

THE UNIVERSITY OF ILLINOIS – URBANA-CHAMPAIGN

# Connectivity and Accessibility of UIUC Campus Bike Paths

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Quantitative Measures for Bicycle Infrastructure

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## Introduction

University campuses are spatially complicated places. This complexity increases with size, and as the campus gets bigger, efficient movement from place to place matters more and more. Combined with societal pressure for responsible energy use and increased daily physical activity, city planners and public health officials have begun to focus on promoting “active transport” methods for moving from place to place within the built environment.<sup>1</sup> Active transport generally includes walking or cycling between destinations, and while scholars have generally focused on the “walkability” of cities, cyclists and “bikeable” cities have gone largely unstudied. This paper seeks to begin to fill that absence by assessing the connectivity and accessibility of the bicycle network of the University of Illinois – Urbana-Champaign (UIUC) main campus. Network analysis techniques and spatial statistics are used to analyze how proposed longitudinal improvement to the network will affect cyclists’ ability to travel from place to place. Using novel GIS-based methods, this study augments the existing academic and planning studies on the campus bicycle facilities as well as the wider body of transportation planning literature to answer three questions:

1. What is the current accessibility and connectivity of UIUC campus bicycle pathways?
2. What will be the accessibility and connectivity of the planned campus bicycle pathways?
3. What would be the accessibility and connectivity of the UIUC campus absent a dedicated bicycle network?

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<sup>1</sup> Frumkin et al, *Urban Sprawl and Public Health: Designing Planning and Building for Health Communities* (Island Press: Washington DC, 2004).

## Background: Why the University Campus

In general, people use three modes of transport to get from place to place in urban spaces. They use wheeled motorized modes such as cars, wheeled non-motorized modes such as bicycles, and they use their feet. Depending on where you are, the environment may lend itself better or emphasize certain modes of transport over others, and this can often be traced to a transportation planning decision based on the dominant mode at the time. In most places in the United States, this mode is the automobile.<sup>2</sup> Movement in the United States broadly depends on an individual's access to a car, and this has had implications which will not be much discussed here. However, in spite of the dominance of cars, many places purposefully emphasize non-motorized transport because vehicular travel is either inconvenient or impractical. This seems to occur in locations where destinations and users co-exist in ultra-high density settings, and the area enclosing these destinations is small.<sup>3</sup>

Many university campuses fit this description well, particularly large ones which are themselves the focal point of the surrounding built environment. They have a large number of users moving between destinations which are very close together, and as a result automobiles are neither efficient nor practical for transportation: the distances are too short to warrant driving between destinations, it would be impossible to store the number of cars necessary inside the small enclosed area without the users having to move by other means from the parking facilities to their destinations anyway, and managing the amount of generated traffic would be very difficult. These problems only increase with scale, and large universities such as UIUC are therefore ideal locations for non-motorized traffic.

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<sup>2</sup> Michael Southworth, "Designing the Walkable City," *Journal of Urban Planning and Development* 131, no. 4 (December 2005): 1–12, doi:10.1061/\_ASCE\_0733-9488\_2005\_131:4\_246\_.

<sup>3</sup> Ibid.

The university setting provides a unique look into a pedestrian-heavy transportation environment without the same level of spatial competition from motorized transport as in most cities, and therefore is well-suited for researching improvements to non-motorized transport networks. UIUC is an excellent case study because a great deal of effort and study has gone into redesigning and improving the bicycle infrastructure both on campus as well as in the surrounding municipalities to adequately serve its large bicycling community. UIUC's population statistics published for the 2012-13 academic year show that 44,520 students, 2,548 faculty, and 7,801 staff populate its campus; without question a huge number of people.<sup>4</sup> We cannot estimate the current number of bicycles ridden on campus because registration is neither required nor promoted, but the community recognizes that the number of riders is large and their presence is a noticeable part of the transportation culture on campus.<sup>5</sup> The 2013 Draft Campus Bike Plan notes that "University policies currently prioritize walking, bicycling, and transit over automobiles in the core campus area."<sup>6</sup> UIUC is an example of a place where bicycles are not only prominent but their use is structurally encouraged, and therefore a well-connected network is a must if the needs of this community are to be met.

Several studies commissioned and completed by the University, the Champaign-Urbana Mass-Transit District (CUMTD), and the cities of Champaign and Urbana have addressed a comprehensive array of important design, safety, and policy issues regarding campus cycling and cycleways. For instance, the Draft Campus Bike Plan and the CUMTD study completed by TY Lin both suggest physical improvements which will improve how pedestrians, cars, and cyclists navigate street intersections which are currently confusing and, therefore, unsafe. One example includes the

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<sup>4</sup> "Facts 2012-13: Illinois By The Numbers" (University of Illinois Department of Public Affairs, 2013), <http://illinois.edu/about/overview/facts/facts.html>.

<sup>5</sup> UIUC Facilities and Services Transportation Demand Management Department, "Draft Campus Bike Plan," May 2013.

<sup>6</sup> Ibid.

intersection at Green and Wright Streets where it is entirely unclear whether bicyclists should obey the traffic lights or the pedestrian walk signals, and neither motorists nor cyclists know to whom they should yield in the case of a green light. The Draft Plan also proposes policy improvements regarding the funding of maintenance of bike paths, noting that the funding as well as the repair of the current bicycle network is poor. Both studies also mention improvements in connectivity and accessibility, but they do not include a quantitative method for verifying that changes to the network in fact improve connectivity and accessibility between locations on campus.<sup>7</sup> In fact, it is not altogether clear from reading these studies what they are referring to when referencing “accessibility” and “connectivity,” since this terminology is used often in relation to all manner of networks.

The results of these studies are invaluable and provide answers to many questions about improving the experience and safety of bicyclists as well as those with whom they share the space. However, in order to determine if a location is truly “bicycle-friendly” there must be a way to measure if the network provides connectivity outcomes similar to those of other non-motorized transportation networks, and also if these outcomes are better than before implementing changes. This gap in the research methodology of the transport studies also occurs in academic planning literature on similar topics, and this paper seeks to show how measures of geometric connectivity and accessibility can serve as powerful tools in measuring the success of a transport network, particularly for bicycles but also for any active transport mode.

As we mentioned, terminology is important, and so before continuing let us define and explain what accessibility and connectivity mean in the context of this paper. Rodrigue, Comtois,

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<sup>7</sup> UIUC Facilities and Services Transportation Demand Management Department, “Draft Campus Bike Plan”; TY Lin International, *University District Bike/Transit Safety Study*; Clark-Dietz, Inc., *Campus Area Transportation Study Phase II Executive Summary*, Transportation Study (Champaign County Illinois: University of Illinois - Champaign-Urbana, July 2005).

and Slack (2006)'s book *The Geography of Transport Systems* outlines in detail the analytical aspects of transportation geography from many different angles and using many different methods. While I will give a brief overview of the concepts here, their book provides greater depth and those interested should refer to it for more information. The quantitative methods used in this analysis are explained in the Methodology section.

