations and the directness of routes to those destinations, or what is generally called network connectivity. Measures of accessibility from homes to schools, shopping centers, health facilities, transit stops and other locations of interest are traditionally based on estimated travel distance via the street network. Studies of pedestrian accessibility generally use the street network or sometimes a more limited network of streets that can be safely used by pedestrians. But unlike vehicles, pedestrians are not confined to the street network and their actual travel network around the city may include formal pedestrian facilities, such as pedestrian over and under passes, walkways, and greenbelt paths, together with informal routes, such as those through parks, parking lots, shopping centers, and other public facilities. In general, focusing on the street network ignores pedestrian travel off of this network, including the sometimes substantial travel involved in getting to and from the street.

This study explores the effect of the pedestrian network on pedestrian accessibility and connectivity in a variety of low-density suburban neighborhoods in the City of Davis, where the pedestrian network is substantially more extensive than the street network. The pedestrian network in Davis is unusual, given sidewalks on all streets and many off-street paths, what we call *a robust pedestrian network.* We focus on the question: how much difference does the pedestrian network make to pedestrian connectivity and thus accessibility? We compare a variety of measures of connectivity and accessibility based on the pedestrian network versus the street network in different suburban settings and for accessibility to different land use activities, such as schools and retail centers. We have two major motivations for documenting the degree to which the pedestrian network enhances pedestrian accessibility over the street network alone: to inform research, and to inform policy.

2. MEASURING ACCESSIBILITY AND CONNECTIVITY

Accessibility is a concept that is difficult to define and even more difficult to measure (Handy, 2002). Hansen (1959) defined accessibility as “the potential for interaction.” It is commonly measured with respect to the cost of reaching potential destinations, where cost is often represented by travel distance, or conversely, as the number of destinations reachable within a specified travel distance (see Handy and Niemeier, 1996). Accessibility is thus a function of both proximity and connectivity. Proximity is determined by land use patterns – what is located where, how close one thing is to another. Connectivity is a measure of the quantity of the connections in the network and thus the directness and multiplicity of routes through the network. From a transportation standpoint, only connections to destinations are important, so connectivity in some cases is defined with respect to the locations of potential destinations. The distinction between connectivity and accessibility measures is thus sometimes hard to discern.

Dill (2004) examined common measures of connectivity for bicycling and walking (Table 1). Dill's work presents studies that focused on network structure primarily in grid networks, and thus some of the suggested measurements are not applicable to low-density suburban areas and for neighborhoods with a developed pedestrian network. Most of the measures presented in Table 1 were calculated using a representation of the local street network such as the "TIGER" GIS files from the U.S. Census Bureau or a GIS network from a local source. None of these studies included pedestrian links that are not part of the local street network.

TABLE 1 Common Measures of Connectivity (adopted from Dill 2004)

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 to activities	Aultman-Hall et al. (1997); (mean, maximum, percent of homes meeting minimum standard)

In our study, we examine three network-related measures. The first, Link to Node Ratio (LNR), is a measure of connectivity independent of origins and destinations. The second, “pedsheds,” is measured with respect to a specific origin, and the third, Pedestrian Route Directness (PRD, is measured with respect to a specific origin and destination. The second and third measures can be categorized as location specific connectivity measures. The last measure, the number of households within a specified distance of an origin, is also a commonly used as an accessibility measure. We based our methodology on a similar study by Chin et al. (2008) that tested the same three measures in Australia using aerial photos to assess the pedestrian network.

The first measure, Link to Node Ratio (LNR), is often adopted due to its low data requirements and simplicity of operation. LNR is the ratio of road links (segments of a road between two intersections) to the number of nodes (intersections and sometimes cul-de-sac ends), with higher values indicating a network that provides more route options and more direct connections (Handy at all, 2003; Ewing, 1996). The LNR is implicitly based on the perspective of planning for motorized traffic planning, where each additional intersection has the potential to reduce traffic flow at any one intersection and to increase route options. A related set of measures looks at types of intersections, such as the percentage of intersections that are 4-way intersections (i.e. four links attach to that node) (Cervero and Kockelman, 1997), or on the other end of the spectrum, the percentage of intersections that are not dead-ends (where cul-de-sacs are nodes with only one link) (Fan and Khattak, 2008).

A pedshed is defined as the area that can be reached from a given origin by walking along the network for a specified distance as a percentage of the area of a circle with a radius of the same distance (Porta et all, 2005; Bejleri et al, 2009). Using this approach requires the researcher to select nodes from which to measure the pedshed. Pedsheds can be thought of as a measure of "service area," though they do not account for the number of potential users in this area or, if measured from residential locations, the number of potential destinations. A similar measurement of effective walking area (EWA) is sometimes used to combine land use patterns by counting the number of parcels within a specified network distance from a destination, such as a school or transit station (Dill, 2004).

The third indicator employed in this study is derived from the second measure and uses the number of households within the pedsheds rather than the number of parcels or the size of the area. This indicator is especially relevant in high density and mixed density areas where the number of parcels is not a good indicator for the potential users in the area. It is important for analyses of school location and for developing strategies to promote walking to school.

3. METHOD

In this section we discuss the construction of the pedestrian network in GIS form for Davis, California. The City of Davis is proud to have over 100 miles of multi-use paths and bike lanes, creating an extensive network for bicyclists and pedestrians (Buehler and Handy, 2008). Starting from the street network, we considered a variety of methods for adding links to the street network in areas rich with pedestrian pathways and for taking out links that are available to cars, but not for pedestrians. Our expanded GIS network represents over 60 miles of additional pedestrian route options in Davis, links that are not part of the 500 mile city street network (Figure 1).

