Evaluating the Connectivity of a Bicycling Network

Peter G Furth (corresponding author)
Northeastern University, room 400 SN
360 Huntington Ave
Boston, MA 02115
p.furth@neu.edu

Peyman Noursalehi
Northeastern University, room 400 SN
360 Huntington Ave
Boston, MA 02115

word count: 5,468 + 10 figures / tables

Revised, November 15, 2014

ABSTRACT

Unlike road networks and transit networks, bicycling networks can suffer from a lack of connectivity, especially considering that the mainstream population is unwilling to ride on many main roads. For this reason, improving network connectivity is widely recognized as an objective of bicycle planning; however, planners lack connectivity metrics that they might use, for example, to justify investments. We propose as a measure of connectivity that can be applied to a designated bicycling network. It is the fraction of origin-destination (O-D) pairs that can be served using that network, allowing a short access distance at both the origin and destination end. Because population and employment data can generally be obtained for traffic analysis zones (TAZs), we suggest using a sample of points from each TAZ as origins and destinations, weighted by population and (for job destinations) employment in the TAZ. Two methods of calculating connectivity are explored, the first using the general street network for access to the bicycling network, and the other allowing access along an abstracted network, while accounting for barriers such as rivers, railroads, and highways. Results of a case study of the metro Boston greenway network finds similar results from both methods, though the first is found to be superior for several reasons. The case study finds that by adding critical connecting links and extensions to the bikeway network that increase its length by a factor of 2.5, the fraction of home-work pairs that will be connected by the network increases by a factor of 13. This immense and disproportionate increase in connectivity reflects the importance of providing critical connecting links and of having understandable and computable connectivity metrics.

CONNECTIVITY AND BICYCLING NETWORKS

The primary function of any transportation network is to connect origins and destinations. For roadway networks, it is almost inconceivable that there would be sections cut off from other sections (apart from islands). Similarly for transit networks, it is virtually always the case that if any two points are in the coverage area, it is possible to get from one to the other using transit. For these modes, connectivity is critical, but is not given a lot of attention (except perhaps when a bridge fails!) because it can usually be taken for granted.

For bicycling, if one defines the network to be all the roads and paths along which bicycling is legally permitted, then bicycling networks are also well connected since bicycling is permitted on almost all roads. But, recognizing that most people are unwilling to ride a bicycle on many roads, particularly multilane roads and roads with fast traffic, one could take an alternative view that a city's bicycling network is limited to the set of links that the mainstream population is willing to ride on, as suggested by Mekuria, Furth, and Nixon (MFN) (1). With this more limited and practical definition, so many links can drop out of the bicycling network that what remains is highly disjoint.

Another reason that many bicycling networks in the U.S. exhibit poor connectivity is that bicycle paths are often built as once-off projects as opportunities arise, rather than following a well planned and funded program. The metropolitan Boston area reflects this legacy; none of the region's seven greenway paths that are at least 1.5 miles in length touches another.

Transportation network metrics such as network length or number of people living near it make sense when network connectivity can be taken for granted, as it usually is for auto and transit networks. However, the practical meaning of those metrics is completely undercut if the network is disjoint as many bicycling networks are. MFN showed, for example, that more than 60% of San Jose's road miles provide a low traffic stress environment. That is a vast network length, and it comes with a few hundred meters of nearly the entire population – but those statistics are meaningless because most of those low stress road sections don't connect to one another, making it impossible get "from here to there" on a bicycle unless one is willing to ride on high stress links.

For these reasons, bicycling planner, probably more than planners of any other transportation mode, recognize the need to improve connectivity, and often seek to justify bike infrastructure investments based on the connectivity they will bring. However, they lack a measure of connectivity, and when investment decisions are data-driven, having clear, understandable metrics that align with societal objectives is critical.

Therefore, the goals of this research are (1) to describe a measure of network connectivity that is appropriate for bicycling networks, (2) to develop and test two methods for calculating this measure, and (3) to show how adding links that create critical connections can lead to immense improvements in bicycle network connectivity. The greenway network of metropolitan Boston is used as a case study.

OTHER METRICS OF CONNECTIVITY AND ACCESSIBILITY

Connectivity is studied extensively in graph theory, though often in relation to purposes other than personal transportation (e.g., electronic communication, disease transmission, social media). Dill (2) provides a review of connectivity metrics that have been used in the context of walking and bicycling. Most, including block length, block size, block density, intersection density, street density, connected node ratio (ratio of "real" intersections to nodes, in which "nodes" are "real" intersections plus the end of cul-de-sacs), and various ratios involving number of links and number of nodes, affect distances within a small neighborhood (e.g., distance to get to the other side of a block). Though of interest for walking, those metrics have only marginal relevance to bicycling, where the main concern is not getting around within a small neighborhood, but getting from one neighborhood to another.

One metric, however, that can have direct applicability to cycling is pedestrian route directness (PRD), a metric that real estate developers may use as an alternative to maximum block length when seeking permits in the Portland area. For any pair of points, it is the ratio of a pedestrian route distance to straight-line distance; for an area, it would have to be applied as an aggregation over some set of point pairs. (Dill reports that because of uncertainty about how an area aggregation is to be done, this method has never yet been in permit applications.) The concept readily extends to a wider geography where it can be relevant for bicycling, informing investment decisions for new bicycling infrastructure. Dill shows how, for specific pairs of points, this measure points to clear differences in connectivity between homes and the closest transit station, but also suggests that the measure may be impractical for general use because of the aggregation problem (there are so many pairs of points that could be evaluated).

However, MFN (1) show that with modern computing tools, it is possible to evaluate bicycling paths between a vast number of pairs of points and aggregate results. Representing every block in the city by a point, they evaluated every block pair in the city, finding the ratio of distance along the bicycling network to distance along the general street network. This ratio, called a *detour factor*, is almost identical to the PRD, the difference being that it uses street network distance instead of airline distance as a base. In addition, MFN is the first study that acknowledges that when the mainstream population's needs are accounted for, many point pairs in a city may turn out to not be connected. They introduced two new metrics of connectivity appropriate to bicycling networks: the fraction of pairs that is connected, and the fraction of pairs that is connected with a detour factor lying below a certain threshold.