Rodrigue, Comtois, and Slack define accessibility as “the measure of the capacity of a location to be reached by, or to reach different locations.”<sup>8</sup> They go on to describe how location and distance make for unequal accessibility between places, and that connectivity is the level to which the locations are linked to each other. Understanding the connectivity of a network allows us to understand the accessibility of that network's locations. Transportation networks exist because they connect locations, and therefore a better transportation network allows more people to travel to more places more easily. Dill commented that “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.”<sup>9</sup>

Quantifying accessibility and connectivity for a network allows us to understand its structure because we can examine these characteristics in relation to each other. This information is especially useful when comparing two networks or the same network over time, and the theoretical basis for this will be explained in later sections. These definitions of accessibility and connectivity apply to all references to accessibility and connectivity throughout this paper.

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<sup>8</sup> Jean-Paul Rodrigue, Claude Comtois, and Brian Slack, “Transportation and Geography,” in *The Geography of Transport Systems* (New York: Routledge, 2006), 1–37.

<sup>9</sup> Jennifer Dill, “Measuring Network Connectivity for Bicycling and Walking.”

## Background Literature

In order to examine “bikeability” and specifically connectivity and accessibility in the literature, I found two groups of information: academic publications which research and evaluate aspects of active transport in the modern city, and planning studies commissioned by municipalities and completed by practitioners. I will discuss each in turn to establish a picture of the state of bikeability analysis, and the role or non-role of connectivity and accessibility therein.

### Academic Writings

There are two main angles from which academics write about walkable and bikeable cities. The first addresses the public health concerns which 1) arise from an automobile-centric society and 2) can be ameliorated by increased active transport. Trapp et al (2011) studied active school transport (AST) among schoolchildren in Perth, Australia examining how AST is influenced by several factors from individual to environmental scales. They noted that surveys in the US and the UK indicated sharp declines in AST, and found that “[s]chool proximity, street network connectivity and traffic exposure in school neighborhoods was associated with boys (but not girls) cycling to school.”<sup>10</sup> While the report focuses on the reasons why schoolchildren do or do not ride bicycles to school, the authors operate from a premise that cycling allows AST from greater distances and that, therefore, the known health benefits of cycling can be realized by more people if certain criteria are met. The authors point out early on that research on active transport focuses primarily on walking, and that research is absent about the correlates of cycling to school.<sup>11</sup> However, these conclusions and findings can easily be extended beyond the focus on schoolchildren to include anyone traveling

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<sup>10</sup> Georgina S A Trapp et al., “On Your Bike! A Cross-Sectional Study of the Individual, Social and Environmental Correlates of Cycling to School,” *International Journal of Behavioral Nutrition and Physical Activity* 8, no. 123 (2011), <http://www.ijbnpa.org/content/8/1/123>.

<sup>11</sup> Ibid.

to/from work and leisure because if we change the demographic and the location, the ultimate outcome remains the same: people benefit from actively transporting themselves to where they want to go, and can do so to greater effect from greater distances by bicycle. We can then suggest that changes in aspects of connectivity will further improve the network's ability to serve users, and therefore also have serious positive implications for public health.<sup>12</sup>

The second major theme on this subject comes from academic urban planning and focuses on improving the functionality of urban design for non-motorized transport. These writings posit that we live in a moment of evolution where, as a result of consumer pressures on development, cities are transforming to de-emphasize the automobile. The consumer demands have been matched and perhaps reinforced in the United States by policies enacted at the federal level, including the Intermodal Surface Efficiency Act 1991 and the Transportation Equity Act for the 21<sup>st</sup> Century 1998. These legitimize non-motorized transport as not only a recreational activity but also as a means to travel from place to place. However, many studies such as Southworth's paper "Designing the Walkable City" also admit that the retrofitting of cities designed for cars may prove very difficult.<sup>13</sup>

Southworth's paper exemplifies the disproportionate emphasis in the literature on "walkability" over other modes of non-motorized transport. While his paper mentions that pedestrians and cyclists in cities share many concerns and considerations from a planning standpoint, he purposefully excludes bicycles from his analysis.<sup>14</sup> However, he lays out six criteria for a walkable city which encompass the needs and demands of both pedestrians and cyclists:

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<sup>12</sup> David Berrigan, Linda W. Pickle, and Jennifer Dill, "Associations between Street Connectivity and Active Transportation," *International Journal of Health Geographics* 9, no. 22 (2010): 1–18.

<sup>13</sup> Michael Southworth, "Designing the Walkable City," 1.

<sup>14</sup> Ibid.

- “Connectivity of path network, both locally and in the larger urban setting;
- “Linkage with other modes: bus, streetcar, subway, train;
- “Fine grained and varied land use patterns, especially for local serving uses;
- “Safety, both from traffic and social crime;
- “Quality of path, including width, paving, landscaping, signing, and lighting; and
- “Path context, including street design, visual interest of the built environment, transparency, spatial definition, landscape, and overall explorability.”<sup>15</sup>

In spite of Southworth’s focus on walkability and his impression that cyclists’ needs are fundamentally different from those of pedestrians, each of these criteria are as important for cyclists as for pedestrians. Moreover, the focus by professional planning reports on the latter five of these points specifically *for* cyclists indicates that they are in fact quite pertinent to developing a bike-friendly environment, as we will discuss later.

Several articles explore connectivity within the walkable city context. Tal and Handy (2012) examined how the physical layout of the pedestrian network affects connectivity and accessibility in a “robust pedestrian network.” Using similar methods to my own study, they concluded that walkability increases with connectivity and accessibility, and they imply that such a network ought to be at least as extensive as the street-network, if not moreso.<sup>16</sup> Tal and Handy, along with Dill (2004), Berrigan et al (2010), and Winters et al (2013) all agree that a successful non-motorized transport network not only extends to many places within a given area, but also allows users to move among

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<sup>15</sup> Ibid, 4-9.

<sup>16</sup> Gil Tal and Susan Handy, “Measuring Nonmotorized Accessibility and Connectivity in a Robust Pedestrian Network,” *Journal of the Transportation Research Board* 2299 (2012): 48–56, doi:10.3141/2299-06.

these places with ease.<sup>17</sup> This echoes Southworth's criteria, and recognizes the value of quantitative measurement as a means for validating the effectiveness of a network.