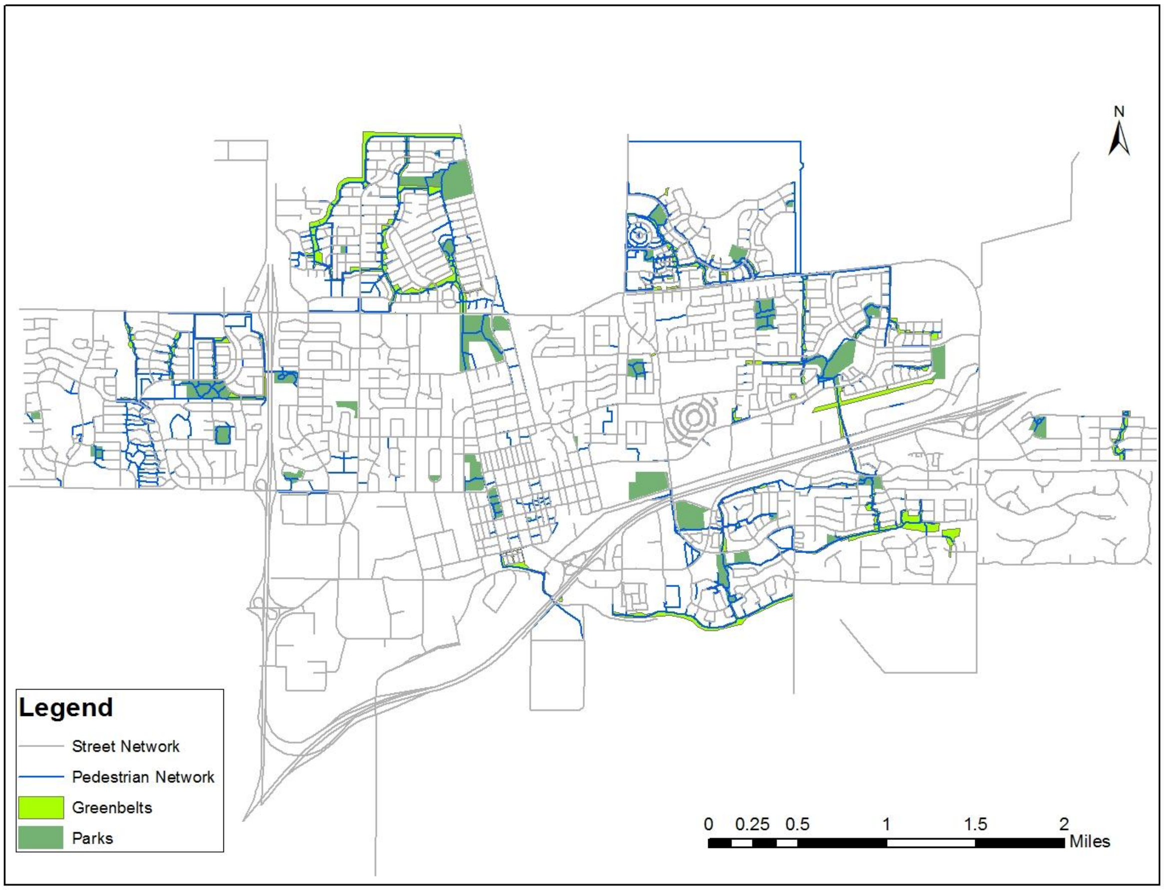

FIGURE 1 Davis Pedestrian Network

3.1 Network Building

We used the existing street network as the base for building the pedestrian network. We developed this network based on the assumption that all off-street paths work for walking, as all are designated as multi-use rather than bicycle-only paths. We assume that all of the local streets with a speed limit of 20 miles per hour or higher but with sidewalks are accessible for pedestrian, except for limited-access roads, such as freeways. More detailed work in the future may limit these assumptions for different users (mainly different age groups), based on the quality of the link surface, traffic count, safety, and more.

We based our network on a GIS street network produced by the City of Davis. This street network does not include any data on the safety or availability of street segments for pedestrian , or data on pedstrian links that are not part of the street network. To build a map of the pedestrian network from this street network mpa, we started by determining which streets or roads are inaccessible to non-motorized travel based on safety considerations, such as high traffic and lack of sidewalks (see for example, Vikas, 2008). Because pedestrians are more sensitive to small differences in distance than drivers, we considered several additional refinements to the GIS network to achieve more accurate estimates of walking distances. Although typical GIS representations of street networks work fine for the purposes of analyzing vehicle traffic, they have many shortcomings from the standpoint of pedestrian travel.

The representation of sidewalks and crosswalks in the GIS network presented our first challenge, with the options shown in Figure 2. Each option yields a different travel distance and link-to-node ratio. In the first option, we represent each street as a single link, aiming for a simple network with one node per intersection. This option does not represent the actual walking distance to the nearest crosswalk and from there to the destination, and it neglects the street's width. The second option includes a link for each sidewalk and crosswalk in a way that represents actual walking on streets that cannot be crossed outside of the designated crosswalk. This option creates a network that represents a street crossed by two other streets using 24 links and 8 nodes. The third option keeps the sidewalk represented by a link on each side of the street, but instead of creating a link for each sidewalk combines the two sidewalk links together on each intersection to represent a crosswalk. This option is a relatively simple way to model wide streets on a

