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One-Way Streets and Bicycle Contraflow: Impact on Connectivity and Accessibility for Low-Stress Bicycling

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1 **ABSTRACT**

2 One-way restrictions on local streets, which tend to have low traffic stress, can create a
3 significant barrier to low-stress cycling. Contraflow, a treatment that undoes one-way restrictions
4 on bike travel has the potential to improve low-stress connectivity. While contraflow is applied
5 routinely in Netherlands and Belgium, it has been sparingly applied in the US. We propose
6 refined measures of connectivity and accessibility that account for one-way restrictions by
7 requiring a low-stress roundtrip path between origins and destinations. Different methods of
8 associating origin-destination demand from polygons to a street network are analyzed. These
9 methods are particularly important where there are one-way restrictions and irregular street
10 networks because of the assumptions they entail regarding first- and last-segment travel. In a
11 case study of Greater Boston, we find that with the current bike network, low-stress connectivity
12 between homes and jobs would increase from 1.2% to 8.7% if one-way restrictions on local
13 streets were eliminated. We also find that even with a dense mesh of low-stress main bike routes,
14 connectivity would still be 16% lower without contraflow on local streets than with. These
15 results suggest that creating a network of main bike routes isn't always enough; it is also
16 important to provide contraflow on local streets. The Boston study also found that providing
17 contraflow on selected links representing only 3% of local one-way street mileage delivers 40%
18 of the connectivity impact of universal contraflow. Based on this finding, a method is proposed
19 for prioritizing streets for contraflow conversion.

1 INTRODUCTION

2 One-way streets are common fixtures in urban street networks, particularly in older cities with
 3 narrow local streets and limited off-street parking. By default, direction restrictions on one-ways
 4 apply equally to automobiles and bicycles. For autos, these restrictions are not usually onerous,
 5 leading only small increases in distance traveled and never disconnecting the network. For bikes,
 6 the effect would be the same if cyclists used all the same roads as cars. However, majority of
 7 people are willing to ride bikes only on streets with low traffic stress (1). If high-stress roads are
 8 eliminated from consideration, the remaining network of low-stress streets and bike paths,
 9 compared to the automobile network, tends to be sparser, poorly connected, and possessing less
 10 redundancy, making it less resilient (2). In such a network, one-way restrictions can increase
 11 travel distance substantially and, more seriously, can disconnect parts of a city from the rest of
 12 the bike network.

13 Contraflow, which means permitting bicycles to travel in both directions on a one-way
 14 street, can eliminate this barrier effect. However, while contraflow is widely practiced in some
 15 countries and has long been recognized in the *Manual on Uniform Traffic Control Devices* (3),
 16 its usage in the US is limited.

17 Previous studies (2, 4) have shown how roads with high traffic stress, together with
 18 natural and man-made barriers such as rivers and freeways, create barriers to cycling, sometimes
 19 dividing a city into islands with no connection to each other. However, studies of low-stress bike
 20 networks have paid little or no attention to the barrier effect of directional restrictions. While
 21 some studies have used network models that account for directionality, they have evaluated
 22 connectivity by considering travel in one direction only, from home to a destination. But if one-
 23 way restrictions make it such that there is a low-stress path from A to B but not back to A, can A
 24 and B really be considered connected?

25 This research takes a closer look at how one-way restrictions affect the low-stress bike
 26 network. More specifically, it seeks to answer the following questions. In real bike networks,
 27 how big an impact do one-way restrictions have on connectivity? How much of this barrier effect
 28 could be undone by applying contraflow routinely on local streets, as practiced in some other
 29 countries? And is there a way to determine which one-ways would contribute the most to
 30 connectivity if treated with contraflow? The next sections of this paper provide background on
 31 one-way streets, contraflow, and low-stress bike network analysis. Sections that then follow
 32 cover methodology, the case study, and a way to prioritize streets for contraflow conversion.

33 ONE-WAY STREETS AND CONTRAFLOW

34 Virtually every one-way street that exists today was originally two-way. Conversion to one-way
 35 has generally been for one of three reasons, all related to growth in automobile use beyond the
 36 level for which the streets were built. On local streets in older neighborhoods, the main reason
 37 for one-way restrictions has been to create more space for parking, leaving a single-lane channel
 38 for moving traffic. A second and more recent reason for one-way restrictions on local streets is to
 39 divert through traffic away from neighborhood streets by making it either impossible or difficult
 40 to cut through a neighborhood. One-way restrictions intended as traffic diversions have been
 41 applied systematically in some places such as Boston's South End neighborhood and in
 42 Brookline (MA), near the Boston University Bridge. Finally, on arterial streets, one-way
 43 restrictions are generally put in place to increase traffic capacity. Because one-way operation

eliminates left-turn conflicts with opposing traffic at intersections, it makes traffic flow more efficient.

On local streets, it is reasonable to ask, why should one-way restrictions applied to autos be also applied to bikes? A street may be too narrow for autos to get by one another, but bikes can almost always get by. One-ways that have been created to divert traffic are intended to protect neighborhood streets from the danger and nuisance of *autos*, not bikes; ironically, such restrictions are contrary to cyclist safety because they prevent cyclists from using quiet, neighborhood streets which, in general, are safer than arterials.

Contraflow can be provided in one of three ways. The method best known in the US is striped contraflow bike lanes. A second way, far more common in Europe, is for contraflow to be signed but not striped – that is, there is usually no “contraflow lane” *per se*, but bikes are allowed to ride two-way (just as on most two-way local streets, there are no lanes marked for the two directions). A third way, commonly applied on one-way arterials, is to provide a two-way separated bike path.

In Netherlands and Belgium, most local streets that are one-way allow bicycle contraflow. A briefing by the European Transport Safety Council summarizes safety studies from European cities that show contraflow to be safe, with a very low crash rate and a lower proportion of crashes on contraflow streets involving contraflow cyclists than those riding with-flow (5). Because of this positive safety record, France in 2015 joined Belgium and Netherlands in making contraflow the default treatment on local streets in 30 km/h zones (6). This is consistent with a fact sheet published by the European Commission recommending ubiquitous application of contraflow on one-way local streets to improve safety by increasing predictability (7).

In the U.S., bikeway design guides published by both NACTO (8) and AASHTO (9) offer guidance for designing contraflow streets, but neither indicate whether contraflow ought to be applied routinely or sparingly. The number of contraflow applications in the US is generally understood to be small; for example, in the city of Boston, while there are more than 100 miles of one-way streets, only one short block has bicycle contraflow.