Furthermore, Winters et al (2013) note a marked influence of infrastructure on active transport and an abundance of spatial data about urban transportation networks (including maps and GIS data), but they also note an absence of its use in evaluating bicycle networks and bikeability. Their objective to “build a planning tool that identifies areas more conducive and less conducive for cycling” attempts to make use of abundant urban GIS data, and explicitly assumes that increased connectivity and accessibility lead to more bikeable networks.<sup>18</sup> They conclude that mapping bikeability, however you do it, accomplishes two things. First, planners are able to visually determine which places are evidentially in need of improvement, particularly in relation to locations of interest. Second, mapping provides a visual aid for users, which makes route-planning simpler and can potentially prevent conflicting route-use with pedestrians and cars.<sup>19</sup>

## Planning Documents

These two issues – locating problem areas and preventing conflict between users – are where planners take over. Many large cities including Portland, Oregon and Vancouver, British Columbia as well as smaller townships have incorporated bicycle transport into their master plan documents. The Village of North Aurora (Illinois) Non-Motorized Transportation Plan cites the same motivations as the academics of both aforementioned disciplines for improving active transport facilities: the health benefits of cycling and the shift away from automobile dependence.<sup>20</sup> Like Trapp

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<sup>17</sup> Jennifer Dill, “Measuring Network Connectivity for Bicycling and Walking” (presented at the Transportation Research Board 2004 Annual Meeting, TRB, 2004), <http://reconnectingamerica.org/assets/Uploads/TRB2004-001550.pdf>; David Berrigan, Linda W. Pickle, and Jennifer Dill, “Associations between Street Connectivity and Active Transportation”; Meghan Winters et al., “Mapping Bikeability: A Spatial Tool to Support Sustainable Travel,” *Environment and Planning B: Planning and Design* 40 (2013): 865–83, doi:10.1068/b38185.

<sup>18</sup> Meghan Winters et al., “Mapping Bikeability: A Spatial Tool to Support Sustainable Travel.”

<sup>19</sup> Ibid.

<sup>20</sup> League of Illinois Bicyclists, *Village of North Aurora Non-Motorized Transportation Plan*, June 2001.

et al, they indicate that safety and perceptions of safety matter a great deal in the choice to bicycle instead of drive; and like Southworth they agree on many of the same fundamental needs for the network so that it will serve its users.

The League of Illinois Bicyclists (LIB) prepared the North Aurora plan, and along with the transportation plans of the Oregon Department of Transportation (ODOT), the Champaign-Urbana Mass Transit District (CUMTD), and the UIUC Draft Campus Bike Plan, we find a common theme among these documents, namely that they all focus on aspects of bicycling as it relates to other forms of transport, particularly vehicular traffic. The document “The Road Network is the Bicycle Network: Bicycle Suitability Measures for Roadways and Sidepaths,” jointly compiled by the LIB and the Chicago Area Transportation Study, defines several mathematical “level of service” indices which determine if a road-based cycleway or sidepath effectively serves the user. The indices focus on cyclist’s safety and evaluate the risks cyclists face from motorized traffic, and as a result contain at least one variable related to motorized vehicles and/or vehicular infrastructure.<sup>21</sup> They account for things such as speed limits, width of the lane and shoulder, and traffic volume, and the output value can be used to determine if the roadside space is sufficient for a cycleway. These analytical methods are included in most bicycle master plans, and they are very useful for improving stated goals for improvements in safety because they attempt to minimize risk from motorists.<sup>22</sup> However, safety is only one part of determining if cycleways adequately serve their users. The ability and ease to reach destinations is also important.

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<sup>21</sup> Ed Barsotti and Gin Kilgore, *The Road Network Is the Bicycle Network: Bicycle Suitability Measures for Roadways and Sidepaths* (League of Illinois Bicyclists and the Chicago Area Transportation Study, 2001).

<sup>22</sup> UIUC Facilities and Services Transportation Demand Management Department, “Draft Campus Bike Plan”; American Association of State Highway and Transportation Officials, “Draft AASHTO Guide for the Planning, Design, and Operation of Bicycle Facilities,” February 2010; Oregon Department of Transportation, *Facility Design Standards* (Oregon Department of Transportation, 1995); League of Illinois Bicyclists, *Village of North Aurora Non-Motorized Transportation Plan*; Ed Barsotti and Gin Kilgore, *The Road Network Is the Bicycle Network: Bicycle Suitability Measures for Roadways and Sidepaths*; TY Lin International, *University District Bike/Transit Safety Study*.

Unlike these metrics which focus on safety and risks from motorized transport, connectivity and accessibility methods measure how well the network performs for enabling movement of people from place to place compared to an ideal network. In effect it compares an actual network to the ideal, maximally connected and efficient network.<sup>23</sup> These methods can be a powerful tool for planners, especially when comparing existing infrastructure to potential future projects because improvement can be measured with little uncertainty, and can easily be modeled using GIS software which may already be employed to visualize transport plans. “Level of service” is a broad concept, and so we must also consider the bicyclist in isolation and determine if, in the absence of cars and pedestrians, their network satisfactorily conveys them to destinations. In other words, we are looking to see whether the cycleways insulate riders from vehicular and pedestrian traffic, or if the riders must leave the network – and therefore expose themselves to the danger which planning seeks to mitigate – to arrive at their destinations. If the latter is true, then the plan has not done its job.

This forms the foundation of my research on UIUC bike paths. I evaluate the accessibility and connectivity of the current bicycle network and assess whether or not changes to the network improve these important measures. I also examine accessibility and connectivity of the motorized transport network to provide a benchmark for comparison. A comprehensive discussion of the methods that were used follows in the next sections.

## **Methodology**

### **Connectivity and Accessibility Measures**

Accessibility and connectivity are measured using a branch of mathematics known as graph theory. Using graph theory, we are able to convert real transportation networks into planar networks

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<sup>23</sup> Jennifer Dill, “Measuring Network Connectivity for Bicycling and Walking.”

made up of vertices and edges (or more simply nodes and links). First we create a distance matrix of the network in question, which contains the distances between each and every location on the network. An example matrix is shown below. Note that for purposes of this study, the distance values used represent the shortest path between locations.

	Location 1	Location 2	Location 3
Location 1	0	10 miles	5.2 miles
Location 2	10 miles	0	2 miles
Location 3	5.2 miles	2 miles	0

TABLE 1: EXAMPLE DISTANCE MATRIX

Each location represents a node, and the paths between them are edges or links. Once we know the number of nodes and the distances between them (the length of the edges), we can calculate several indices developed by graph theorists which indicate the accessibility and connectivity of the network. I chose alpha and gamma, the link-node-ratio (LNR), and the valued graph or simply accessibility index for studying the UIUC bicycle network.