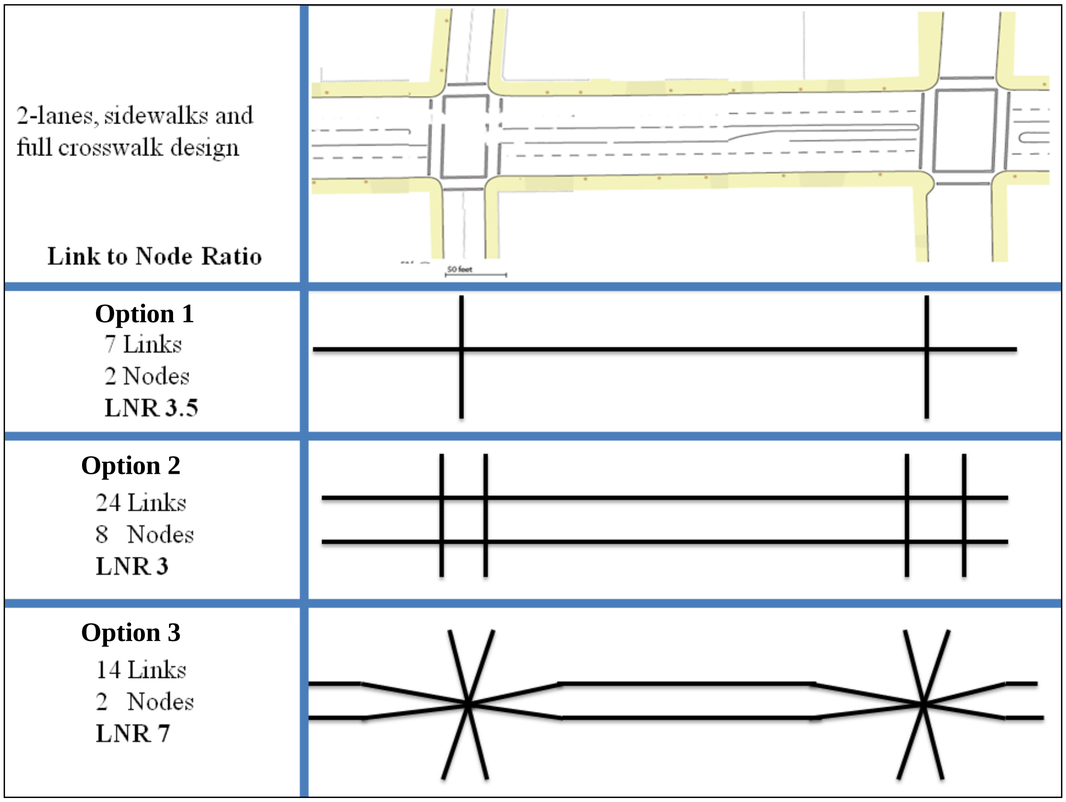

FIGURE 2 Options for Modeling of Sidewalks as Links

GIS network, but it creates a biased link-to-node ratio, since the number of links connected to the same node doubled from 4 streets to 8 links.

When modeling arterial streets we decided to use a single link on the median instead of the more comprehensive approach to modeling each sidewalk, path, and crosswalk. This approach reflects actual travel behavior on streets that can be crossed safely in almost any spot, but may not be satisfying on streets with medians or high levels of traffic that can be crossed only on crosswalks. The single-link approach also represents the most simple and inexpensive method of adjusting the existing GIS network, Options 2 and 3 on the other hand would require a new network design for pedestrian use versus motor vehicles or bicycling.

The second methodological concern is the accurate representation of a pedestrian network that is not part of the street network. A park, for example, includes a variety of pathways that are planned not only to move pedestrian traffic through the park, but also for recreational purposes. Representing pedestrian paths was not straightforward, since those paths are often not planned for the most efficient or shortest route, and do not avoid redundancy, as demonstrated on the right side of Figure 3. Furthermore, pedestrian paths are not planned to minimize intersections, and may have random intersections that do not change actual travel distance or connectivity but may affect measures based on numbers of nodes and links. In this study, we decided to represent the actual park pathways in the network, thereby keeping the redundant route options. In the illustrated case, the final network included four 3-way intersections, rather than the two 4-way intersections in the simpler network. We did not include“shortcuts” that may be used across open fields or grassy areas unless a clear “goat path” was visible in the field. The off-street pedestrian connections were identified using the city’s bicycle map, Google Maps, and field visits.

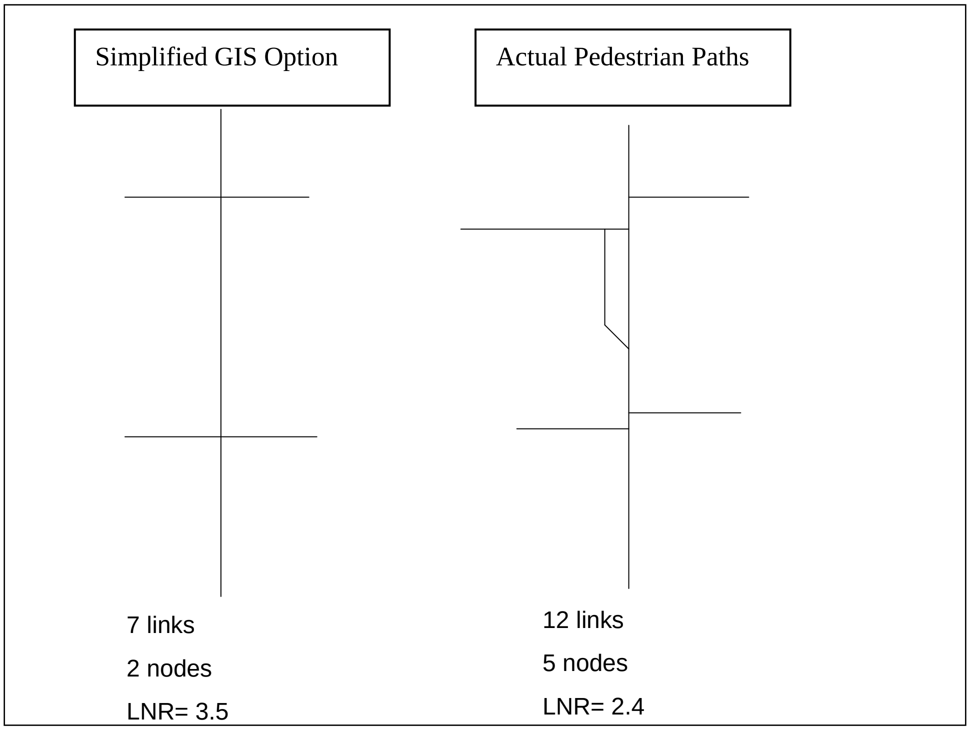

FIGURE 3 Options for Greenbelt Pathways Representation

Although the Davis greenbelts are essentially pedestrian streets, parks and parking lots are less structured and more difficult to translate into a network that will replicate actual travel behavior. In our network we added to the network any pathwaysvisually observed (via aerial photos) in the open area and added additional links if we observed the potential for other shortcuts through the area. This method, similar to the previous, adds links and nodes that may alter the LNR measurement. Similar to parks and other green areas, parking lots, malls, and open spaces are also part of the pedestrian network and were modeled based on the actual paths and walkways in them, or based on a shortest path in the middle of a block for an open space that can be crossed in all directions. This method is somewhat subjective as it based on the actual usage of the space rather than the official usage as shown in the city maps.

