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Impact of One-Way Streets and Contraflow on Low-Stress Bicycle Network Connectivity

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Abstract

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

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

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

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

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

One-Way Streets and Contraflow

Virtually every one-way street that exists today was originally two-way. Conversion to one-way has generally been for one of three reasons, all related to growth in automobile use beyond the level for which the streets were built. On local streets in older neighborhoods, the main reason for one-way restrictions has been to create more space for parking, leaving a single-lane channel for moving traffic. A second and more recent reason for one-way restrictions on local streets is to divert through traffic away from neighborhood streets by making it either impossible or difficult to cut through a neighborhood. One-way restrictions intended as traffic diversions have been applied systematically in some places such as Boston's South End neighborhood and in Brookline (MA), near the Boston University Bridge. Finally, on arterial streets, one-way 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 also be applied to bikes? A street may be too narrow for autos to pass 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 that, in general, are safer than arterials.

Contraflow can be provided in one of three ways. The method best known in the United States 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 the 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, in 2015 France joined Belgium and the 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 United States, bikeway design guides published by both the National Association of City Transportation Officials (*8*) and AASHTO (*9*) offer guidance for designing contraflow streets, but neither indicates whether contraflow ought to be applied routinely or sparingly. The number of contraflow applications in the United States is generally understood to be small; for example, in the city of Boston, although there are more than 100 mi of one-way streets, only one short block has bicycle contraflow.

Contraflow and Neighborways (Bike Boulevards)

Several 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 created by applying contraflow to Hancock Street (*10*), where opposing one-way restrictions prevent through auto traffic. It is noteworthy that whereas Boston's bike network plan since 2013 has recommended the development of neighborways, the city has yet to develop any, and probably will not be able to without using contraflow.

Low-Stress Bike Network Analysis

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

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

Methodology

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

Associating Demand Polygons (Blocks) with the Network

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

Our study used population and jobs data from the U.S. census (jobs data were from its Longitudinal Employer–Household Dynamics program). Both are available at the level of census blocks, which are usually the polygons bounded by the street network. However, as street networks have been edited over the years, block boundaries can differ slightly from the polylines representing streets, and new streets are sometimes added within a block.

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

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

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

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

First, in a real street network, the closest node may be completely outside the block. For example, in Figure 1, consider the block (partially shown in the figure) immediately to the left of the highlighted block. For part of that block, the closest node may be the endpoint of the cul-de-sac in the highlighted block. This is not a correct assignment as the cul-de-sac is not within or adjacent to the block where the demand is present. If the highlighted block were longer in the north–south direction, the end of that cul-de-sac would be the closest node to some of