The alpha index measures connectivity as a ratio of the number of actual circuits in a network to the theoretical maximum number of circuits. Straight-line networks have a value of 0 and fully redundant networks have a value of 1; higher values indicate a more connected network. Alpha is expressed below, where  $l$  is the number of links and  $n$  is the number of nodes:<sup>24</sup>

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<sup>24</sup> Ibid.

$$\alpha = \frac{l - n + 1}{2(n) - 5}$$

The second index, Gamma, measures the number of edges in a network compared to the maximum possible number of edges. A higher value of Gamma indicates a more connected network where there are many direct connections between nodes. Gamma is only calculable for planar (two-dimensional) networks and is one of the best analytical measures because it indicates whether or not locations on the network are as connected as they could possibly be.<sup>25</sup> Gamma is expressed below, where once again  $l$  is the number of links and  $n$  is the number of nodes:

$$\gamma = \frac{l}{3(n - 2)}$$

The link-node ratio (LNR) is the most intuitive index. It is calculated simply by dividing the number of links by the number of nodes, and it gives a value between 0 (no links) and 2.5 (a perfect grid). Dill cites Ewing (1996) and several city plans which have adopted the LNR as a standard for evaluating for evaluating network connectivity. These experts agree that a value of 1.4 is a good goal for urban transportation networks.<sup>26</sup>

The valued graph or simple accessibility index is also very useful. It focuses on the distance or travel time needed to reach all nodes in a network from a particular node. Accessibility can be measured for each node in a network, and the nodal accessibility values can be summed or averaged to measure overall accessibility. To compute accessibility for each node we sum the row in the distance matrix for that node. Since we calculated the distances using the shortest path, this sum yields the minimum distance required to travel between that row-location and all other locations on

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<sup>25</sup> Ibid.

<sup>26</sup> Ibid.

the network, and allows us to compare between locations. Lower values indicate shorter total travel distances, and therefore greater accessibility.

## **Methods and Data**

The purpose of this study is to assess the accessibility and connectivity of existing, proposed, and control bicycle networks on the UIUC campus. I selected these three instances and sought to compare them using the methods above to answer what I believe are the same two fundamental questions undertaken in the Draft Plan, as well as a control question:

1. What is the current accessibility and connectivity of campus bicycle pathways?
2. What will be the accessibility and connectivity of the planned campus bicycle pathways?
3. What would be the accessibility and connectivity of the UIUC campus absent a dedicated bicycle network?

The first two questions supplement any existing transportation planning study and plan; as I mentioned above, the current plan and accompanying study address many concerns but do not specifically evaluate the success of either the existing or the proposed network based on geometric connectivity or accessibility. The calculations used to answer these questions will tell us the individual accessibility and connectivity of each network, and will also indicate the extent to which the planned network improves on the existing one.

The third question is also relevant, because we must remember that the purpose of the UIUC bicycle infrastructure is essentially to insulate and protect cyclists, pedestrians, and motorists from potentially dangerous conflict with one another while simultaneously providing direct routes to locations on campus. This question controls for the very existence of a bicycle only network, and can be answered using an analysis of the street network. If the accessibility and connectivity values

of the bicycle network – existing or planned – are equal or nearly equal to those of the streets, the bicycle network is providing what may be called symmetrical service. This means that cyclists have the same freedom of movement between destinations on a network while always using dedicated cycleways. Combined with the implementation of safety and user-friendliness measures outlined and assessed in the transportation plans and studies, a symmetrical network is a successful network.

The indices mentioned above all first require a way to obtain the number of links, the number of nodes, and the shortest distances between nodes. While this can be done using maps and a ruler, GIS software makes this process simple and efficient. UIUC's Facilities and Services Transportation Demand Management (hereafter referred to as F&S) team kindly supplied me with vector GIS data for the UIUC campus area, including street centerlines, the existing campus bicycle pathways, as well as the planned bicycle pathways as outlined in the Draft Campus Bike Plan.<sup>27</sup> Bearing in mind that I needed to create a distance matrix and that I would be attempting to essentially augment the work of the Campus Bike Plan, I selected a quadrangle of campus bounded by University Avenue, Kirby Drive/Florida Avenue, Lincoln Avenue, and First Street. I processed the F&S GIS data using ESRI's ArcGIS platform and performed a clip operation using a rectangular polygon created from these four road features. This study area also contains nine high-traffic locations of interest to the University, including all five University residence halls (I considered the Ikenberry Commons or "Six Pack" to be one location):

- Ikenberry Commons
- Allen Hall – Lincoln Avenue Residence Hall
- Busey-Evans Hall
- Florida/Pennsylvania Avenue Residence Halls (FAR/PAR)

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<sup>27</sup> UIUC Facilities and Services Transportation Demand Management Department, "Draft Campus Bike Plan."

- Illinois Street Residence Hall (ISR)
- College of ACES Library
- Grainger Engineering Library
- Undergraduate Library
- Illini Union

These nine locations would be used later to develop distance matrices, analyze the distances between major campus locations, and calculate the simple accessibility indices.