The last methodological and planning consideration is the representation of large facilities in the network. Crossing a school, for example, from the point where it connects to the street network to the actual destination on the school site, can sometimes take several minutes. Most GIS street networks usually do not account for this additional travel distance. In addition, in most GIS street networks, these large facilities are connected to the network in one arbitrary point (i.e. there are no different alternative connections from the street to the destination) that may not reflect actual walking options. In the cases of schools, for example, the facility can be entered from many directions, or from a nearby park, and those options have to be represented in the network. Adding these entrances to a facility may dramatically improve pedestrian accessibility.

3.2 Network by Study Area

The city was divided to 9 study areas ordered by the year of annexation (Figure 4). All of the study areas are predominantly residential neighborhoods, except Area 1, which is a mix of small retail, office spaces, and residential use.

The study areas are based on natural barriers or common characteristics (see Table 2) to maximize the internal homogeneity and maximize the variation between areas. Parks and greenbelts potentially add additional links to the pedestrian network and are included in the public green spaces. In some cases privately-owned parks open to the public can add links that are not shown in this table. In West Davis (area 7), for example, the common gardens of the Village Homes neighborhood contribute about half of the added links, but are not included in the acreage of public greenbelt areas.

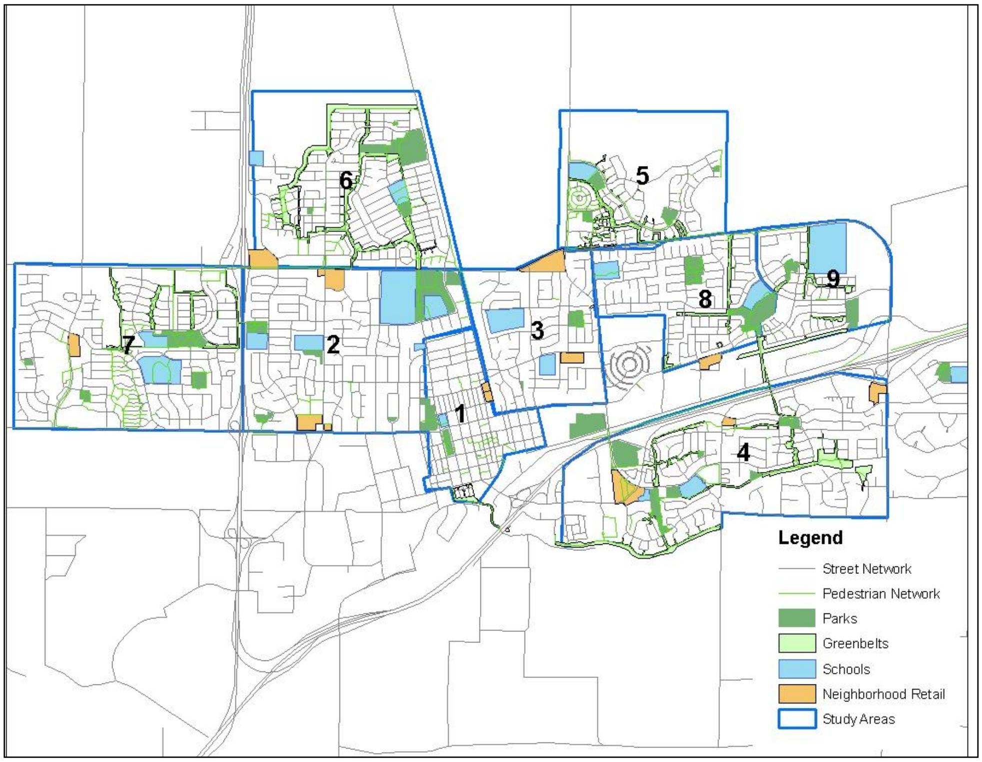

FIGURE 4 Study Areas

TABLE 2 Study Areas Characteristics

#	Name	Year of annexation*	Total area (acres)	Park area	Green belt area	Total green area	Green share of total
1	Down Town	1944	303	4.99	0.28	5.27	1.7%
2	Center West	1955	795	44.43	0.00	44.43	5.6%
3	Center East	1964	447	6.63	0.16	6.78	1.5%
4	South	1966	997	36.99	38.58	75.56	7.6%
5	North East	1970	352	17.94	13.56	31.50	8.9%
6	North West	1973	669	34.38	65.63	100.01	14.9%
7	West	1978	917	5.60	26.09	31.69	3.5%
8	Old East	1981	396	11.98	12.15	24.13	6.1%
9	Upper East	1989	344	4.83	9.30	14.13	4.1%

* last annexation when more than one accord

The City of Davis has expanded substantially in the last sixty years, thus the study areas represent most types of suburban networks and neighborhood design common in the U.S., starting from a grid with small blocks to areas with loops and cul-de-sacs. Davis is rich with parks and green areas, and over the years integrated greenbelts replaced central parks and neighborhood retail centers were developed on main arterials. The effect of neighborhood design on the network is shown in Table 3. The greenbelts and parks, which are the backbone of the pedestrian network, increase the network miles by up to 72.4% from the original street network. The increased length of the pedestrian network in North and West Davis (areas 5, 6 and 7) come mainly from greenbelts and parks that are connected to cul-de-sacs and transform the network into a pedestrian grid. The pathways in the parking lots and other facilities in the downtown area increase the network miles by 7.9%.