Contraflow and Neighborways (Bike Boulevards)

Many cities use bike boulevards, also called neighborhood greenways or neighborways, as a low-cost and effective way of creating key low-stress routes. A neighborway is a route of substantial length following low volume local streets that is suitable as a through route for bikes, but not for autos. In cities like Boston and its neighboring communities in which a lot of their local streets are one-way, the ability to create neighborway routes depends heavily on contraflow. For example, Brookline has a heavily used neighborway route through its Cottage Farm neighborhood that relies on contraflow on two streets (Essex and Ivy), and in Somerville, a new neighborway was recently been created by applying contraflow to Hancock Street (10), where opposing one-way restrictions prevent through auto traffic. It is noteworthy that while Boston’s bike network plan since 2013 has recommended the development of neighborways, the city has developed none yet, and probably will not be able to develop any without using contraflow.

1 LOW-STRESS BIKE NETWORK ANALYSIS

2 Furth, Mekuria, and Nixon (2) introduced the concept of low-stress bike network
 3 connectivity. They proposed a method for assigning a level of traffic stress to streets, and then
 4 measured the connectivity of the network that remains after high-stress links have been removed.
 5 This seminal work, which was applied in San Jose, paid no attention to one-way restrictions,
 6 treating street segments as undirected links, since San Jose has few one-way streets. Similarly,
 7 Furth et al. (11) used undirected links in a low-stress network study in northern Delaware.
 8 Wilmington, a city in that region, has a dense grid of one-way streets, but the authors reasoned
 9 that permitting two-way travel on every link would barely distort connectivity because cyclists
 10 would almost always have a parallel route nearby with the same stress level. However, our
 11 experience analyzing the Boston street network showed such an assumption is not valid where
 12 the local street grid is irregular; there may be a low-stress path from A to B but not from B to A.
 13 It is especially invalid where one-way restrictions are intended for traffic diversion, such as when
 14 a street is divided into one-way segments with opposing direction.

15 Some studies of low-stress bike networks, including Lowry et al. (12), have used network
 16 models with directed (that is, one-way) links, in which two-way streets are represented by a pair
 17 of links while one-way streets are modeled as a single link. However, its analysis of accessibility
 18 looked only at travel in one direction, that is, from home to a destination, without considering
 19 whether there is also a low-stress path to get back home.

20 METHODOLOGY

21 This section describes the two primary aspects of the methodology used to evaluate connectivity
 22 and accessibility in the presence of one-way restrictions. The first regards associating origin-
 23 destination (OD) demand from polygons to the street network, a general problem of bike
 24 network analysis that takes on greater importance where streets are one-way. The second regards
 25 the proposed measures of connectivity and accessibility accounting for one-way restrictions.
 26

27 Associating Demand Polygons (Blocks) to the Network

28 For accessibility studies, demand data such as population and jobs are generally provided in the
 29 form of polygons. This section addresses the issue of how to associate polygon-based demand
 30 data to the bike network, which consists of links and nodes.

31 Our study uses population and jobs data from the US Census (jobs data from its
 32 Longitudinal Employer-Household Dynamics program). Both are available at the level of Census
 33 blocks, which are usually the polygons bounded by the street network. However, as street
 34 networks have been edited over the years, block boundaries can differ slightly from the polylines
 35 representing streets, and new streets are sometimes added within a block.

36 Parcel data (smaller than blocks) have been used for bicycle travel (11) and for walk
 37 access to transit network (13). Conventional, auto-oriented transportation planning uses traffic
 38 analysis zones (TAZs), which are roughly a third of a census tract and are composed of many
 39 blocks. Travel modes other than auto are particularly sensitive to distance and to first- and last-
 40 mile access, and so for bicycle travel, the finer the scale of the demand polygons, the better.
 41 Polygons larger than blocks can readily be subdivided into blocks, with demand allocated by
 42 area, population, or other measure of block size.

1 In auto-oriented transportation planning, polygon-based demand is typically associated
 2 with the network by locating demand at a centroid, with connectors that are drawn to the
 3 surrounding nodes. A connector is a link that can be used as only the first or last segment of a
 4 trip. That allows all demand points within a polygon to reach the network via any of the
 5 polygon's surrounding nodes. For low-stress bicycle travel, where some streets are low-stress
 6 and others are not, centroid connectors to all the nodes surrounding a block or larger polygon is
 7 clearly distorting.

8 For bicycle travel, it is reasonable to assume that demand points (homes, jobs) must be
 9 accessed from a street segment, via an access point which can be considered their address. From
 10 that access point, people are expected to travel along the street segment to one end or the other,
 11 which will then be a node at which they can access the rest of the bike network.

12 Directly assigning demand to nodes is convenient for network analysis. Most GIS
 13 packages have a tool that will divide a study area into Thiessen polygons, also called Voronoi
 14 diagrams, which are the subareas closest to each node. Superimposing Thiessen polygons on the
 15 layer of blocks, the resulting polygons will be subareas of blocks that share a nearest node. A
 16 block's demand can then be allocated over its subareas in proportion to size. With a regular grid
 17 network and a street network that exactly matches block edges, this method of assignment is
 18 completely satisfactory. However, for practical bike network analysis, allocating demand based
 19 on proximity to nodes has several drawbacks.

20 First, in a real street network, the closest node may be completely outside the block. For
 21 example, in Figure 1, consider the block (partially shown in the figure) immediately to the left of
 22 the highlighted block. For part of that block, the closest node may be the endpoint of the cul de
 23 sac in the highlighted block. This is not a correct assignment as the cul-de-sac is not within or
 24 adjacent to the block where the demand is present. If the highlighted block were longer in the
 25 north-south direction, the end of that cul de sac would be the closest node to some of the area
 26 along the block's western edge – again, a clearly wrong assignment.

27 To guard against assigning demand to a foreign node, one might consider finding
 28 Thiessen polygons block by block, using only the nodes within or on the perimeter of a block.
 29 Besides being time consuming, this procedure is hampered by the fact that because nodes are not
 30 always *exactly* on the edge of a block, it is not trivial to find the set of nodes that are on the
 31 perimeter of a block. If one puts a small buffer around a block, there is a risk of including foreign
 32 nodes, especially when a block is bounded on one or more sides by a divided road represented by
 33 a pair of one-way road segments.

34 Rather than assigning demand directly to nodes, the general approach we have come to
 35 prefer assigns demand first to segments, and then makes assumptions about how travelers move
 36 along their segment to an endpoint (node), where they can access the network. To assign demand
 37 to street segments, we apply the Euclidean Allocation tool found in the ArcMap's Spatial
 38 Analyst toolbox to the study area, with the only inputs being the study area polygon and the
 39 street network. Euclidean Allocation creates a raster file (a file of pixels) and labels each pixel in
 40 the study area by the ID of its nearest street segment. This raster is then converted to a polygon
 41 file of segment catchment areas, with each polygon containing the pixels with same ID. These
 42 polygons are analogous to Thiessen polygons, except that they partition a plane into regions
 43 based on proximity to a set of line segments rather than points. Other GIS applications also have
 44 the tools available to perform Euclidean Allocation.