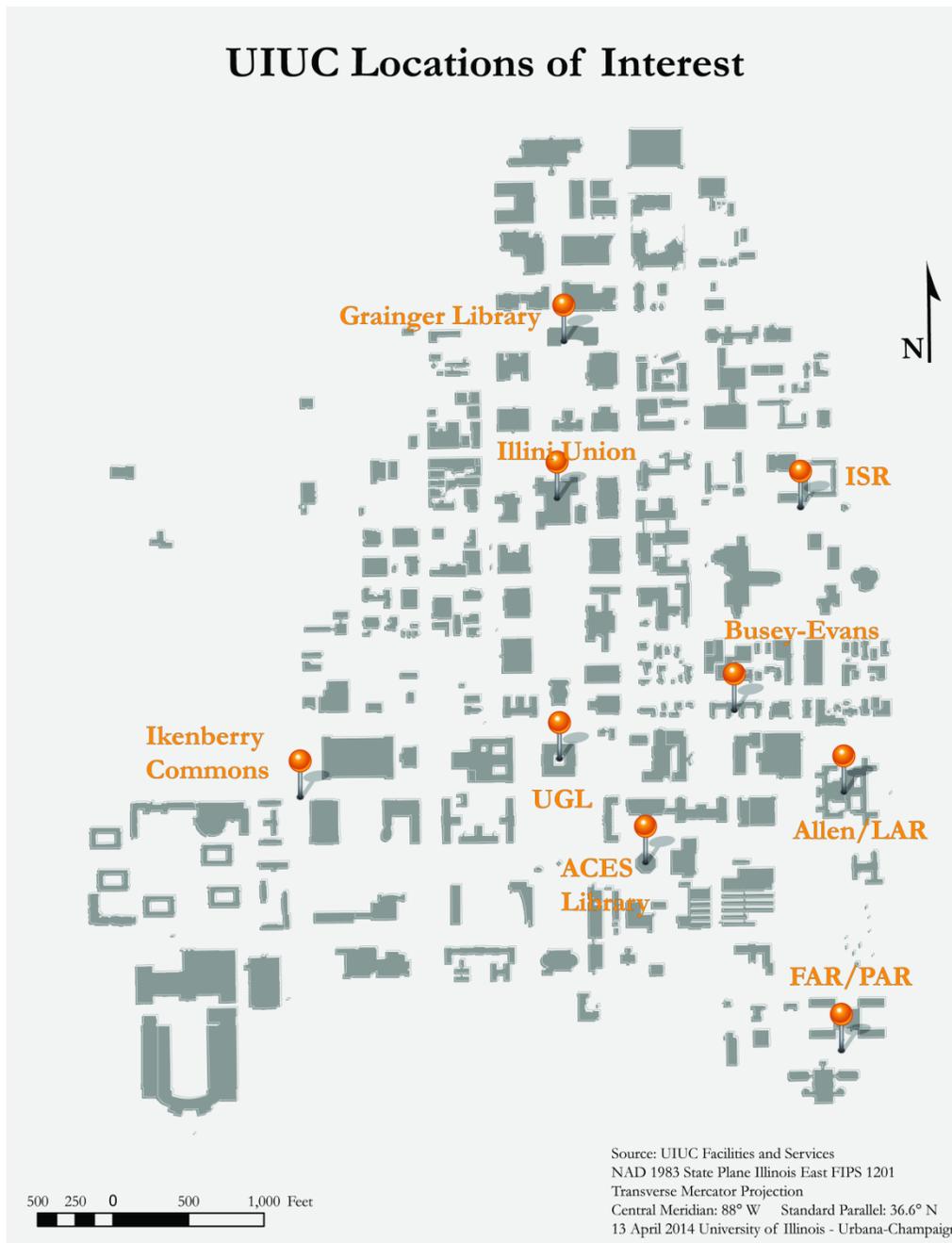


FIGURE 1: UIUC LOCATIONS OF INTEREST

I organized my data into a geodatabase using three feature datasets: one for existing pathways, one for planned pathways, and one for streets. Into each of these I placed the respective clipped line feature class. I found the GIS data to be very “dirty” for my needs. A particular problem was that many line features which appeared to be single seamless paths actually consisted of several

individual features. I cleaned them using several tools native to ArcMap, first using the editing tools to locate and merge lines which segmented between intersections. I then ran the Check Geometry and Fix Geometry tools to check for errors, and planarized each feature class. After checking that these maps were identical to the ones in the Draft Campus Bike Plan, I created a turn feature class for each dataset, and then used the Create Network Dataset wizard to create a network dataset for each. Having processed my data as I did, I selected that connectivity<sup>28</sup> be assessed at endpoints, turns modeled, and that the cost evaluator be the distance along each line segment.

Upon the creation of my network datasets, I ran a row count of the number of intersections and the number of links for each. Each intersection was considered a node of the network, and each link as an edge. The numbers of edges and nodes were used in my index value calculations, which I executed using Microsoft Excel. Then, using the Network Analyst extension, I placed origin-destination (OD) markers on the network at the nine locations of interest mentioned above, and ArcMap calculated the shortest distance travel between locations. ArcMap's Network Analyst requires manually placing separate origin and destination markers at each location, so there is a slight uncertainty to the calculations due to the accuracy of the marker placement. That said, because I had both an origin and a destination at each point, ArcMap's generated origin-destination (OD) matrix calculated that distance as well; my location error ranges from 0-10 feet. Since the spatial information for each feature dataset was identical, I exported the OD locations as a layer and reused them each time I performed distance calculations. The OD solver calculates the shortest distance path between all origins and all destinations placed on the map. This generates a table, which I transcribed into a distance matrix in Excel and from there calculated the simple accessibility indices.

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<sup>28</sup> It should be noted here that "connectivity" in this case is an ESRI term which means that the line feature is a part of, or connected, to the network which the wizard is creating. While this is within the definition described above, the wizard does not calculate connectivity in a spatial-analytical context.

## Results and Discussion

### Connectivity

	Existing Pathways		Planned Pathways		Streets	
Nodes, Edges	61	80	76	122	159	279
Link-Node Ratio	1.31		1.61*		1.75*	
Alpha	0.17		0.32		0.39	
Gamma	0.45		0.55		0.59	

TABLE 2: CONNECTIVITY RESULTS FOR EXISTING, PLANNED, AND STREET PATHWAYS

\* Indicates meeting or exceeding Ewing's threshold

The existing bicycle network has 61 nodes and 80 edges, yielding an LNR of 1.31. This value is somewhat below Ewing's threshold of 1.4, but Dill (citing Handy et al 2006) notes that several cities have adopted a standard LNR of 1.2 as well.<sup>29</sup> Notably, the existing bicycle network meets what has been accepted as an appropriate ratio of locations and links between them for planning purposes. While the transportation studies of campus bicycle infrastructure criticize the quality and safety of the current network, the LNR value tells us that the original planners created a relatively well-connected network, probably before such planning standards were employed. We can therefore analytically conclude that the existing network is adequate in this regard.

The planned bicycle network at the time of writing will have 76 nodes and 122 edges, which computes a 1.61 LNR. While not surprising that the ratio value increased, the value is well above Ewing's recommended 1.4. This tells us that the planned network is increasingly grid-like, and

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<sup>29</sup> Jennifer Dill, "Measuring Network Connectivity for Bicycling and Walking."

superbly so. The individual node and edge counts also tell us that, in comparison to the existing network, the planned network goes to more individual locations (15 more nodes) and there are more ways to get between nodes (42 more edges). At this point it may be possible to conclude that increasing the LNR could be impractical based on the spatial configuration of the built environment on campus, though additional and sophisticated research would be required to answer that question. Regardless, we may state that provided these paths receive proper care and maintenance, the planned pathways exceed current planning conventions in this regard.

We can now engage the analytical power of the alpha and gamma indices, which are useful to compare differences in overall connectivity among networks. The existing network has an alpha index value of 0.17, indicating that 17% of nodes on the network are on a circuit pathway; the alpha for the planned pathways is twice as large at 0.32. This significant improvement in alpha means two things. First, users on the planned network will be able to return to their starting location from nearly one-third of locations on the network without backtracking first, meaning that travel will be more direct. Secondly, the plan nearly doubles the circuitry of the network, so users will be twice as likely to be in a location which is on a circuit pathway. The consequences are significant because from any given starting location, users have a 32% chance that they can travel straight to their next destination rather than having to retrace their path or travel through other nodes.