TABLE 3 Network Characteristics

#	**Name**	**Street Network** (miles)	**Network Type***	**Pedestrian Network** (Miles)	**Pedestrian Network increase**	**Street/area** (Mile/acre)	**Pednetwork /area** (Mile/acre)
1	Downtown	12.6	Grid	13.6	7.9%	0.041	0.045
2	Center West	22.6	Loops	23.4	3.6%	0.028	0.029
3	Center East	12.5	Long blocks, Cul-de-sacs	13.1	5.2%	0.028	0.029
4	South	25.3	Cul-de-sacs	33.9	34.2%	0.025	0.034
5	North East	9.5	Cul-de-sacs	16.4	72.4%	0.027	0.046
6	North West	17.5	Loops Cul-de-sacs	26.5	51.2%	0.026	0.040
7	West	26.8	Cul-de-sacs	34.9	30.2%	0.029	0.038
8	Old East	14.6	Loops Cul-de-sacs	17.3	18.5%	0.037	0.044
9	Upper East	8.1	Cul-de-sacs	9.2	13.5%	0.023	0.027

*follows the typology used by Crane & Crepeau (1998).

4. RESULTS

We measure the connectivity and accessibility of the study areas using the three measurements discussed in Section 2. The LNR was measured for the entire study area, and the pedshed and households within pedsheds were measured for 18 educational facilities and 12 retail centers in the city. We choose to focus on a short walking distance based on five minutes walking distance calculated at 4 miles per hour. This distance of 537m or a third of a mile represents a distance that may have a shorter travel time by walking than by driving, given the two to three minutes needed for starting the car, backing it out, parking it, etc. A similar study by Aultman et al., (1996) that focused on neighborhood pedestrian accessibility used 400 meters as a walking distance, which may be too short to demonstrate differences in a suburban area with relatively large blocks. A study from Davis that focused on biking and walking to soccer games suggests that non-motorized modes were dominant up to a range of just over half mile (Tal and Handy, 2008).

4.1 Link Node Ratio

Link to node ratio is a commonly used indicator to distinguish between grid networks and suburban type networks. In Davis we can see that the street network in the older downtown area has an LNR of 1.83 while the other non-grid areas have LNRs of 1.1 to 1.35 (Table 4).

TABLE 4 LNR

		Street Network			**Pedestrian Network**			**Ped to Street Ratio**
#	**Name**	Links	Nodes	Ratio	Links	Nodes	Ratio	
1	Down Town	211	115	1.83	286	164	1.74	0.95
2	Center West	220	163	1.35	267	189	1.41	1.05
3	Center East	135	116	1.16	155	124	1.25	1.07
4	South	285	242	1.18	452	320	1.41	1.20
5	North East	121	108	1.12	328	221	1.48	1.32
6	North West	222	201	1.10	452	314	1.44	1.30
7	West	289	238	1.21	531	369	1.44	1.19
8	Old East	176	141	1.25	264	189	1.40	1.12
9	Upper East	95	81	1.17	136	90	1.51	1.29
	Sum and Ratio	**1754**	**1405**	1.25	**2871**	**1980**	1.45	1.16

The pedestrian network LNR yielded surprising results. In the grid network of downtown the new links created more nodes and dropped the LNR from 1.83 to 1.74. In the other areas, the pedestrian network shows higher LNR than the street network, with differences of 5 to 32%. We see that the largest improvement in LNR observed in areas where the pedestrian links change the network type from cul-de-sacs to grid as shown in areas 5, 6, 7, and 9 in Figure 4. It can also be observed that areas 2 and 3 have a lower number of new links and nodes, and lower improvement overall.

4.2 Pedsheds

As discussed above, we created 5-minute walk pedsheds around schools and retail centers in each area. The results for this indicator are highly dependent on the location of the school in relation to additional pedestrian links, particularly the way the pedestrian links change the options for entering the school. Overall, we observe that the pedestrian network increases the 5-minute walk area by an average of 12 percentage points (Table 5). Schools located at the end or on a greenbelt or other pedestrian link showed a higher increase as did schools located at the end of a park, because these schools connect to the pedestrian network on at least two sides and not just at the front of the school (Figure 4).

TABLE 5 Pedsheds for 5 Minute Walk from Schools and Educational Facilities

			Area change from street to pednet (percent points)*		
#	**Name**	N	Min	Max	Average
1	Down Town	2	n/s	14.7%	8.4%
2	Center West	4	n/s	10.2%	6.3%
3	Center East	2	n/s	3.3%	1.6%
4	South	2	18.8%	28.2%	23.3%
5	North East	1	n/s	n/s	3.7%
6	North West	2	n/s	32.9%	16.6%
7	West	2	16.6%	17.4%	17.0%
8	Old East	2	7.7%	57.2%	32.4%
9	Upper East	1	n/s	n/s	0.2%
	All Areas	18	4.5%	18.2%	12.2%

* due to a minor changes in the origin location a difference of less than 4% in the area considered as not significant