Segment catchments are then superimposed on the blocks to divide each block into sub-blocks. The demand of each block is then allocated over its sub-blocks in proportion to sub-block area, as given in Equation 1.

$$W_s = \frac{A_s}{A_b} * W_b \quad (1)$$

where

W_s = demand (weight) allocated to sub-block s

A_s = area of sub-block s

A_b = area of the parent block

W_b = demand (weight) of the parent block

Below, we describe four ways in which the demand allocated to a sub-block – and thus, to a street segment – accesses the street network. Each way implies different protocols for first and last block travel. The demand association techniques are illustrated in Figure 1.

Method A: Access the network mid-block

With this method, the demand associated with each street segment accesses the network at the mid-point of the street segment. All travelers to and from a segment are thereby forced to travel on that segment.

This has two important implications for low-stress accessibility. First, if a street segment is high-stress, the homes and destinations on it will be inaccessible. Second, if a street segment is low-stress but one-way, demand from points along the segment has to leave and return by different paths, and therefore demand points along this segment will be inaccessible unless both the ends of the street segment are connected to the low-stress network. Consider, for example, the homes along a one-way street that is only one block long, terminating at a low-stress street at one end and at a high-stress street at the other end. With Method A, all of those homes would be inaccessible, because travel either to or from this segment would have to use the adjoining high stress street.

This method of demand association does not consider that a person in such a situation might ride the wrong way on the first or last block, or might ride on the sidewalk (in either direction), or might walk their bike on the sidewalk. In comparison with the other methods, this method of association imposes the most restricting conditions for accessibility.

Method B: Access the network at either end of the street

With this method, the demand from a sub-block can access the network from either end of its associated street segment. It allows travelers to ignore both high traffic stress and one-way restrictions on their first and last segment. It is equivalent to allowing people to walk or ride their bike on the sidewalk, or (on a low-stress, one-way street) to ride in the street in the wrong direction, for any part of their first and last segment.

This method allows people to access the low-stress network even if they live or work on a high stress street as long as one of the two ends of the street segment containing their origin or destination is connected to the low-stress network. It is the most liberal method as regards first- and last-block travel, and will therefore lead to the highest measures of accessibility and

1 connectivity. Implementing this method involves creating a centroid for each sub-block, with
2 centroid connectors to endpoints of the associated street segment.
3

4 **Method C: Access the network at the nearest segment endpoint**

5 This method divides each sub-block into two polygons based on which segment endpoint is
6 closest, and allows access to the network only via the associated endpoint. When a sub-block is
7 divided, its demand is sub-allocated in proportion to area. For a given block, the resulting
8 polygons represents the subareas of the parent block closest to each half-segment of the street
9 network.

10 Like method B, traffic stress and direction restrictions on the first and last segment of a
11 trip are ignored. On their first and last segment, people are expected to walk or ride on the
12 sidewalk, or ride the wrong way in the street, but for no more than half a block, to reach the
13 closest intersection. For the one-way street segment described with Method A, all of the demand
14 points along that segment will be accessible with Method B, none will be accessible with Method
15 A, and half (those closest to the intersecting low-stress street) will be accessible with Method C.
16