The gamma value for the existing network is 0.45, meaning that 45% of nodes are linked to their maximum potential. Recalling that the gamma index compares the number of links relative to the maximum possible number of links and that a value of 1 is highly unlikely in real-world transportation networks, the gamma value for the existing network is moderately high. However, the planned pathways have a gamma value of 0.55, indicating a 10% increase over the existing pathways. This increase means that users have 10% more potential route options in the planned network

compared to the existing one. On its own, this may not appear to mean much, but if we recall that the purpose of bicycle networks is to insulate cyclists and prevent conflicts between different modes of transport, having a large number of route choices is vital to ensuring that cyclists can protect themselves and others while also getting to their destination using the shortest path. We can therefore conclude that any improvement measured using the gamma index is worthwhile, and the increase as a result of the Draft Campus Bike Plan should be considered beneficial.

To provide a benchmark for evaluating the improvements in connectivity generated by the planned network, I calculated the same indices to describe the current street network in the study area. This allows us to conclude whether or not the bicycle network provides a symmetrical outcome to a circumstance where there were no bicycle paths at all. The street network around main campus has 159 nodes and 279 edges, an LNR of 1.75, an alpha of 0.39, and a gamma of 0.59. This means that the street network has nearly 100 more nodes and 157 more links between them, has 14% more circuits, and is 4% more connected than the planned network. The LNR and index values for the street network are very high but notably the planned network values are only slightly less, particularly the gamma index.

There are several things we should keep in mind as we compare the street data to the bicycle network. Since the bicycle network is not a perfect grid and has to traverse a primarily pedestrian environment, the results tell us that the planned network is really well connected. The fact that the LNR, alpha, and gamma are so similar to the street network indicates a high degree of connectivity and therefore sophistication of the planned network. Furthermore, the planned network delivers transport outcomes nearly as well as the street network could if there were no bicycle paths on the UIUC campus, suggesting that in conjunction with good quality and navigability the planned

infrastructure will serve its users nearly as well as the street network with the added benefits of bicycle use as previously discussed..

We can also account for the higher values for the street network. The streets in Champaign-Urbana are very deliberately gridded. The math tells us that it is not a perfect grid, but it is for all practical purposes as close as we may get. Bicycle networks are by design supposed to get cyclists not only where cars go but also where cars cannot go, and this creates structural differences which are irreconcilable. As a result, we can expect the bicycle network to have a lower LNR, which it did. Moreover, we are studying the bicycle network of a university campus, not a city. A university campus has far fewer cars for many reasons which we discussed earlier, and so the built environment will not require as many locations be included on the bicycle network; it is perhaps judged sufficient to convey people to the Main Quad, but to pave a separate bicycle path to each building is not necessarily practical or even beneficial. Since there are less locations and paths on the network, we can expect the alpha and gamma index values to be slightly lower than the streets, which they were.

While we may at first glance conclude that the planned bicycle network is underserving its users because it does not perfectly match the street network, there are practical considerations which limit the need for perfect scores. In addition, the planned network performs very well, with index values close to those for the much larger and denser street network. This underscores the importance of using these quantitative methods alongside other qualitative design measures which ground these abstract numbers with the reality around the networks they describe.

## Accessibility

The valued graph or simple accessibility index is calculated by summing the rows of a distance matrix. The results of these calculations are shown below for each instance, respectively.

Accessibility Index (miles)	
4.47	Illini Union
3.78	Allen Hall
5.12	Illinois Street Residence Hall
3.68	Busey-Evans Hall
5.72	Ikenberry Commons
6.10	Florida/Pennsylvania Av. Residence Halls
3.74	Undergraduate Library
6.12	Grainger Library
3.60	ACES Library
5.29	<b>Average Accessibility</b>

TABLE 3: ACCESSIBILITY RESULTS FOR EXISTING PATHWAYS IN MILES

Table 3 shows the locations of interest and the accessibility index value in miles. We interpret these numbers in this case as the total one-way distance traveled if someone rode their bicycle from the listed location to all other locations. Larger numbers mean that someone traveling to that location will have to travel a greater distance to get there, therefore locations with a larger index value are considered less accessible than those with smaller values. Those familiar with the UIUC campus will not be surprised that Grainger Library and Florida/Pennsylvania Avenue Residence Halls (FAR/PAR) have very high values, since they are quite remote compared to the Undergraduate Library (UGL) which is very centrally located. (There are graph theory methods for

calculating geometric centrality, though they are not discussed here.) The important conclusions from these indices will, like gamma, come from comparisons to the other networks. However, it is important to note that the average accessibility for the existing network is about 5.3 miles

Planned Accessibility Index (miles)		Existing Index (miles)
2.81	Allen Hall	3.78
3.80	Illinois Street Residence Hall	5.12
2.62	Busey-Evans Hall	3.68
4.01	Ikenberry Commons	5.72
2.59	Undergraduate Library	3.74
4.56	Grainger Library	6.12
2.62	ACES Library	3.60
2.88	<b>Average Accessibility</b>	<b>4.54*</b>

TABLE 4: ACCESSIBILITY RESULTS FOR PLANNED PATHWAYS IN MILES

\*Average of the seven listed locations

As with the connectivity measures, the planned network generates major improvements in accessibility (Table 4). If we compare location for location, there are noticeable drops in index values and therefore distances required to travel to these locations: Illinois Street Residence Hall’s value decreased by 1.3 miles, and Ikenberry Commons’ by 1.7 miles. The average positively plummets, at nearly 2.4 miles less than the existing pathways. Thus, the distances cyclists have to travel to reach prominent destinations on campus are substantially shorter in the proposed network compared to the existing one.

However, the list of locations in the planned network is shorter by two, which leads to a major criticism of the Campus Bike Plan for cyclists. As shown in the figure below, FAR/PAR and the Illini Union effectively disappear from the network with the planned changes.