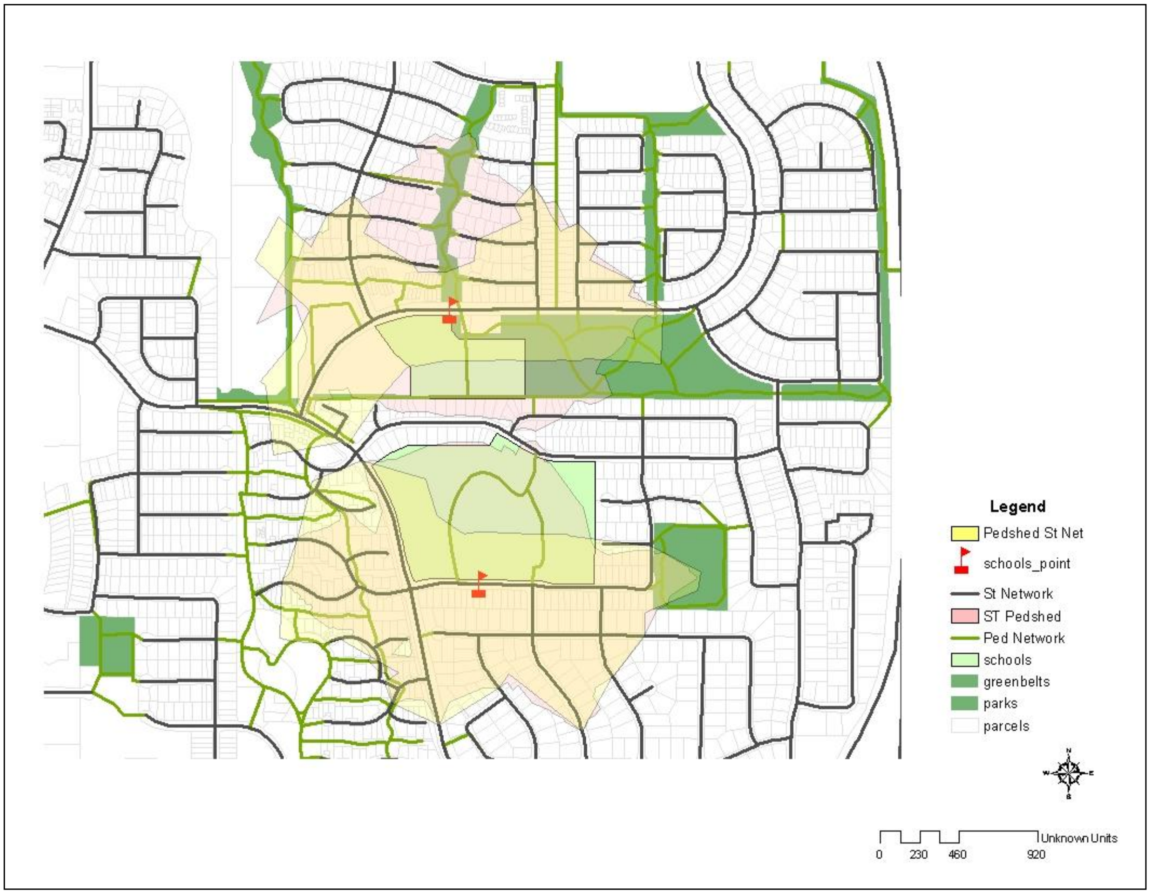

FIGURE 4 Pedsheds for 5 Minute Walk from Schools in West Davis (Area 7)

A similar analysis of a retail center suggests much lower improvement due to the pedestrian network with no significant increase in 5 out of 9 areas, and an average improvement of 5.3% (vs. 12.2% for schools; see Table 6). The low impact of the pedestrian network for retail centers can be attributed to the car-oriented location of most retail centers in Davis. In two areas (#1 and #4), retail centers show a significant increase in pednet area resulting from a back entrance for pedestrians(Table 6).

TABLE 6 Pedsheds for 5 minute Walk from Retail Center

			Area change from street to pednet (percent points)*		
#	**Name**	N	Min	Max	Average
1	Down Town	2	n/s	n/s	0.0%
2	Center West	2	n/s	38.6%	19.1%
3	Center East	2	n/s	n/s	0.0%
4	South	3	n/s	19.9%	6.9%
5	North East	0	-	-	-
6	North West	1	n/s	n/s	2.2%
7	West	1	7.3%	7.3%	7.3%
8	Old East	1	n/s	n/s	1.3%
9	Upper East	0	-	-	-
	All Areas	12	1.0%	9.4%	5.3%

* due to a minor changes in the origin location a difference of less than 4% in the area considered as not significant

We merged the pedsheds with household layers to estimate the number of household that are within a 5 minute walk from a school or retail center, as a measure of accessibility. This measure removes the bias created by large parks that are added into the pedsheds when a pedestrian network is used (as reflected in the lower school in Figure 6). The overall results suggest that by using the street network we underestimate the number of households within 5 a minute walk from a school by more than 40%. The wide variation in results also reflects the importance of the school location with respect to the pedestrian network.

TABLE7 Number of Households 5 Minute Walk from Schools and Educational Facilities

			Percent point change in number of HH within 5 minutes walk street vs. pednet		
#	**Name**	N	Min	Max	Average
1	Down Town	2	n/s	4.5%	3.8%
2	Center West	4	n/s	n/s	n/s
3	Center East	1	n/s	n/s	n/s
4	South	2	25.4%	59.7%	41.6%
5	North East	1	202%	202%	202%
6	North West	2	10.7%	29.5%	20.1%
7	West	2	19.1%	29.9%	24.5%
8	Old East	2	11.2%	58.5%	29.9%
9	Upper East	1	-	-	-
	All Areas		33.6%	47.5%	40.2%

* due to a minor changes in the origin location a difference of less than 4% in the area considered as not significant

Overall, we observed some correlation between accessibility and area characteristics, as reflected in Table 2, with higher scores in areas with more greenbelts and a more developed pedestrian network.

5. DISCUSSION

The overall results suggest that by using the street network we underestimate the number of households within 5 minute walk from different desired destinations in Davis by more than 40% in some cases. The highest differences are seen in newer neighborhoods that have an extensive pedestrian network as part of park and greenbelt areas. More modest differences are seen in areas with large, relatively square parks that increase the distance between potential origins and destinations and in areas with low connectivity on both the street and the pedestrian network.

Additionally, we find that the link-to-node ratio is not a good indicator for pedestrian networks. We demonstrate that in a grid network the introduction of new pedestrian links may reduce the overall LNR. Overall, our finding suggests that the LNR measure can reflect the differences between a grid network and a suburban network, but cannot reflect minor differences between areas or adequately account for the effect of pedestrian-only connections. While the LNR has no distance component and measures connectivity without respect to destinations, the other indicators examined include actual travel distance to or from a specific location and therefore are affected by the location of the measured facility, not only by the area characteristics. They are more effective in accounting for the presence of pedestrian-only links.