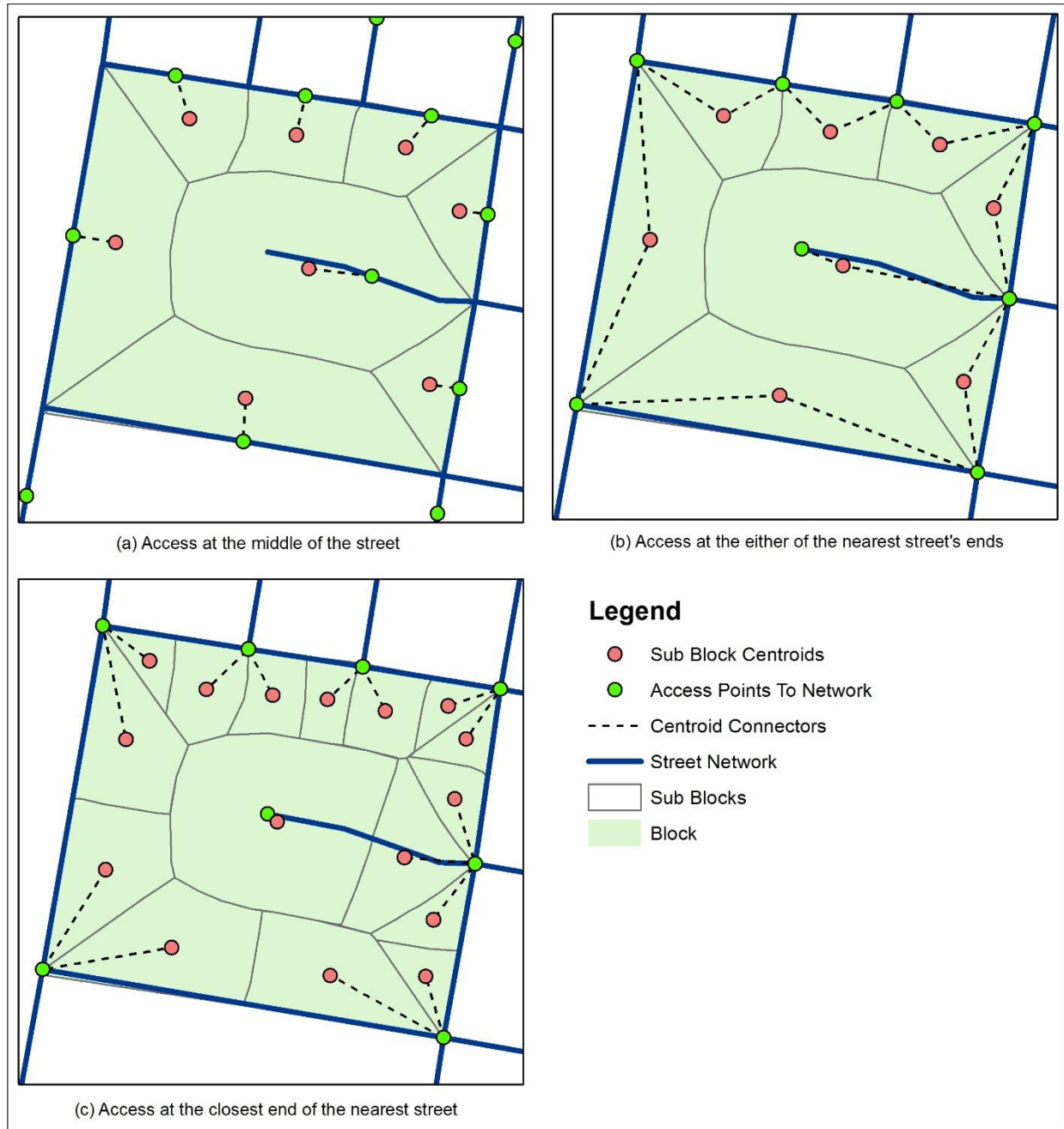


Figure 1 Methods for Associating Demand Polygons to a Street Network

It is also possible to use a combination of methods A, B, or C based on the block length. For example, on short segments, demand from sub-blocks can be assigned to both street-ends. On longer segments, the sub-blocks can be further broken down and their corresponding demand assigned to one of the street-ends or at mid-segment depending on their location along the segment. Our case study uses Method C, but tests methods A and B as a sensitivity test.

Connectivity Measures Accounting for One-Way Restrictions

Generalizing definitions found in (2) to account for one-way restrictions, a pair of points (i, j) is considered to be connected if there is a round trip path ($i-j-i$) between them on the low-stress network and if the round trip path does not have excessive detour. Detour is measured as the difference in length between the low-stress round trip route and the unrestricted round trip route (that, is, the shortest path without regard to traffic stress), expressed as a fraction of the unrestricted route length.

For this study, as in (11), to avoid the all-or-nothing effect of a single limiting amount of detour, we define two thresholds for detour, considering a pair of points fully connected if detour is less than 20%, fully disconnected if detour exceeds 100%, and partially connected in between. These threshold values are comparable to those proposed by Furth et al in (11). An analyst may choose different detour thresholds based on case study specific characteristics. Strength of connection c_{ij} , which ranges from 0 to 1, is given by Equation 2 and expresses the degree to which an OD pair $i-j$ is connected.

$$c_{ij} = \begin{cases} 1.25 * \left(2 - \frac{D_{Low_{ij}}}{D_{High_{ij}}}\right) & \text{if } \begin{aligned} &D_{Low_{ij}} \leq 1.2 * D_{High_{ij}} \\ &1.2 * D_{High_{ij}} < D_{Low_{ij}} \leq 2 * D_{High_{ij}} \\ &D_{Low_{ij}} > 2 * D_{High_{ij}} \end{aligned} \\ 0 \end{cases} \quad (2)$$

where

$D_{Low_{ij}}$ = distance of path $i-j-i$ on the low stress network

$D_{High_{ij}}$ = distance of path $i-j-i$ on the entire network (including high stress links)

when $i = j$ (origin and destination are located at the same spot), c_{ij} is set to 1.

As discussed earlier, demand originates on street segments, not at nodes. However, only distances measured along the network are used. The lengths of the first and last partial segment are ignored.

For a given origin i , the total number of jobs that are accessible on the low-stress network is A_i , as given in Equation 3, found by summing the number of jobs at all destinations j (D_j) weighted by the connectivity factor c_{ij} . Accessibility is a property of a node and of the subblocks that access the network via that node. As such, it can be mapped to indicate which areas of the city have high or low accessibility (many or few accessible jobs). Overall network connectivity X , given in Equation 4, is the fraction of all OD pairs in the network that are connected. It is also the weighted average of accessibility over all origins, divided by total destinations in the study area. In the rest of this study, connectivity is expressed as a percentage of total OD pairs connected as defined in Equation 4.

$$A_i = \sum_j (c_{ij} * D_j) \quad (3)$$

$$X = \frac{\sum_i (A_i * O_i)}{(\sum_i O_i) * (\sum_j D_j)} \quad (4)$$

As formulated for this study, these accessibility and connectivity measures do not include a distance-based propensity. It could be applied, as it has in other studies such as (11), by multiplying c_{ij} in Equation 3 by a decreasing function of $DLow_{ij}$ to reflect a declining willingness to use a bike over longer distances. Including a distance-based propensity is probably better for estimating bicycling demand, but for policy analysis, omitting it allows one to isolate the effect of bike network connectivity from the effect of distance, so that poor accessibility in neighborhoods that are distant from job centers is not “blamed” on the bike network.

As a practical matter, to speed data processing and avoid storing a large table of origin-destination results, shortest paths are calculated by looping over origin nodes i and finding the shortest path tree rooted there. To find the return paths from all nodes to i , directionality of all links is flipped, and we find a shortest return path tree terminating at i .

CASE STUDY

Greater Boston, including the municipalities of Boston, Brookline, Cambridge, and Somerville, is used as a case study site. Street network data, including bike paths, is available on MassGIS website, published by Massachusetts Department of Transportation. Bike path and bike lane data were also obtained from municipalities directly.

MassGIS street network data contain fields indicating whether a street is one-way and its direction. We found the one-way data to be unreliable – many streets coded as two-way are actually one-way. Therefore, we manually verified each street’s directionality against Google Maps. (Because Google Maps is widely used for navigation, its directionality information was assumed to be correct.) To facilitate the data cleaning process, we created an app in GIS that symbolizes one-way streets with an arrow and allows a person to easily flag and correct streets with incorrect direction data.

Data on bicycle contraflow was likewise manually checked. It is important that contraflow be coded explicitly so that a street’s direction can be identified as two way for bikes and one-way for cars. In the study area, one-ways constitute over 25% of street mileage (Table 1), excluding freeways. Most of these one-ways are local streets. Only 0.6% of the study area’s one-way street mileage has contraflow, most of it on local streets. For this purpose, two-way streets with a median were counted as two-way streets, even if they are modeled in GIS as a pair of one-ways.