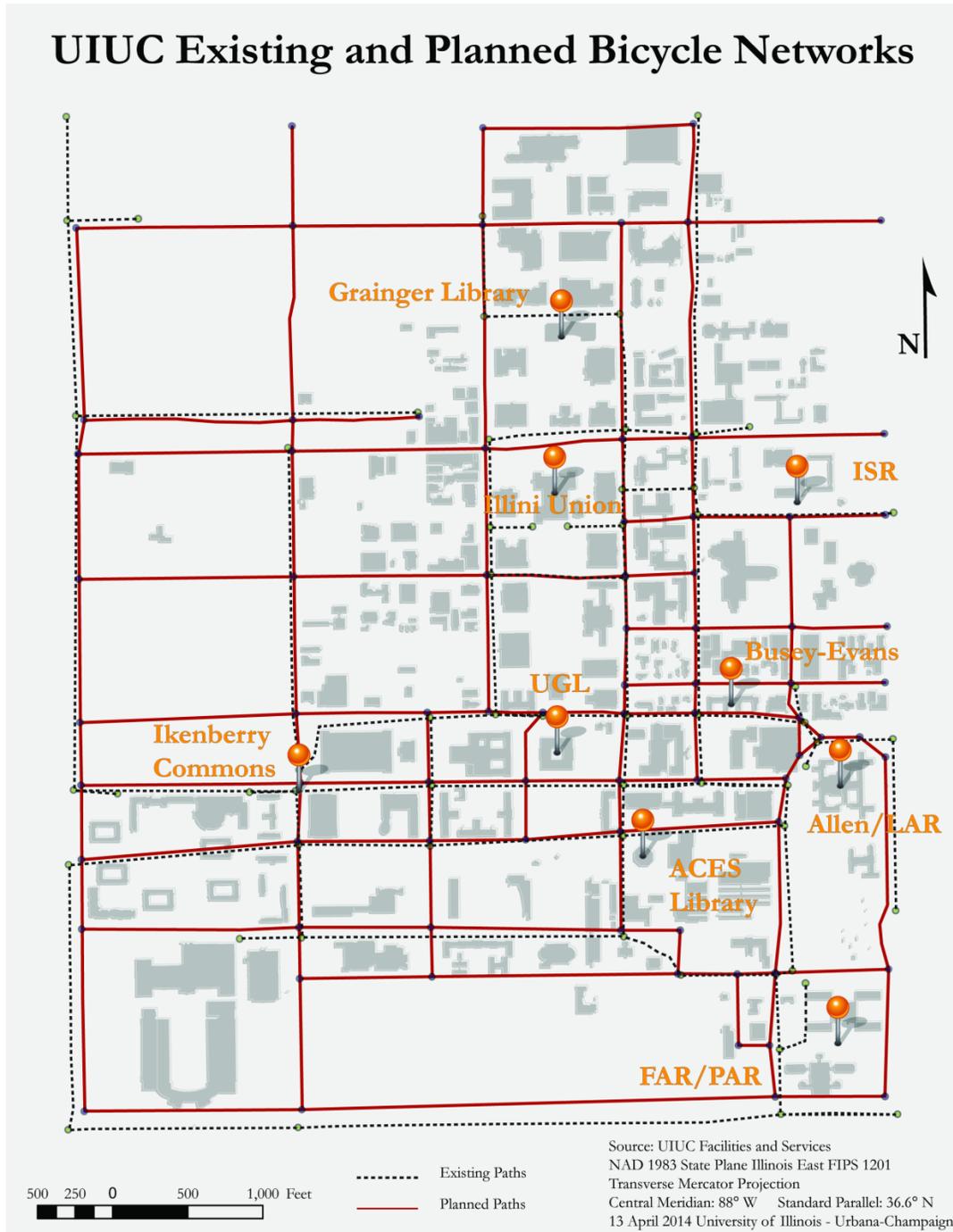


FIGURE 2: EXISTING AND PLANNED BICYCLE NETWORKS

Some may argue that removing these two nodes from the planned bicycle network is a semantic difference and that cyclists would not be prevented from reaching these destinations, but I think consistency is an important issue when designing a bicycle network. Cyclists are used to being able to reach the Union and FAR/PAR by bike pathways, and removing the two destinations may create unintended conflict. Planners have developed a foundational understanding that cyclists, pedestrians, and automobiles each deserve their own separate transportation infrastructure – the planning documents cited in this paper all emphasize minimizing conflict between cyclists and other modes of transportation as a matter of safety and organization using this understanding. This goal of separating the different modes of transport has great merit, and the Draft Campus Bike Plan and the North Aurora plan both cite crash statistics to make this point.<sup>30</sup> The consequence of this approach, however, is that planners cannot reasonably expect cyclists to use the cycling infrastructure as intended (meaning as often as possible so as to achieve the desired transportation outcomes) while simultaneously removing previously-accessible locations from the network. So, while the planned network average accessibility *index* is indeed substantially less (and therefore better) than that of the existing network, the actual accessibility is comparatively *lower* because the network has eliminated two key destinations including a student residence hall. This is a vexing problem which touches on issues of planning as well as environmental psychology, and certainly merits further research.

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<sup>30</sup> UIUC Facilities and Services Transportation Demand Management Department, “Draft Campus Bike Plan”; League of Illinois Bicyclists, *Village of North Aurora Non-Motorized Transportation Plan*.

Accessibility Index (miles)	
4.41	Illini Union
3.79	Allen Hall
5.06	Illinois Street Residence Hall
3.62	Busey-Evans Hall
5.67	Ikenberry Commons
6.10	FAR/PAR
3.68	Undergraduate Library
6.06	Grainger Library
3.29	ACES Library
<b>5.21</b>	<b>Average Accessibility (miles)</b>

TABLE 5: ACCESSIBILITY RESULTS FOR STREETS IN MILES

In light of the elimination of key nodes from the planned pathways, we cannot make a meaningful comparison between the planned network and the street control because destinations which are accessible by car are not by bicycle. However, if we compare the existing network to the streets, we find that the average accessibility of the existing network is eight-hundredths of a mile longer than the value for streets – so the two networks have very comparable levels of accessibility. This means that a cyclist must ride an average of 422.4 feet farther than a car must drive to reach all destinations. I cannot account for this discrepancy other than that a bicycle path must be unable to avoid a one-way street or a long block somewhere, and a user may have to travel further to get to a

destination. Still, it is noteworthy that the two networks offer such similar levels of accessibility between important campus locations.