As expected we observed that the differences between the pedestrian network and the street network is higher in the vicinity of schools, which are located inside the neighborhood, than on retail centers located on arterials between residential areas.. Conversely, a large and wide park, even if well connected, may put houses farther away from a destination on average, thereby increasing travel distances and reducing accessibility. We believe that the shape of the green area (i.e. a linear greenbelt versus a square-shaped park) affects network accessibility together with the location of its pedestrian connections to the street network. In addition, the connectivity to specific retail areas was dramatically improved by accounting for backside connections to the neighborhood rather than just the connections through the parking lot.

6. CONCLUSIONS

This study has demonstrated the significant impact that off-street pedestrian links can have on pedestrian connectivity and accessibility We demonstrate that suburban areas with lower housing density and a pedestrian network based on pathways, parks, and greenbelts, as found in parts of Davis, can have a higher level of connectivity and accessibility than measured in a more traditional grid network with four-way intersections and small blocks. Accounting for actual pedestrian connectivity, particularly the connections to schools and other public facilities, can lead to both better planning and more accurate research with respect to the conditions that promote walking.

While this study demonstrates the need for developing GIS pedestrian networks rather than relying on GIS street networks for both planning and research, it also highlights many important methodological considerations. The particular approach chosen for representing the network in GIS can have a substantial impact on measures on connectivity. Further explorations of these issues, in a wider variety of settings, is an important next step. In addition, in this study we focused on the pedestrian network rather than the bicycle network. More detailed analysis is needed to understand differences between these as well as differences in the networks relevant to bicyclists of different abilities. Finally, this work should be extended to other measures of accessibility to assess the importance of accounting for pedestrian facilities.

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REFERENCES

Allen, E. (1997) Measuring The New Urbanism With Community Indicators. In *Contrasts And Transitions,* American Planning Association National Conference American Planning Association, San Diego, CA.

Al-Hagla, K. S. (2009). Evaluating new urbanisms walkability performance: A comprehensive approach to assessment in Saifi Village, Beirut, Lebanon. Urban Design International, 14(3), 139-151.

Aultman-Hall, L., Roorda, M. And Baetz, B. (1997) Using GIS For Evaluation Of Neighborhood Pedestrian Accessibility. *Journal Of Urban Planning And Development*, 123, 10-17.

Boarnet, M. And Crane, R. (2001) The Influence Of Land Use On Travel Behavior: Specification And Estimation Strategies. *Transportation Research Part A*, 35, 823-845.

Bejleri, I., Steiner, R. L., Provost, R. E., Fischman, A., & Arafat, A. A. (2009). Understanding and Mapping Elements of Urban Form That Affect Children's Ability to Walk and Bicycle to School. Transportation Research Record: Journal of the Transportation Research Board, 2137(-1), 148-158.

Boer, R., Zheng, Y., Overton, A., Ridgeway, G. K., & Cohen, D. A. (2007). Neighborhood design and walking trips in ten US metropolitan areas. American journal of preventive medicine, 32(4), 298-304.

Boarnet, M. And Sarmiento, S. (1998) *Can Land-Use Policy Really Affect Travel Behavior? A Study Of The Link Between Non-Work Travel And Land-Use Characteristics*. Urban Studies, 35, 1155-1169.

Buehler T. And S. Handy, (2008) Fifty Years Of Bicycle Policy In Davis, California *Transportation Research Record* Volume: 2074 Issue: 1 P. 52

Canepa, B. (2007). Bursting the Bubble: Determining the Transit-Oriented Development's Walkable Limits. Transportation Research Record: Journal of the Transportation Research Board, 1992(-1), 28-34.

Carnoske, C., Hoehner, C., Ruthmann, N., Frank, L., Handy, S., Hill, J., . . . Brownson, R. (2010). Developer and realtor perspectives on factors that influence development, sale, and perceived demand for activity-friendly communities. Journal of physical activity & health, 7, S48.

Cerin, E., B. E. Saelens, J. F. Sallis, And L. D. Frank. (2006) Neighborhood Environment Walkability Scale: Validity And Development Of A Short Form. *Medicine & Science in Sports & Exercise*., Vol. 38, No. 9, Pp. 1682–1691,.

Cervero, R., & Kockelman, K. (1997). Travel Demand And The 3Ds: Density, Diversity, And Design. *Transportation Research D, 2* (3), 199–219

Chin, K.P. Van Niel, B. Giles-Corti And M. Knuiman, (2008),Accessibility And Connectivity In Physical Activity Studies: The Impact Of Missing Pedestrian Data, *Preventive Medicine*, **46** (1) P. 45

Dill, J (2004) Travel Behavior And Attitudes: New Urbanist Versus Traditional Suburban Neighborhoods, Conference Proceedings, *Transportation Research Board Annual Meeting*, Washington, DC

Crane, Randall, & Crepeau, Richard. (1998). *Does Neighborhood Design Influence Travel? A Behavioral Analysis Of Travel Diary And GIS Data. UC Irvine: Center For Activity Systems Analysis*. Retrieved From: Http://Www.Escholarship.Org/Uc/Item/5qq985sv

Ewing, R. And S. Handy. (2009) Measuring The Unmeasurable: Urban Design Qualities Related To Walkability." *Urban Design*, Vol. 14, No. 1, Pp. 65-84.

Ewing, R. (1996). *Pedestrian- And Transit-Friendly Design: A Primer For Smart Growth*. Washington: Smart Growth Network

Evenson, K. R., Sotres-Alvarez, D., Herring, A. H., Messer, L., Laraia, B. A., & Rodríguez, D. A. (2009). International Journal of Behavioral Nutrition and Physical Activity. International Journal of Behavioral Nutrition and Physical Activity, 6, 44.

Fan, Y., & Khattak, A. J. (2009). Does urban form matter in solo and joint activity engagement? Landscape and urban planning, 92(3-4), 199-209.

Frank, L., & Kavage, S. (2009). A national plan for physical activity: the enabling role of the built environment. Journal of physical activity & health, 6, S186.

Frank, L., Sallis, J., Conway, T., Chapman, J., Saelens, B., & Bachman, W. (2006). Multiple pathways from land use to health: walkability associations with active transportation, body mass index, and air quality. Journal of the American Planning Association, 72(1), 75-87.