Accessibility is a property closely related to connectivity. It is a property of a point (and can then be aggregated to larger areas), indicating the degree to which that point is connected to destinations of interest. It concerns both the relative location of homes and other destinations and transportation options for reaching destinations. Handy and Clifton (3) explore in detail the concept of accessibility as it might be applied to neighborhoods for which walking and bicycling are the chief modes of travel. With respect to bicycling, though they acknowledge that the unsuitability of many streets for cycling should affect accessibility, they do not suggest metrics that take that into account.

McNeil (4) and Lowry et. al. (5) propose just such a metric of accessibility by bicycle, calling it "bikeability." Like other accessibility measures, this metric accounts for the number of destinations that can be reached from a given point. To reflect the unsuitability of some streets for bicycling, they use an unsuitability scale (1 is the best, greater numbers indicate worse level of service for bicycling) and generate an effective length for each link which is link length multiplied by their unsuitability score. Calculating this metric for a number of zones in a city, they mapped those with better and worse bikeability.

The concept of increasing effective length of a link to reflect its unsuitability for cycling was perhaps first applied by Klobukar and Fricker (6), who used that principle to develop a metric for evaluating bicycling networks that can be interpreted as a combination of the average unsuitability that bicyclists are subject to and the extra distance cyclists go to find a lower-effective-length route. Drawbacks of using unsuitability to increase a link's effective length, rather than to exclude it from the network, are that the bicycling network retains the full connectivity of the road network, and that results involving inflated distances are difficult to communicate to the public.

PROPOSED CONNECTIVITY METRIC FOR A DESIGNATED BICYCLING NETWORK

All of the aforementioned studies address the question of how well the full road network serves bicycling needs. That can be distinguished from the problem we consider here, which is how well does a designated bicycling network – one that has been limited to links that have a high suitability for bicycling – serve bicycling needs, considering the general street network as nothing more than a means to access the designated bicycling network.

The metric we propose is the fraction of origin-destination (O-D) pairs that are connected via the bicycling network, subject to limits on access distance and without exceeding excessive detour. A trip table (O-D matrix), if available, can be used as a source for weighting O-D pairs, as in MFN(1); however, O-D data is often scarce, out of date, or based on models of questionable reliability. Instead, we propose a simpler weighting method based on widely available one-dimensional data on population and employment by traffic analysis zone (TAZ). In American practice, TAZs are always a subset of a census tract, and are sized so that they have about 3,000 residents. In auto-oriented network analysis, it is taken for granted that there will be good access from a TAZ to the highway network, and so each TAZ is typically represented by a centroid with one or more connectors to nearby nodes in the road network. For bicycling, however, equal access from all parts of a zone to a designated bicycling network cannot be taken for granted. This is partly because the lower speed of bikes makes longer-distance access paths unattractive (akin to the transit access problem). More importantly, it is because the streets a person might have to use to access the bicycling network can offer a hostile environment for bicycling. Thus, unlike for transit access, the distance limitation for access to the bicycling network is not based on a travel time budget, but on the need to limit exposure to bike-unfriendly streets.

To address the issue of which points in the city do and do not have access to the bicycling network, we represent each TAZ not by a single centroid, but by a sample of points. For the applications reported in this paper, we use five sample points per TAZ, with each sample point representing one fifth of the TAZ's population and employment. That sample size is intended to strike a balance between providing spatial variability and avoiding an exploding problem size. The case study area has about 300 TAZ's, and so with 5 sample points per TAZ the number of origin-destination pairs analyzed becomes 1500 x 1500.

Because population and activity density correlates highly with intersection density, the sampling frame from which sample points are drawn is the set of street intersections in the TAZ. Intersections are selected at random with equal probability.

Two methods, described below, were developed and tested for evaluating the proposed metric. They require far less data than the method applied in MFN (1). Unlike in MFN, there is no need to know or gather data on the characteristics of all the street segments of a city. It is only necessary to specify a bicycling network considered suitable for bicycling.

METHOD 1: USING THE STREET NETWORK FOR ACCESS

In method 1, the full street network, excluding only those streets on which cycling is prohibited (e.g., freeways), is treated as the access network. No attempt is made to assess the suitability of streets in the access network for cycling. This in turn demands a small access distance limitation; in our case study, 1 km. With this short a distance, even if the streets on somebody's access path are stressful to cycle on, one can bear with that for a short distance, perhaps walking one's bike or riding on the sidewalk at a slow pace.

Allowing access over long distances would distort the analysis because it would admit long access paths along stressful streets – and if that is considered acceptable, there is no point in having a designated bicycling network. At the same time, using a short distance also creates a potential distortion – points beyond the distance threshold that have low-stress access paths will be treated as disconnected. To limit this kind of distortion, the bicycling network should be expanded to include important low stress access paths ("fingers") that reach into neighborhoods.

Many government agencies offer geo-datasets of the street network. They may lack informal short-cuts that cyclists use, which knowledgeable users can add where they are important for network access.

Connectivity analysis for a given point begins by determining where it can connect to the bicycling network. All links and partial links in the access network within the access limit are identified. Next, all intersections between this cluster and the bicycling network are identified; they are called access points. An example is shown in Figure 1, in which eight access points are identified. This process of identifying access points is carried out for each sample point. If no access points are found, the point is not connected the network.