Table 1 Mileage Details of One-Ways in the Study Area

	Mileage	Mileage with Contraflow
Local One-way	324.3	1.74 (0.5%)
Non-Local One-Way	85.6	0.6 (0.7%)
All One-Way Streets	409.9	2.34 (0.6%)
All Streets	1,526.6	

Both the current street network and a proposed network were analyzed to discern the effect of one-way restrictions. The current street network has rather poor connectivity overall based on our analysis, with less than 2% of all the possible home to work trips are possible using only the low-stress links. The case study also examines a scenario using the Bikeways for

1 Everybody (BforE) network proposed by the Boston Cyclists Union, which is a dense grid of
2 low-stress main bike routes through the study area. The BforE network includes 27 miles of
3 contraflow, including 3 miles on local streets and 24 miles on non-local streets. Every street in
4 the study area was assigned a level of traffic stress (LTS) based on LTS version 2.0 criteria (14).
5 Figure 2 maps the study area's local and non-local one-way streets overlaid on its non-local, low-
6 stress streets and paths in both present day and BforE networks.
7

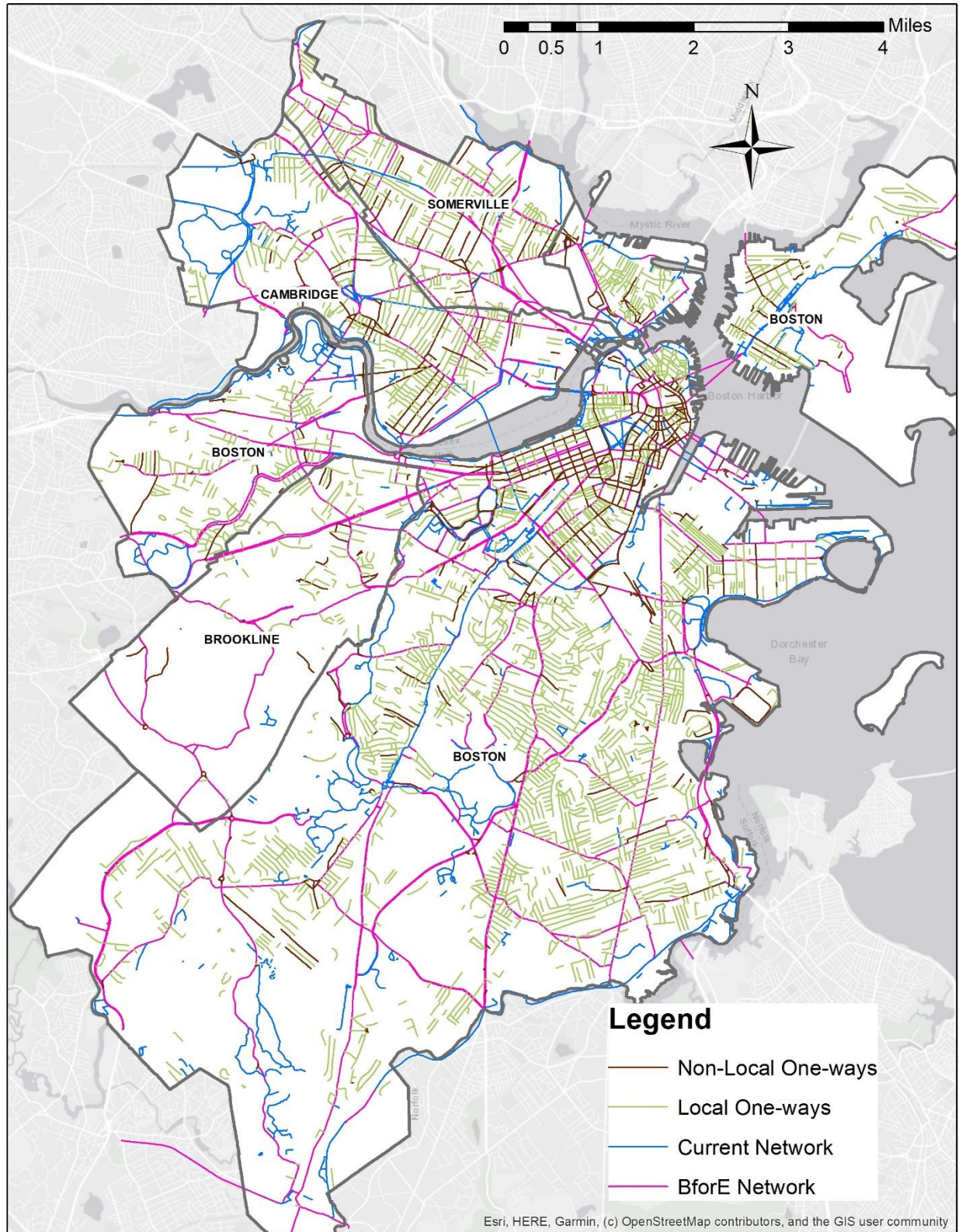


Figure 2 Greater Boston Area Showing One-Way Streets Overlaid with Present Day and BforE Bike Networks

Results

Connectivity for the current network and the proposed Bikeways for Everybody (BforE) network is given in Table 2 for a base case and several alternative scenarios. The base measurement accounts for one-way restrictions and the need for round trip travel, and uses method C for associating demand to the network. In the current network, low-stress connectivity is 1.2% of all possible home-based-work trips, while with BforE, it is 64%. The low level of connectivity in the current network stems mainly from the lack of through routes, while in the BforE case, it stems mainly from small, scattered pockets that are not connected to the through routes.

Results are quite sensitive to the method chosen to associate demand with the network. While we found connectivity to be 1.2% with method C, which allows sidewalk riding or wrong-way riding for up to half of the first- and last-block length, connectivity was only 0.7% with method A, which imposes the strictest conditions on first- and last-block travel, and was 1.4% with method B, which is the most liberal in terms of first- and last-block travel conditions. The results for the different demand association methods follow a similar trend for the BforE network scenario. We chose method C as our base method of demand association as it offers a good balance between the two extreme assumptions in methods A and B.

Table 2 Connectivity of the Current and BforE Networks Using Different Demand Association Methods

	Current network	Bikeways for Everybody network
With demand association method C (base)	1.2%	64.0%
With demand association method A	0.7%	46.0%
With demand association method B	1.4%	72.2%
One-way connectivity, home to job (method C)	1.8%	71.5%
One-way connectivity, job to home (method C)	2.3%	72.4%
With contraflow everywhere (change)	12.1% (+10.9%)	81.9% (+17.9%)
With contraflow on all local streets (change)	8.7% (+7.5%)	80.4% (+16.4%)