Gebel, K., Bauman, A., & Owen, N. (2009). Correlates of non-concordance between perceived and objective measures of walkability. Annals of behavioral medicine, 37(2), 228-238.

Greenwald, M,Boarnet, M. (2001) Built Environment As Determinant Of Walking Behavior: Analyzing Nonwork Pedestrian Travel In Portland, Oregon. *Transportation Research Record*, Vol. 1780, P. 33-41.

Grow, H. M., Saelens, B. E., Kerr, J., Durant, N. H., Norman, G. J., & Sallis, J. F. (2008). Where are youth active? Roles of proximity, active transport, and built environment. Medicine & Science in Sports & Exercise, 40(12), 2071.

Handy, S. And K. Clifton. (2001) Evaluating Neighborhood Accessibility: Possibilities And Practicalities, *Journal Of Transportation And Statistics*, Vol. 4, No. 2/3 (November/December), Pp. 67-78.

Handy S, (2002), *Accessibility- Vs. Mobility-Enhancing Strategies For Addressing Automobile Dependence In The U.S*. Prepared For The European Conference Of Ministers Of Transport May 2002

Handy, S. (1996), Urban Form And Pedestrian Choices: A Study Of Austin Neighborhoods, *Transportation Research Record*, No. 1552, Pp. 135-144,

Handy, S., R. Paterson, And K.Butler.(2003), *Planning For Street Connectivity: Getting From Here To There*. Planning Advisory Service Report. Chicago, IL: American Planning Association.

Hansen, W G. (1959). How Accessibility Shapes Land Use. *Journal Of The American Planning Association*, 25(2), 73-85

Hess, Paul M. (1997) *Measures Of Connectivity* [Streets: Old Paradigm, New

Investment]. Internet Resource.

Hess, Paul, Anne Moudon, Mary Snyder, And Kiril Stanilov. (1999). Site Design And Pedestrian Travel. *Transportation Research Record* 1674: 9-19.

Leyden, K. M. (2003). Social capital and the built environment: the importance of walkable neighborhoods. American journal of public health, 93(9), 1546.

Mately, M., Goldman, L. M. And Fineman, B. J. (2001) Pedestrian Travel Potential In Northern New Jersey. *Transportation Research Record,* 1705, 1-8.

Mcginn P., K. Evenson, A. Herring, S. Huston, (2007) The Relationship Between Leisure, Walking, And Transportation Activity With The Natural Environment, *Health & Place*, Volume 13, Issue 3, Pages 588-602

McCormack, G., Shiell, A., Doyle-Baker, P., Friedenreich, C., Sandalack, B., & Giles-Corti, B. (2009). Testing the reliability of neighborhood-specific measures of physical activity among Canadian adults. Journal of physical activity & health, 6(3), 367.

McCormack, G., Spence, J., Berry, T., & Doyle-Baker, P. (2009). Does perceived behavioral control mediate the association between perceptions of neighborhood walkability and moderate-and vigorous-intensity leisure-time physical activity? Journal of physical activity & health, 6(5), 657.

Mehta, Vikas (2008) Walkable Streets: Pedestrian Behavior, Perceptions And Attitudes *,Journal Of Urbanism: International Research On Placemaking And Urban Sustainability*,1:3,217— 245

Messenger, T. And Ewing, R. (1996) Transit-Oriented Development In The Sunbelt. *Transportation Research Record,* 1552, 145-152.

Moudon, A. V., Lee, C., Cheadle, A. D., Garvin, C., Schmid, T. L., & Weathers, R. D. (2007). Attributes of environments supporting walking. American journal of health promotion: AJHP, 21(5), 448.

Porta, S., & Renne, J. L. (2005). Linking urban design to sustainability: formal indicators of social urban sustainability field research in Perth, Western Australia. Urban Design International, 10(1), 51-64

Randall T.A. And B.W. Baetz, (2001) Evaluating Pedestrian Connectivity For Suburban Sustainability, *J. Urban Plan D-ASCE* **127** , Pp. 1–15

Rane, R., & Daniere, A. (1996). Measuring Access To Basic Services In Global Cities. *Journal Of The American Planning Association*, *62*(2), 203. Retrieved From Masterfile Premier Database.

Reilly, M. K. (2002) The Influence Of Urban Form And Land Use On Mode Choice - Evidence From The 1996 Bay Area Travel Survey. *Presented At The Annual Meeting Of The Transportation Research Board,* Washington, DC.

Sallis J.F., M.F. Johnson, K.J. Calfas, S. Caparosa And J.F. Nicholds, (1997) Assessing Perceived Physical Environmental Variables That May Influence Physical Activity, *Res. Q. Exerc. Sport* **68** , Pp. 345–351

Schlossberg, M., Et Al. (2007) *How Far, By Which Route, And Why? A Spatial Analysis Of Pedestrian Preference*, In MTI Report 06-06, Mineta Transportation Institute &

College Of Business, San José State University, San José, CA

Sergio Porta And John Luciano Renne (2005) Linking Urban Design To Sustainability: Formal Indicators Of Social Urban Sustainability Field Research In Perth, Western Australia Urban Design *International* 10, 51–64.

Song, Y. (2003) *Impacts Of Urban Growth Management On Urban Form: A Comparative Study Of Portland, Oregon, Orange County, Florida And Montgomery County, Maryland*. National Center For Smart Growth Research And Education, University Of Maryland.

Tal, G. And S. Handy. (2008) Children’s Biking For Non-School Purposes: Getting To Soccer Games In Davis, CA. *Transportation Research Record*, No. 2074, Pp. 40-45.

U.S. Department Of Health And Human Services. (1996) *Physical Activity And Health*, A Report Of The Surgeon General. Atlanta,.

Van Dyck, D., Deforche, B., Cardon, G., & De Bourdeaudhuij, I. (2009). Neighbourhood walkability and its particular importance for adults with a preference for passive transport. Health & place, 15(2), 496-504.