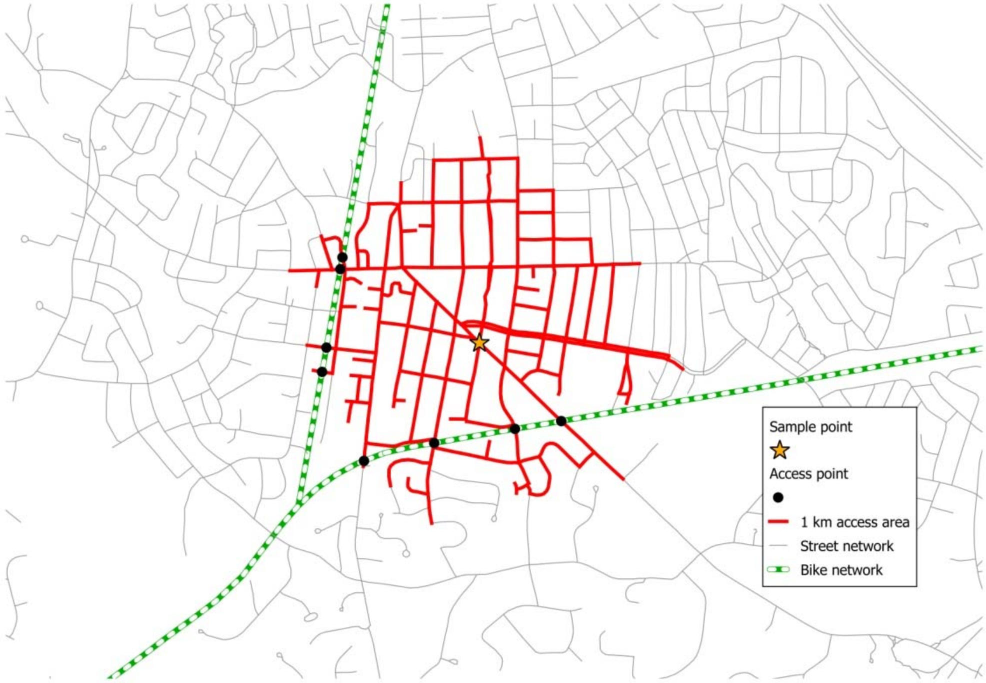


Figure 1 Discovering network access points

.

Next, we find and store the shortest path distance between each pair of access points in the bicycling network.

Next, we seek the shortest path between those points using the access network for up to the specified access distance at the origin and destination end, and the bicycling network in between. If D_1 is the minimum distance along the access network between access point P and origin point O, and likewise D_2 is the minimum distance along the access network between the destination D and its access point Q, and D_3 is the minimum distance along the bicycling network between P and Q, then path O-P-Q-D is chosen if and only if for all the other possible Ps and Qs,

$$|D_1 + D_2 + D_3| \leq |D'_1 + D'_2 + D'_3| \quad (1)$$

That distance, along with the shortest distance on the full street network from O to D, is then stored for post-processing, where limits on allowable detour factor are then applied.

Figure 2 shows an example of a shortest path that includes access at each end and travel along the network. Also shown for comparison is the shortest path between the two sample points using only the street network. Note that this algorithm does not automatically assign a sample point to its closest access point. It realistically assumes that a user might bike further along the access network in order to reduce the overall trip length. A possible refinement could be to weight distance along the access network, reasoning that people may be willing to trade off a slightly longer distance along the bicycle network for a shorter distance along access roads.

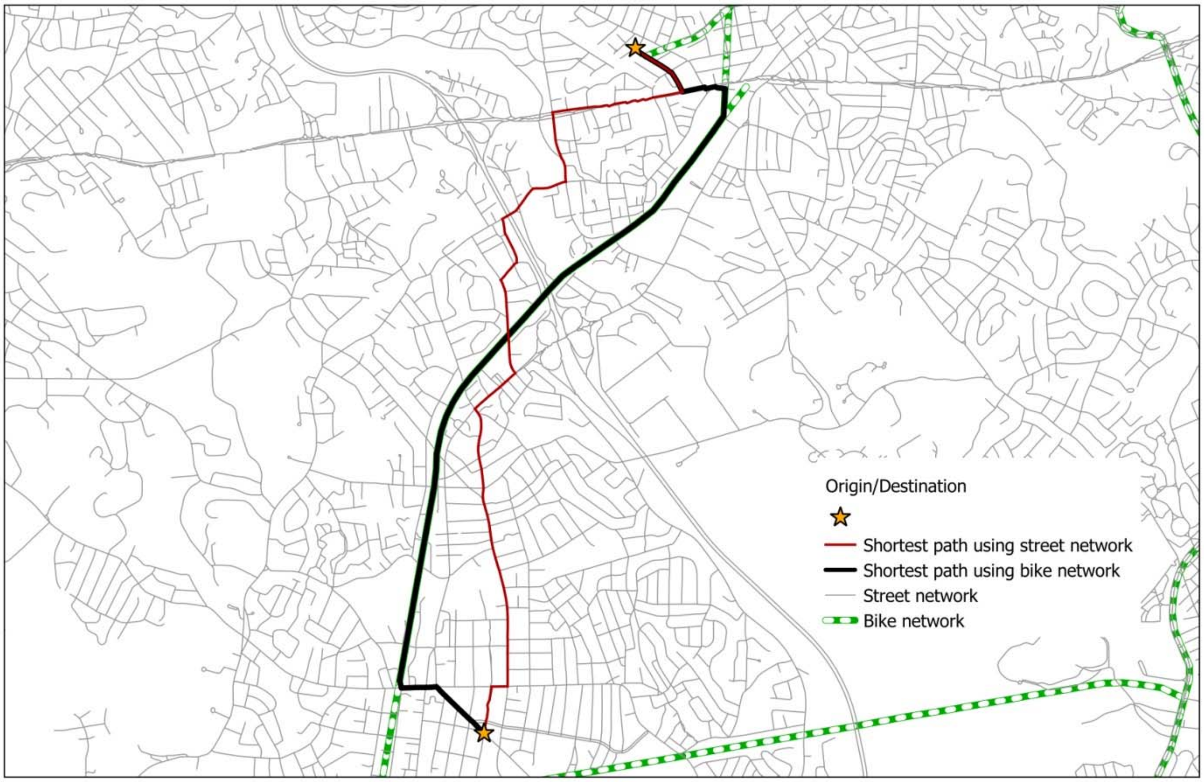


Figure 2 Shortest path between an origin and a destination using the street network for access

Method 2: Airline Access with Barriers and Connection Points

We also developed and tested a second approach that does not rely on having a routable access network dataset. In this approach, the access network is abstracted. It is assumed that a sample point can connect to the bicycling network if the airline distance between the two is less than or equal to a given distance, with turns allowed in order to bypass barriers. Our case study limited the access distance to 1 km.

Similar to Method 1, this method is only reasonable if the allowed access distance is small. Even then, however, this method can systematically overstate network access where there are barriers to cycling between sample points and the bicycling network such as rivers, and railroads, and highways.