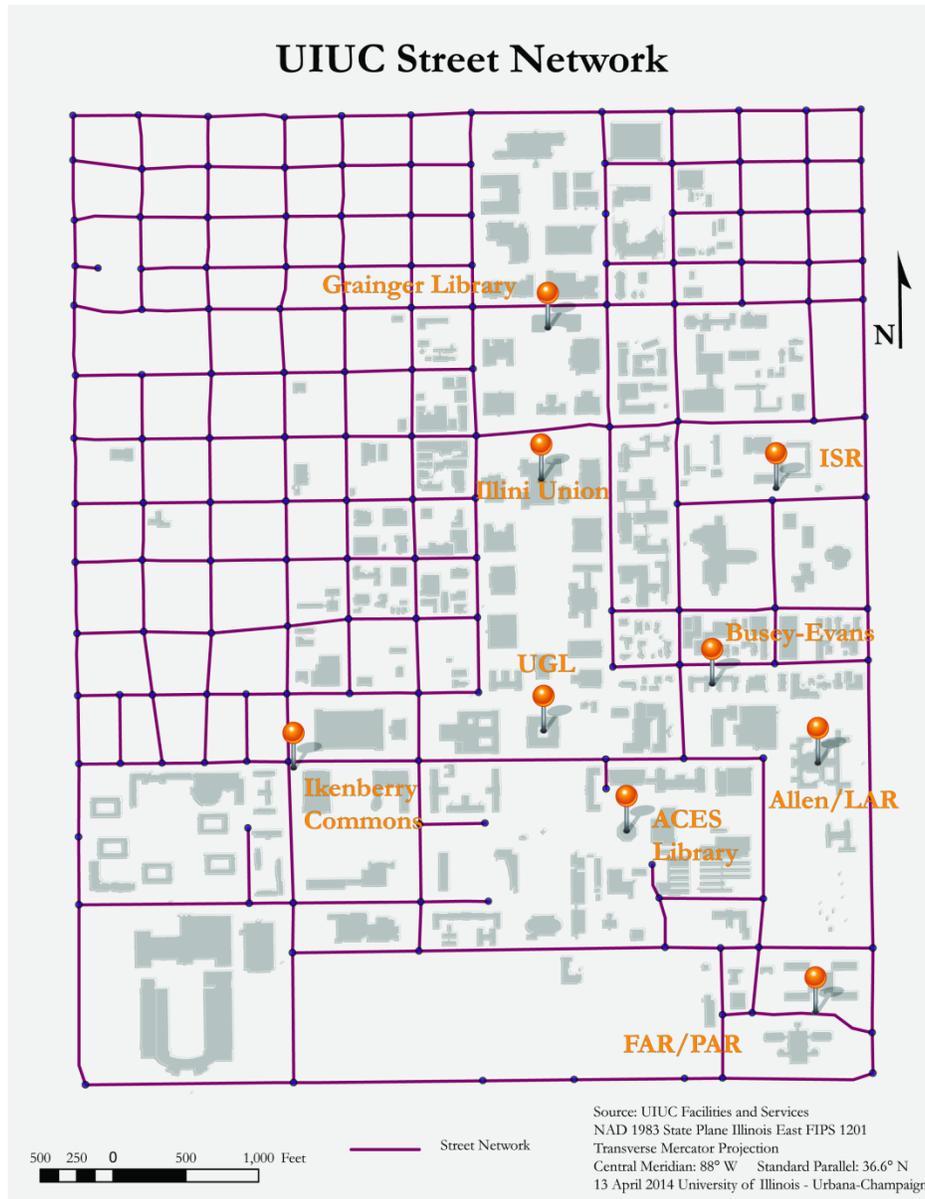


FIGURE 3: UIUC STREET NETWORK

## Synthesis

The results here indicate that the changes to the UIUC network do in fact improve connectivity over the existing network. Moreover, the planned network lowers the average shortest-distance path between libraries, dormitories, and the Union by nearly the same amount as a control scenario without paths at all. While we may assume that a bicycle master plan will address and improve connectivity as a matter of course – and the language in the plans claims that they do – it seems counterintuitive that this simple test not be included in the research process to confirm that this is so. Ultimately what these accessibility and connectivity analyses show is that while planners and bicycle advocates may seek to improve bicycle infrastructure, we need a way to quantify and subsequently verify that any changes will improve the functionality of the network and the ease with which a rider can travel from one location to another

Furthermore, we have uncovered an issue which I cannot resolve here: what to do when locations are not present on the network but need to be accessible by everyone, particularly locations which suddenly cease to be on the bicycle network. This is as much a philosophical issue as it is a physical planning one, and is especially pertinent in a campus setting where the major stakeholders are pedestrians and cyclists. Further research into the efficacy of planning infrastructure as well as the psychology of transportation-network users may yield insights about how cyclists' behaviors and safety change when nodes are dropped from the network and thereby provide solutions to improving the network even further.

We should also note a significant caveat to these findings. In calculating connectivity and accessibility measures, I assumed that every path on campus is “rideable”. By this I primarily mean that the surface is free of damage and holes so that barring all other traffic hazards facing cyclists, they will not face significant danger by simply riding over the surface. The Campus Bike Plan notes

that the actual bicycle infrastructure in many parts of campus requires extensive repairs to make it safe and usable.<sup>31</sup> While the methods of my study are useful for networks which are rideable, further research into determining what makes a “rideable path” and repeating the connectivity and accessibility analysis having removed “unrideable” sections would give a more accurate picture of the connectivity and accessibility of the bicycle network. This gives rise to other questions about how to analyze physical path quality. The Federal Highway Administration has developed methods for measuring the ride quality of roads, but research into their use for bicycle paths would be required before applying them.<sup>32</sup>

## Conclusions

This paper first and foremost studies the geometric connectivity and accessibility of the University of Illinois – Urbana-Champaign’s bicycle network. Using data collected and provided by the University and drawing on methods from graph theory, I found that the current planned bicycle network improves substantially upon the existing one. Furthermore, I found that the planned network provides nearly symmetrical service as the street network, which satisfies a goal of planning professionals to provide a separate space for cyclists to travel to their destinations.

One important conclusion from these results is that the measures used here provide planning analysts with the means to compare networks to networks, assessing their characteristics on their own terms. This can be immensely useful in designing and updating bicycle infrastructure such as is happening at UIUC. Use of these methods also points out that while we may not be surprised that the proposed network improved the overall connectivity and accessibility of campus locations,

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<sup>31</sup> UIUC Facilities and Services Transportation Demand Management Department, “Draft Campus Bike Plan.”

<sup>32</sup> United States Federal Highway Administration, “System Conditions,” in *2010 Status of the Nation’s Highways, Bridges, and Transit: Conditions & Performance*, 2010, 1–5, <http://www.fhwa.dot.gov/policy/2010cpr/chap3.htm#body>; United States Federal Highway Administration, “Present Servicibility Rating and Present Servicibility Index,” n.d.

the changes to the network layout removed high-traffic locations, including the Illini Union, from the network. This makes the victory somewhat hollow, because forcing cyclists to leave the network to reach destinations undermines efforts to produce a good and well-connected network.

Quantitative methods which verify that changes improve accessibility and connectivity while also enabling analysts to look closely at those changes is a valuable resource for planners, and should be included alongside existing research methodologies when preparing planning documents.

As mentioned, the philosophical questions of what makes a good bicycle network have not been answered with any consensus, nor perhaps truly asked. The other major conclusion of this paper is that while the literature on active transport focuses very much on walking and consequently neglects bicyclists and their needs, the extensive research into walkability lends itself directly to bicycles. As Southworth indicated, the bicycle has become a legitimate form of personal transport in the United States. While some have tried to analytically determine level of service for cyclists, these analyses always examine cyclists in relation to other modes of transport. This begs more fundamental questions about what cyclists themselves need in terms of networks and infrastructure, and we must ask and answer those questions before we can truly consider how cyclists interact with other transport users. This study has a more narrow focus, but its analysis raises many important questions about broader bicycle planning which need addressing before we can better plan for bicycle infrastructure in the modern city.

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