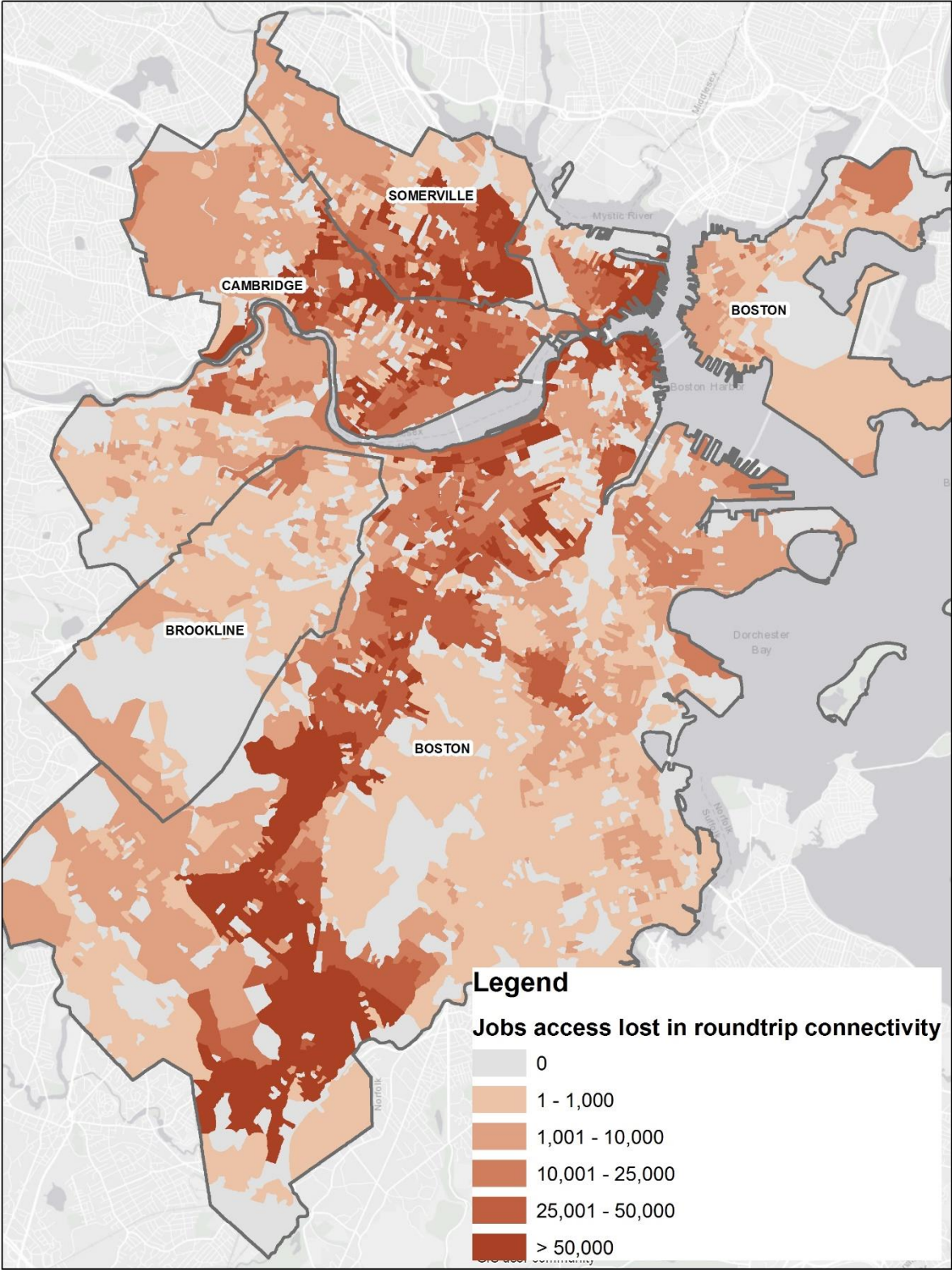
The results also confirm the importance of measuring connectivity in terms of round trips rather than one-way. Connectivity appears to be 1.8% when travel in only the home-to-job direction is considered, and 2.3% if travel in the opposite direction were considered instead. However, when round trips are considered (base case), connectivity is only 1.2%. Because round trip accessibility has a “weakest link” relationship between outbound and inbound route for every OD pair, average round trip accessibility is worse than both average outbound and average inbound accessibility. The distortion from neglecting to consider round trips is not evenly spread across the city, but is concentrated in certain neighborhoods where one-way patterns facilitate low-stress bike travel in one direction but not another, as shown in Figure 3.

Table 2’s results indicate that one-way restrictions have a large barrier effect in the current network, reducing connectivity from 12.1% to 1.2% – meaning that area residents have 90% fewer jobs accessible via low-stress bicycling because of one-way restrictions. Allowing

1 contraflow on local streets only would undo much of that harm, bringing connectivity back up to
2 8.7%, giving area residents low-stress accessibility to 7 times more jobs than currently. Figure 4
3 shows the geographic distribution of accessibility gains from implementing local street
4 contraflow. Neighborhoods with a lot of one-way streets such as Dorchester, Roxbury, and much
5 of Somerville would gain low-stress bike access to over 100,000 jobs. Large gains can also be
6 seen in Hyde Park, a neighborhood with few one-way streets, because of new low-stress routes
7 created through adjacent neighborhoods.

8 Even with the Bikeway for Everybody network, the impact of one-way restrictions is
9 large – removing those restrictions on local streets only would increase connectivity from 64% to
10 80%. This result shows that to achieve good bike connectivity, it is not enough to provide a
11 dense mesh of through routes. The barrier of one-way restrictions also has to be removed so that
12 streets and small neighborhoods are not cut off from the low-stress bike network.

13 Table 2 shows a very small impact of contraflow on non-local streets in the BforE case.
14 This does not indicate any lack of need for contraflow on non-local streets; rather, this result
15 arises only because the Bikeways for Everybody network already includes contraflow on critical
16 non-local streets.



1
2 **Figure 3 Difference Between Number of Accessible Jobs with Single Direction versus**
3 **Roundtrip**