Therefore this method required the additional modeling of barriers, which were drawn manually as a geographic data layer. Another data element had to be modeled as well – points that allow access through a barrier (e.g., a bridge or underpass), called breach points. Figure 3 shows an example of barriers and breach points near a sample point.

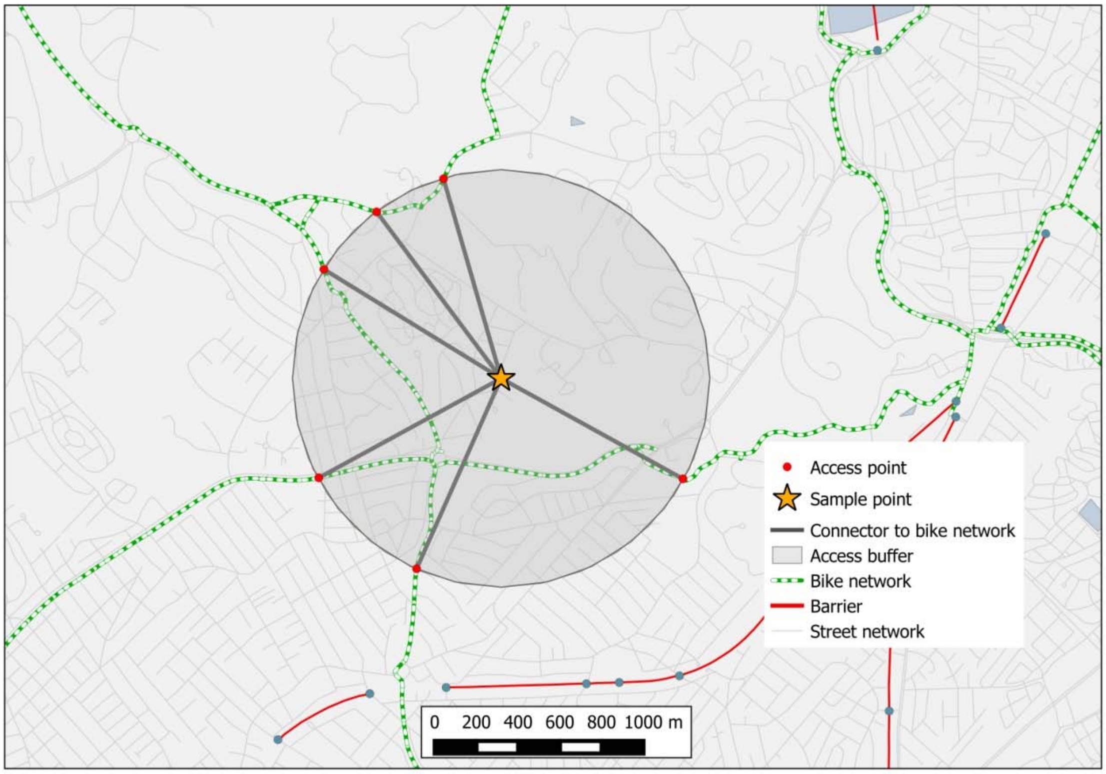


Figure 3 Connections to bike network for a sample point

Barriers were modeled if they were within 1 km (the access distance limit) of the network and if they prevent bicycle crossings over at least 400 m. (The rationale for the 400 m limit is that street grids frequently have gaps of this size, and so barriers shorter than 400 m could be treated as part of the "background."

Including segments shorter than 400 m does not distort results, and so erring was on the side of inclusion.) That meant including as barriers arterial highways with infrequent crossings.

Breach points were then modeled wherever a barrier could be crossed, such as at bridges, underpasses, or highway crossings. It was important to include breach points at the endpoints of barriers.

In order to faithfully model access limitations to the bicycling network, we also had to model as barriers long breaks in the street network; for example, one such break is where a large cemetery separates a neighborhood from a nearby bicycle path. Overall, the process of identifying barriers turned out to be more subjective than desirable; there was no objective method of ensuring that every barrier was accounted for. We relied on expert local knowledge to review maps to ensure that areas modeled as accessible to the network really were. Those checks led to the addition of a few barriers.

Once the barriers, breach points, and sample points were identified, the next step was to determine which points have access to the network. Buffers were drawn at the allowable access distance from the sample point. If there were no intersections between buffer and network, the point is disconnected from the network.

Consider first the case in which there are no barriers within the buffer of either the origin or destination point. If the distance between origin and destination is less than the access limit (1 km), the points are in each other's buffer meaning they are clearly connected. That distance is multiplied by a factor γ which converts airline distance into an equivalent network distance; we used a value of $\gamma = 1.25$.

Otherwise, a user starting at the origin can connect to the greenway at any access point, and then follow the greenway network to any of the destination's access points, which are in turn connected to the destination through direct lines. Let D_1 be the airline distance between connection point P and origin point O, and D_2 the airline distance between the destination D and its connection point Q, and D_3 the network distance between P and Q. The path O-P-Q-D is chosen if and only if for all the other possible Ps and Qs,

$$|\gamma(D_1 + D_2) + D_3| \leq |\gamma(D'_1 + D'_2) + D'_3| \qquad (2)$$

Airline distance between all origin-destination pairs was also calculated as a basis for evaluating the detour factor. Note that equation 2 implies that a user is not necessarily going to connect to the bike network at its closest point, but rather at the one that minimizes the overall trip length (with airline travel weighted by γ).

The pseudocode for this procedure is as follows:

Connect_samplePoint_to_accessPoints (Graph, S1, connectionCostMatrix)

```
// this function finds access points for the given sample point,
// and computes the cost of connecting them to each other
// S1 is a sample point
accessPoints = [intersection points of 1km buffer around sample point and network]
for point in accessPoints:
    connectionCostMatrix [S1][point] =  1.25*length of the straight line
                                connecting  origin and connection point
```

Connect_two_samplePoints (Graph, S1, S2, connectionCostMatrix, costMatrix)

```
// S1 and S2 are the two sample points
costMatrix [S1][S2] = inf
// Find the shortest path between S1 and S2
```

```
for point in connectionCostMatrix[S1]:
    for point2 in connectionCostMatrix[S2]:
        if ShortestPathLength(point, point2) + connectionCostMatrix[S1][point] + connectionCostMatrix[S2][point2] < costMatrix[S1][S2] then:
            costMatrix [S1][S2] = ShortestPathLength (point, point2) + connectionCostMatrix[S1][point] + connectionCostMatrix[S2][point2]
```

Next, consider the case in which one or more sample points have a barrier in their buffer. In such a case, the access path can pass through and turn at a breach point. All breach points within the buffer that can be reached by a direct line (not blocked by a barrier) are identified. Let the distance to breach point i be D_i, and let B equal the original access distance budget (1 km). The remaining access budget will then be $B – D_i$. A buffer whose radius equals the remaining budget will next be drawn around each breach point. Any place that this buffer intersects with the network then becomes an access point, unless the line leading to it is blocked by a barrier. If blocked, we search for other breach points not yet visited that can be directly reached within the buffer. The process is repeated recursively until the access budget is exhausted and every breach point reached has been processed.

Figure 4 illustrates this logic. With the initial buffer, three connection points are found. But there is also an uninterrupted line to two breach points. From each of those points, a new buffer whose radius equals the remaining access budget is drawn. The buffer around the southern connection point yields two more connection points, as does the buffer around the northern connection point. In total, this sample point has 7 access points.

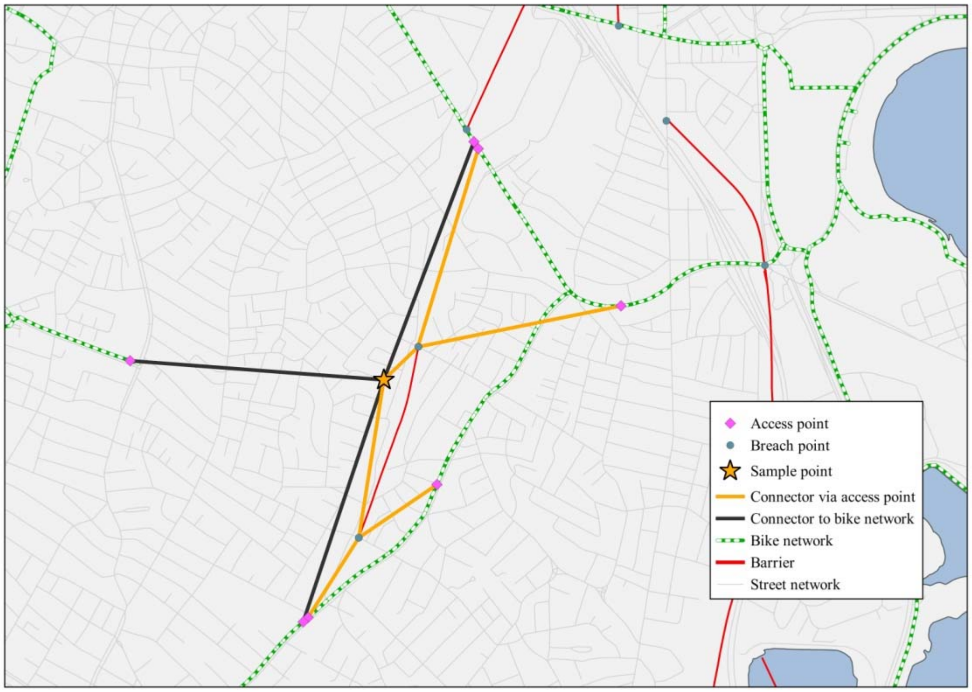


Figure 4 Turning at breach points to find access points shadowed by a barrier

The pseudocode for finding the connection distance between points whose access is affected by barriers is as follow:

```
Find_connection_points(G,S1)
// G is bike network
// S1 is a sample point
access_buffer = buffer(S1, 1000) // draw a buffer with radius 1000 m
if access_buffer intersects G:
    connections = [intersection points]
for c in connections:
    if line(c,S1) crosses a barrier:
        connections.remove(c)
        Connect_through_breachPoints(G, S1, B = 1000, connections)
    else:
        connectionCostMatrix[S1][c] = length (line(c,S1))
```

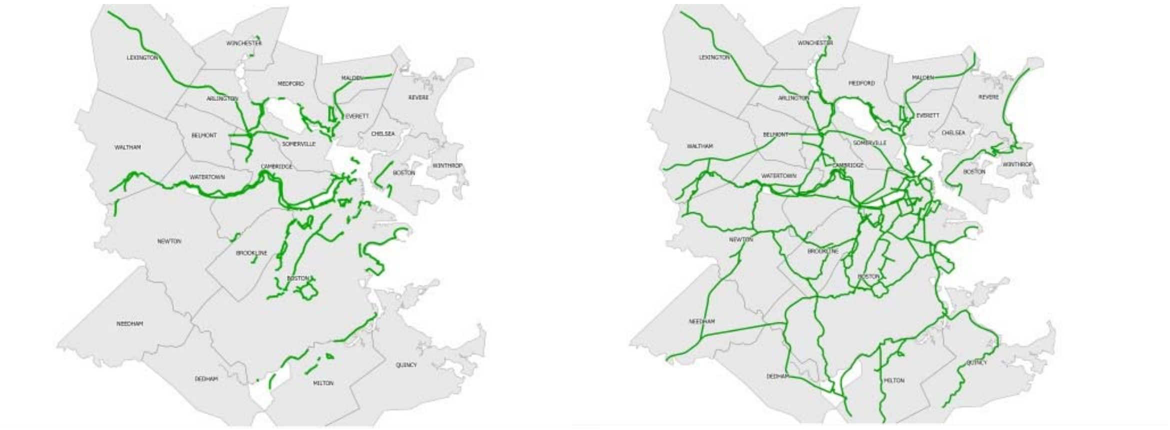
```
Connect_through_breachPoints(G, S1, B, connections)
if there exists a breachPoint in access_buffer of S1:
    H = [all breach points in the buffer]
    for hPoint in H:
        $d_i$ = length(S1, hPoint)
        buff = buffer(hPoint, B-$d_i$) // a buffer of radius B-$d_i$ around access point
        if buff intersects with G:
            I = [all intersection points]
            for intPoint in I:
                if line(hPoint,intPoint) crosses a barrier:
                    Connect_through_breachPoints(G, hPoint, B-$d_i$, connections)
                else:
                    connections.append(intPoint)
                    connectionCostMatrix[S1][intPoint] = $d_i$ + length(hPoint,intPoint)
```

```
Connect_two_SamplePoints_with_barriers (Graph, S1, S2)
// S1 and S2 are sample points,
Find_connection_points(G,S1)
Find_connection_points(G,S2)
Connect_two_samplePoints (Graph, S1, S2, connectionCostMatrix, costMatrix)
```