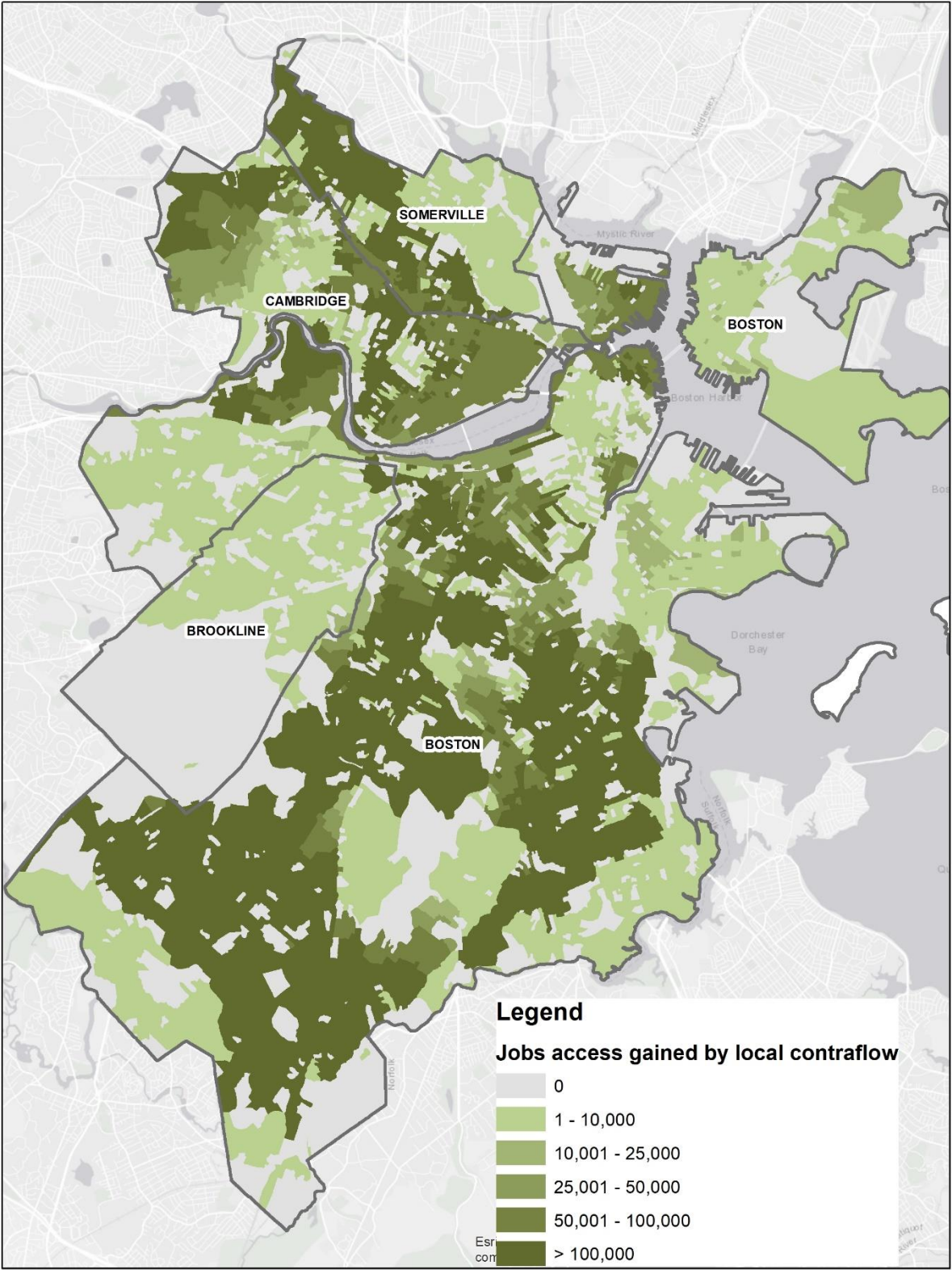


Figure 4 Jobs Access Gained by Adopting Local Contraflow

1 PRIORITIZING STREETS FOR CONTRAFLOW CONVERSION

2 Not every one-way street would contribute the same to improving low-stress bike connectivity if
 3 contraflow were allowed on it. One might ask, if only limited application of contraflow is
 4 allowed, where would it best applied? Several criteria might be considered, including safety,
 5 local attitudes, and the current level of wrong-way riding observed, as suggested by Burkin (10).
 6 Another is the degree to which a street, in the context of the city's bike network, would
 7 contribute to improved overall connectivity to jobs or other destinations of interest.

8 Following Lowry (12), we propose using "weighted centrality" as an approximate
 9 measure of a street's contribution to overall connectivity. In graph theory, an edge's or link's
 10 centrality is the number of OD pairs (node pairs) for which the link is part of the shortest path.
 11 With weighted centrality, each OD pair is weighted by the size of the origin and the destination
 12 as shown in Equation 5. McDaniel, Lowry, and Dixon (15) found that weighted centrality
 13 correlated well with observed bicycle counts.