CASE STUDY OF BOSTON'S GREENWAY NETWORK

Metropolitan Boston has seven greenways at least 1.5 miles long, including paths along the seashore, along the Charles, Muddy, and Neponset Rivers, and three more rail trails. Remarkably, not one of them touches another. Dill and McNeil (7) have shown that the mainstream population lies in the group that Geller (8) has termed "interested but concerned," people who find the idea of riding a bicycle for transportation appealing but are uncomfortable dealing with the traffic stress involved in riding on busy streets. This mainstream population is more likely to find it attractive to be able to ride to work if they could ride along a greenway. However, the lack of connectivity between Boston's greenways means that the only people who could enjoy this opportunity are those who happen to live and work along the same greenway – a very limiting restriction.

Recently, Furth et. al. (9) proposed an expanded and connected greenway network for metro Boston, building on opportunities for new greenways along rail corridors, historic parkways, and in overly wide road rights of way within which new linear parks could be fashioned. "Greenway" here is defined as a path suitable for transportation by bicycling as well as on foot and lying in a natural setting. The proposed network also includes a limited number of on-road connectors, which are either cycle tracks along busy roads or signed routes along quiet neighborhood streets. In the 20-municipality region lying roughly within 10 miles of downtown Boston, there are now 91 miles of greenway path. The proposed network increases the network length to 229 miles, of which only 26 miles are on-road connectors; more than 90 percent of the proposed network is paths lying in a green setting.



(a) existing **(b) proposed**

Figure 5 Greenway network of metro Boston

These existing and proposed greenway networks are analyzed as bicycling networks using the two methods described in this paper. Connectivity from homes to two kinds of destinations was calculated: jobs and other homes. The distribution of residents and jobs by TAZ was supplied by the Metropolitan Planning Organization.

Maximum Detour Factor

There is a limit beyond which people consider a route involving a lot of detour simply unavailable. Such a limit is also desirable from a policy perspective. Without such a limitation, points two miles apart could be considered connected if there was network path between them that was 8 miles long (say, because it involved riding to the center of the city and then back out again). While the maximum detour that people will tolerate varies from person to person, any reasonable maximum should offer a good comparison between network alternatives.

For both methods, the detour limitation is enforced by means of a maximum detour factor. For method 1, the detour factor is the ratio of the path length (including the access paths and the path through the network) to the shortest path using the street network, and the maximum allowed value is 1.33, consistent with MFN (1) and drawing on research reported in (10) and (11). For method 2, the detour factor is the ratio of path length to airline distance between the two points, and the maximum allowed detour factor is 1.33 * 1.25 = 1.67, where the factor 1.25 is a conversion from airline to network distance.

Results

Figure 6 shows the TAZs in the study area, the proposed greenway network, and the sample points (five per TAZ) within the access buffer. TAZs tend to be very small around downtown Boston, hence the dense appearance of sample points in that area. (Recall that sample points are not equally weighted, but rather by one fifth of the population and (when considered a job destination) jobs in its TAZ.

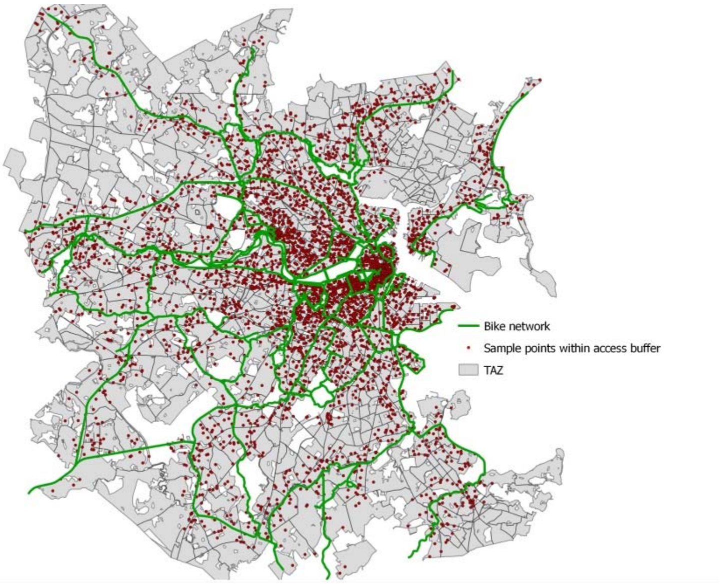


Figure 6 Sample points within access buffer of proposed network

Figure 7 shows the barriers and breach points that were modeled for Method 2.

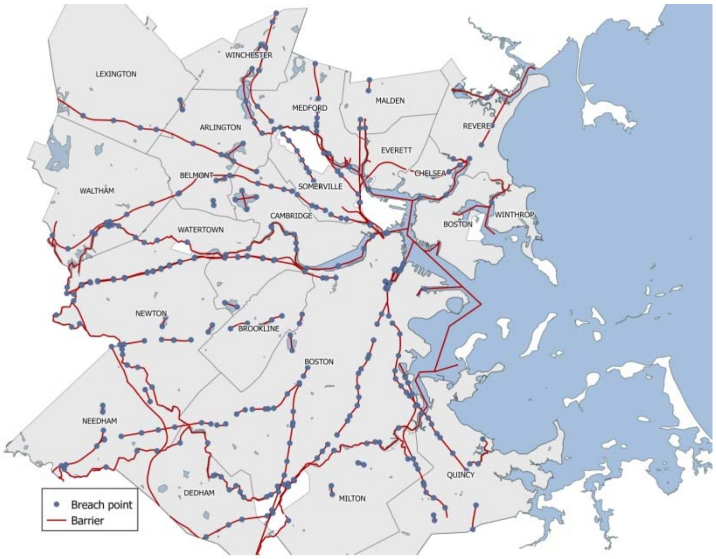


Figure 7 Barriers and breach points

Table 1 reports connectivity results for both the existing and proposed network. Method 1, which finds access paths along the street grid, is inherently the more accurate method, and so we focus first on its results. What stands out first is the large increase in connectivity. While the size of the network grew by a factor of 2.5, the home-work connectivity increased by a factor of 13 (from 2.6% to 33.9%), and the home-home connectivity by a factor of 16 (from 1.4% to 22.9%). The disproportionate growth in connectivity comes from connecting existing but disconnected links, allowing those existing resources to be used more intensely.

Table 1: Connectivity for the existing and proposed greenway network

	Method 1 (Access along Street Grid)		Method 2 (Airline Access with Barriers)	
	Existing	Proposed	Existing	Proposed
Home-work pairs connected	2.6%	33.9%	1.2%	38.1%
Home-work pairs disqualified for excessive detour	0.3%	10.5%	0.0%	12.3%
Home-work pair unconnected even with unlimited detour	97.1%	55.7%	98.8%	49.6%
Total	100%	100%	100%	100%
Home-home pairs connected	1.4%	22.9%	0.7%	28.5%
Home-home pairs disqualified for excessive detour	0.1%	14.1%	1.4%	13.5%
Home-home unconnected even with unlimited detour	98.5%	63.0%	98.0%	58.0%
Total	100%	100%	100%	100%

Home-work connectivity is greater than home-home connectivity. This is reasonable since jobs in the region tend to be concentrated in the center where they are relatively well served by bike paths, while homes tend to be more dispersed and therefore less likely to be near a bike path.

The detour factor has considerable effect on connectivity, especially for the proposed network in which more than 10% of home-work pairs and 14% of home-home pairs have a network connection that is disqualified because it involves excessive detour. Figure 8 shows an example of an O-D pair whose connecting path involves excessive detour under Method 2. (Under Method 1, this pair also has excessive detour).

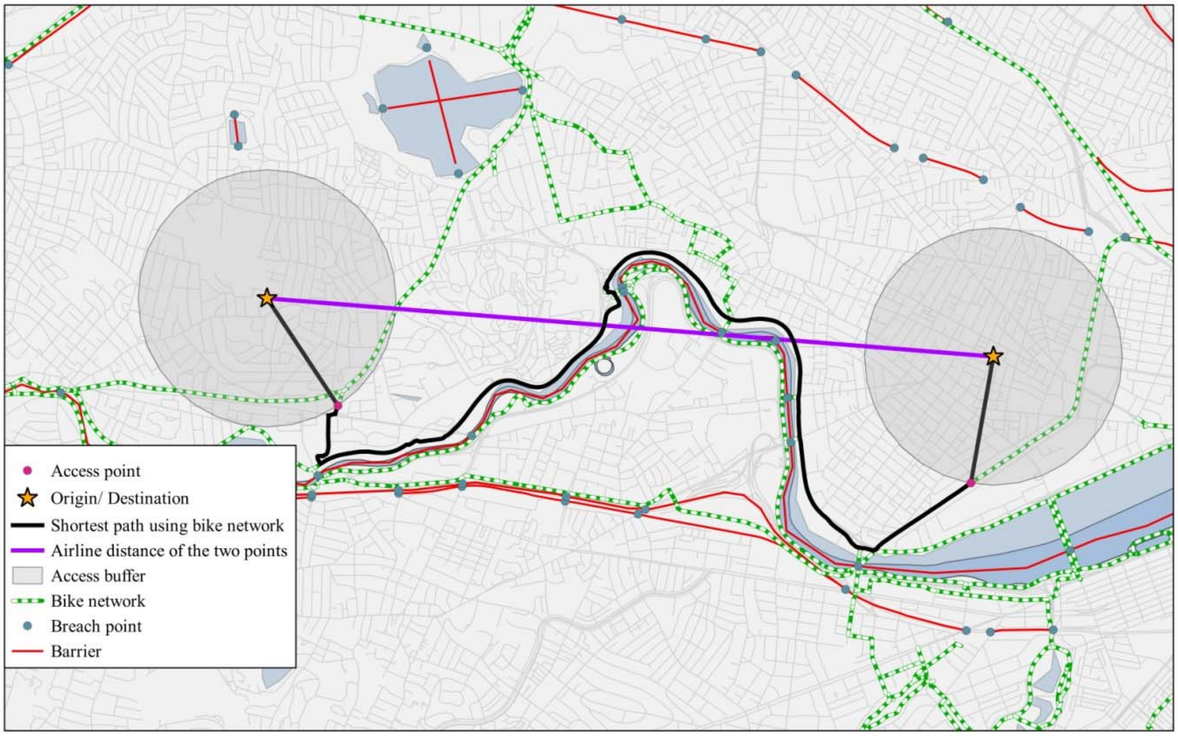


Figure 8. An O-D pair that is disqualified due to excessive detour (Method 2). Network distance = 13.2 km while airline distance = 5.7 km.

Sensitivity Analysis

Sensitivity analysis was done with respect to two parameters: the number of sample points per TAZ and the detour factor. For the proposed greenway network, using Method 1, as the number of sample points per TAZ varied from 5 to 3 to 1, the fraction of jobs connected fell from 33.9% to 32.7%, and the fraction of homes connected fell from 22.9% to 22.0%. Note that because the area studied has 300 TAZ's, a single sample point per TAZ still results in a moderately large sample size. It may be that greater differences would be seen in an analysis of a smaller area with fewer TAZs.

Figure 9 shows sensitivity to allowed detour factor for the two methods. The connectivity metric clearly increases with allowed detour, with diminishing returns but no obvious break point.