$$WC(e) = \sum_i \sum_j O_i * D_j * e_{ij} \quad (5)$$

15 where

16 $WC(e)$ = weighted centrality of edge (link) e

17 O_i = Population at origin i

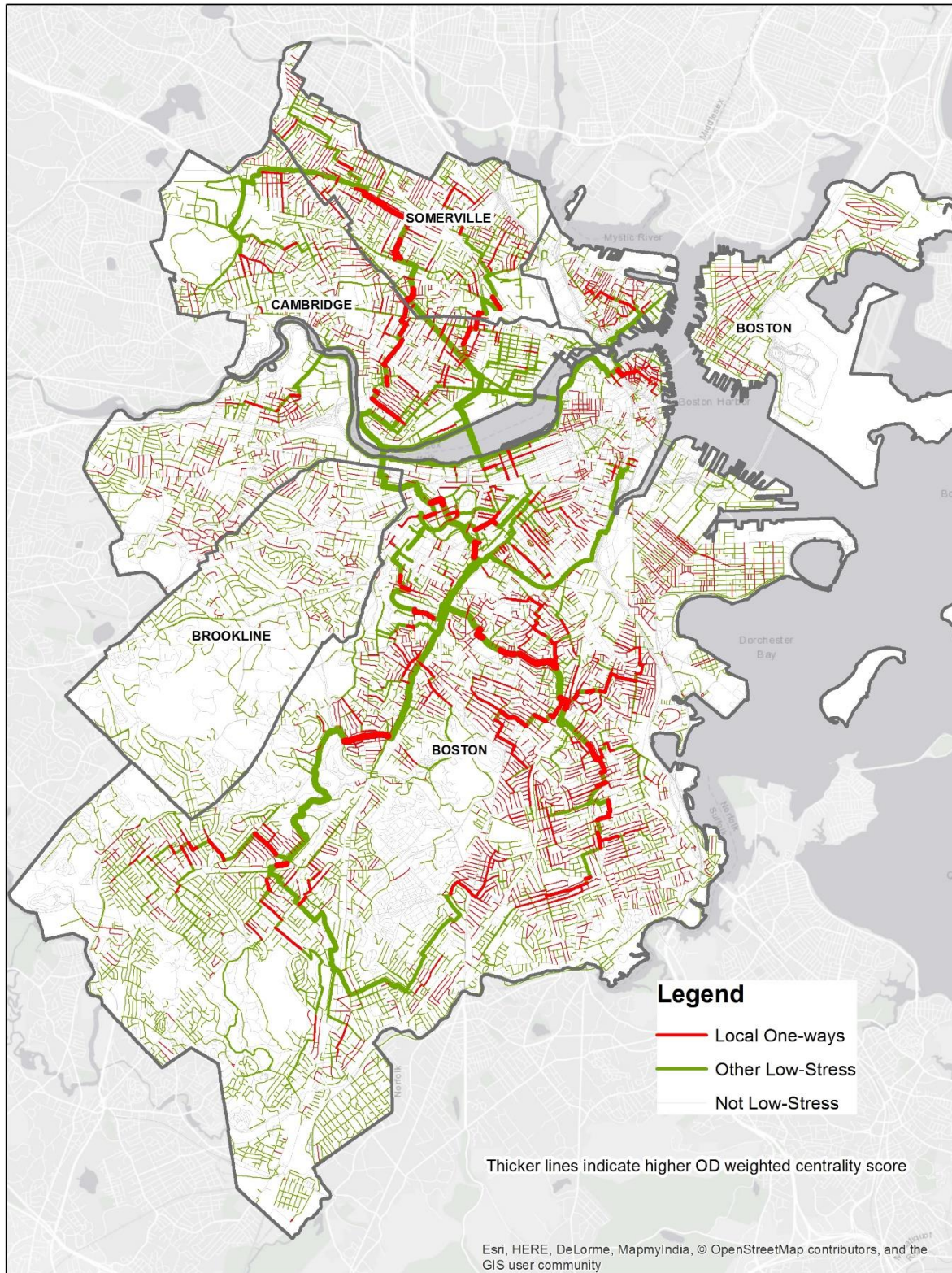
18 D_j = Jobs at destination j

19 $e_{ij} = 1$ if edge e is on the shortest path from i to j ; 0 otherwise

20
 21 A link's weighted centrality will be greater if it is part of shortest paths between origins
 22 and destinations with a large number of population and jobs, respectively. Weighted centrality
 23 cannot be seen as an exact measure of incremental contribution because any street's contribution
 24 to connectivity is dependent on which other streets have contraflow. However, in real networks,
 25 these dependencies have a predictable character, and so we believe that as long as the total
 26 number of links that can be changed is more than a few, difference in weighted centrality will be
 27 a good measure of contribution in any scheme that reasonably selects links for improvement.

28 Figure 5 shows the weighted centrality on every link (thicker means more people are
 29 expected to use it) if contraflow were allowed on all local streets. Local one-way streets are
 30 shown in red color. Thus, heavy red lines indicate streets that would likely see a lot of bicycle
 31 use if contraflow were allowed. Segments like this can be found in many study area
 32 neighborhoods. Of interest to the authors is that one of them, Leon Street, is a street on our
 33 university campus on which we both ride the wrong way daily.

34 One element that increases a link's centrality is when it helps make a connection with the
 35 network's existing main bike routes such as the Charles River Path and Southwest Corridor Path.
 36 This result confirms guidance from Burkin (10) that a connection to an existing path makes
 37 contraflow more valuable.



1
2

Figure 5 Centrality Map of the Street Network. Thicker Lines Represent Higher Centrality

With local one-way segments sorted based on their centrality score, we applied contraflow in increments of 10 miles to the current network, increasing low-stress connectivity as shown in Figure 6. Each 10-mile increment represents about 3% of the study area's one-way mileage. The figure shows big gains for the first few increments, with decreasing returns. Adding contraflow to 10 miles of one-way streets with the greatest change in weighted centrality increases connectivity to 4.1%, which is nearly 40% of the gain that would be realized by adopting universal contraflow on local streets. This shows that a substantial fraction of the benefit of local contraflow could be realized at relatively little cost.

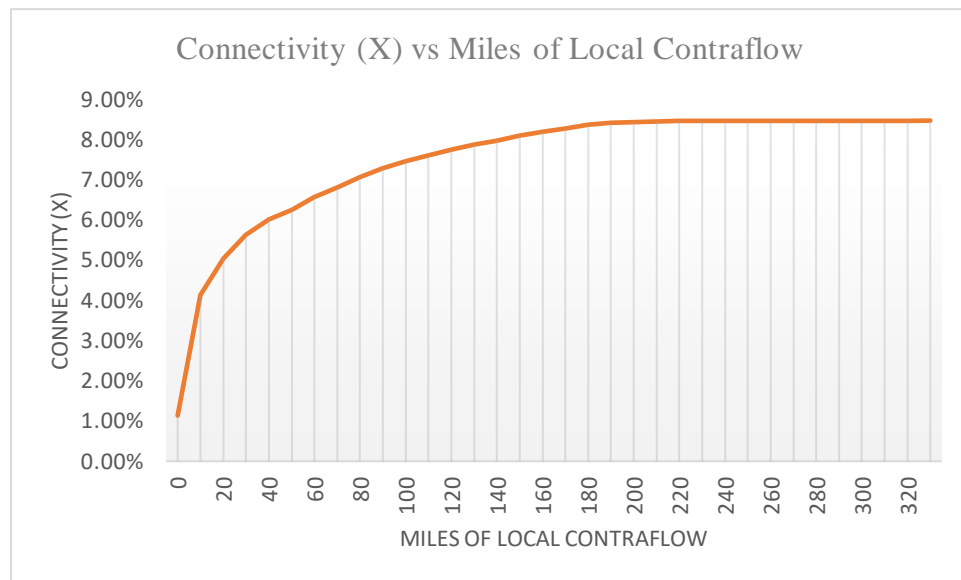


Figure 6 Incremental Benefits of Local Contraflow

CONCLUSION

One-way restrictions can create a significant barrier to low-stress cycling. In the Greater Boston area, these one-ways reduce low-stress network connectivity by 90%. Allowing contraflow on all local one-way streets – a practice followed in several European countries restores most of the connectivity lost due to one-ways. Applying contraflow to only 3% of local streets can achieve 40% of the total gain possible if streets are chosen based on change in weighted centrality.

In a city with a lot of one-way streets, creating a dense network of through routes does not obviate the need for contraflow, without which many streets and small neighborhoods may still be unable to access the low-stress bike network. At the same time, in cities with many one-way streets, contraflow can be an indispensable tool for developing neighborways (bike boulevards).

Methodologically, where there are one-way restrictions, measures of accessibility and connectivity will be distorted unless roundtrip connectivity is accounted for. The method by which demand data, which generally comes in polygons, is associated to the street network, can be critical for analysis involving one-way streets, because it determines what kind of first- and last-block travel is permissible.

1 AUTHOR CONTRIBUTION STATEMENT

- 2 The authors confirm contribution to the paper as follows: study conception and design: Furth and
3 Putta; data collection and GIS modeling: Putta; analysis and interpretation of results: Putta and
4 Furth; draft manuscript preparation: Putta and Furth. All authors reviewed the results and
5 approved the final version of the manuscript.

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