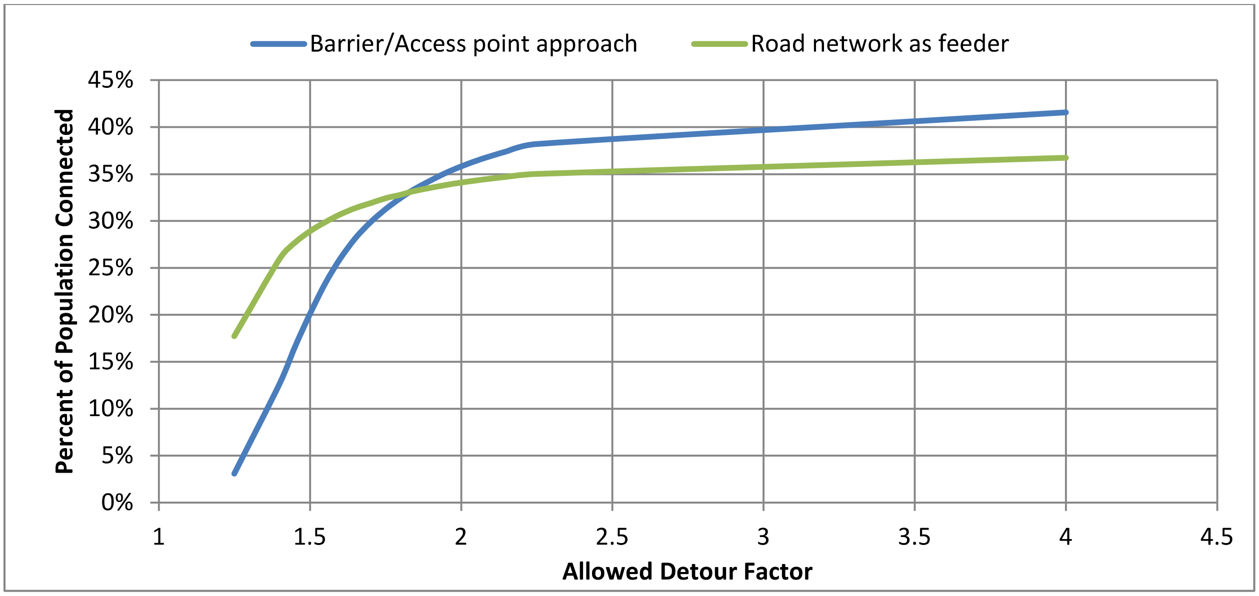


Figure 9: Home to home connectivity versus allowed detour factor

CONCLUSION AND DISCUSSION

Connectivity is a critical factor for bicycle network design. From a methodological point of view, we have demonstrated the viability of a metric of the connectivity offered by a designated bicycling network. From a policy point of view, we have demonstrated in a case study how network additions that provide critical connections can yield enormous, disproportionate increases in connectivity.

Two methods of calculating the proposed connectivity metric were described, of which method 1 (using the street network for access) seems clearly superior so long as a routable street network dataset is available. However, the similarity of results for the two methods suggests that using airline access might be an acceptable approximation when street network data is not available.

Either method can be applied and extended in many ways, such as limiting results to trips of a certain distance considered suitable for bicycle, evaluating connectivity from disadvantaged neighborhoods, and prioritizing and sequencing investments. While the case study applied the method to a network of greenway paths (with on-street connectors), it can just as easily be applied to any designated bicycling network. In such a case, care must be taken that the network is limited to links deemed suitable for bicycling. This caution is given because sometimes published bicycling networks include links that may be the best available, even though they would not meet suitability criteria of the mainstream population.

The strength of the proposed method is that it avoids the need to evaluate streets for their suitability for bicycling, except for whatever evaluation is needed to determine what links belong in the designated bike network. At the same time, that feature is also a weakness, because it doesn't guard against access paths that require using high stress links. This weakness is mitigated by limiting access distance, which in turn brings some potential distortion. It therefore seems clearly preferable, if the extra effort can be afforded, to use the more involved method for evaluating bicycling networks described in MFK (1) in which every street is evaluated for its suitability for bicycling.

Further research would be valuable to provide a stronger basis for the acceptable detour factor.

REFERENCES

1. Mekuria, Maaza, Peter Furth, and Hilary Nixon. "Low-stress bicycling and network connectivity." Mineta Transportation Institute Report 11-19 (2012).
2. Dill, Jennifer. "Measuring network connectivity for bicycling and walking." 83rd Annual Meeting of the Transportation Research Board, Washington, DC. 2004.
3. Handy, Susan L., and Kelly J. Clifton. "Evaluating neighborhood accessibility: Possibilities and practicalities." Journal of Transportation and Statistics 4.2/3 (2001): 67-78.
4. McNeil, Nathan. "Bikeability and the Twenty-Minute Neighborhood: How Infrastructure and Destinations Influence Bicycle Accessibility." *Transportation Research Record* 2247, pp. 53-63 (2011).
5. Lowry, Michael B., et al. "Assessment of communitywide bikeability with bicycle level of service." Transportation Research Record: Journal of the Transportation Research Board 2314 (2012): 41-48.
6. Klobucar, Michael S., and Jon D. Fricker. "Network evaluation tool to improve real and perceived bicycle safety." Transportation Research Record: Journal of the Transportation Research Board 2031 (2007): 25-33.
7. Dill, Jenifer and Nathan McNeil. "Four types of cyclists? Examination of Typology for Better Understanding of Bicycling Behavior and Potential." Transportation Research Record: Journal of the Transportation Research Board 2387 (2013): 129-138.
8. Roger Geller, *Four Types of Cyclists*, (Portland, OR: City of Portland, Office of Transportation, 2006), http://www.portlandonline.com/transportation/index.cfm?a=158497&c=44671
9. Furth, Peter G., David Loutzenheiser, Steven Miller, and Peyman Noursalehi. "A Greenway Vision for Metro Boston." Proceedings of Fábos Conference on Landscape and Greenway Planning 2013:Pathways to Sustainability. University of Massachusetts, Amherst, April 12-13, 2013.
10. Broach, Joseph, Jennifer Dill, and John Gliebe. "Where do cyclists ride? A route choice model developed with revealed preference GPS data." Transportation Research Part A: Policy and Practice 46.10 (2012): 1730-1740.
11. Winters, Meghan, et al. "How far out of the way will we travel?." Transportation Research Record: Journal of the Transportation Research Board 2190.1 (2010): 1-10.