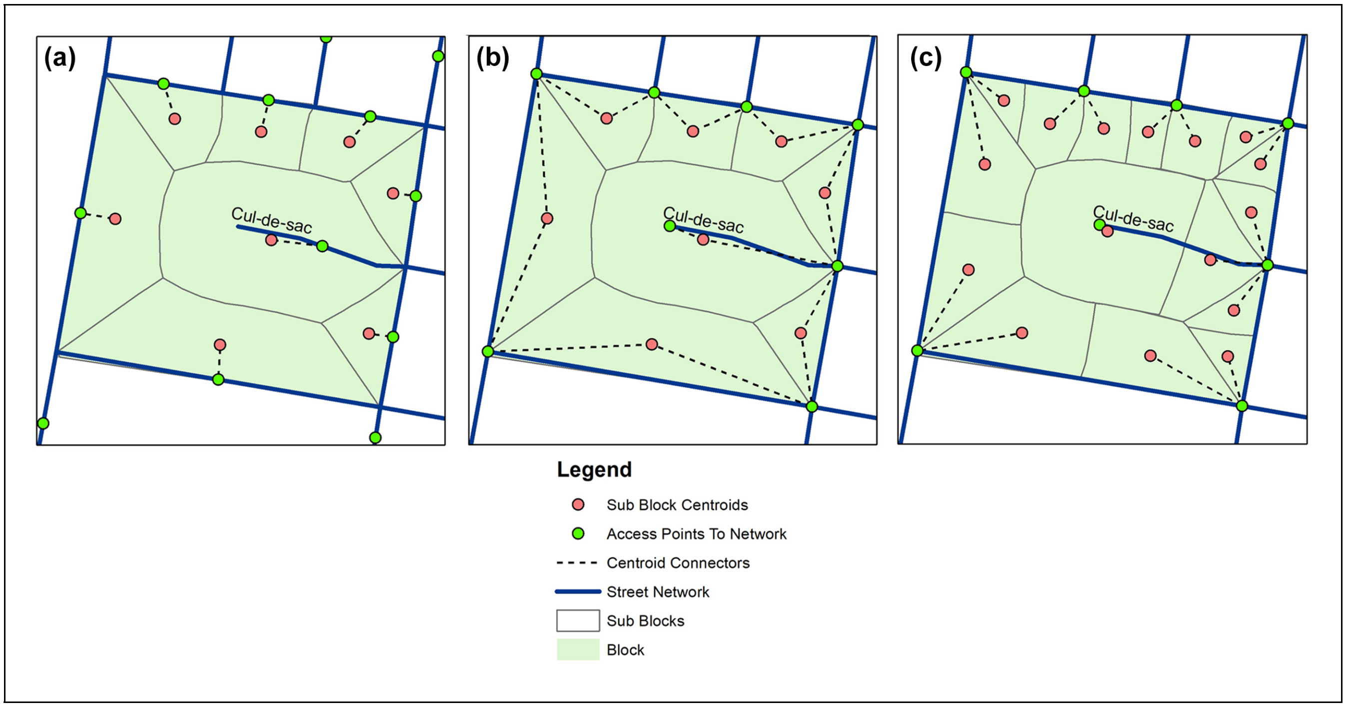

Figure 1. Methods for associating demand polygons with a street network. (*a*) Access at the middle of the street; (*b*) access at either of the nearest street's ends; (*c*) access at the closest end of the nearest street.

the area along the block's western edge—again, a clearly wrong assignment.

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

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

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

$$W_s = \frac{A_s}{A_b} * W_b \tag{1}$$

where

$W_s =$ demand (weight) allocated to subblock s,
$A_s =$ area of subblock s,
$A_b =$ area of the parent block, and
$W_b =$ demand (weight) of the parent block.

In the following sections, we describe three ways in which the demand allocated to a subblock—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 restrictive conditions for accessibility.

Method B: Access the Network at Either End of the Street

With this method, the demand from a subblock 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 connectivity. Implementing this method involves creating a centroid for each subblock, with centroid connectors to the endpoints of the associated street segment.

Method C: Access the Network at the Nearest Segment Endpoint

This method divides each subblock into two polygons based on which segment endpoint is closest, and allows access to the network only via the associated endpoint. When a subblock is divided, its demand is suballocated in proportion to area. For a given block, the resulting polygons represent the subareas of the parent block closest to each half-segment of the street network.

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

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 subblocks could be assigned to both street ends. On longer segments, the subblocks could 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 used Method C, but tested Methods A and B as a sensitivity test.

Connectivity Measures Accounting for One-Way Restrictions

Generalizing definitions found in Furth et al. 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 (*2*). Detour is measured as the difference in length between the low-stress round trip route and the unrestricted round trip route (i.e., the shortest path without regard to traffic stress), expressed as a fraction of the unrestricted route length.

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

$$c_{ij} = \begin{cases} 1 & DLow_{ij} \leq 1.2 * DHigh_{ij} \\ 1.25 * \left(2 - \dfrac{DLow_{ij}}{DHigh_{ij}}\right) & if\ \ 1.2 * DHigh_{ij} < DLow_{ij} \leq 2 * DHigh_{ij} \\ 0 & DLow_{ij} > 2 * DHigh_{ij} \end{cases} \tag{2}$$

where

$DLow_{ij}$ = distance of path *i-j-i* on the low-stress network,

$DHigh_{ij}$ = distance of path i-j-i on the entire network (including high-stress links), and
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 is 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 O-D 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 was expressed as a percentage of total O-D pairs connected, as defined in Equation 4.

$$A_i = \sum_j \left(c_{ij} * D_j\right) \tag{3}$$

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

As formulated for this study, these accessibility and connectivity measures did not include a distance-based propensity. It could be applied, as it has been in other studies such as Furth et al. (*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 O-D results, shortest paths were 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 was flipped, and we found a shortest return path tree terminating at i.

Case Study

Greater Boston, including the municipalities of Boston, Brookline, Cambridge, and Somerville, was used as a case study site. Street network data, including bike paths, are available on the 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 were 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 were modeled in GIS as a pair of one-ways.

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 being achievable using only low-stress links. The case study also examined a scenario using the Bikeways for Everybody (BforE) network proposed by the Boston Cyclists Union, which is a dense grid of low-stress main bike routes through the study area. The BforE network includes 27 mi of contraflow, including 3 mi on local streets and 24 mi on nonlocal streets. Every street in the study area was assigned a level of traffic stress (LTS) based on LTS version 2.0 criteria (*14*). Figure 2 maps the study area's local and nonlocal one-way streets overlaid on its nonlocal, low-stress streets and paths in both present day and BforE networks.

Results

Connectivity for the current network and the proposed BforE network is given in Table 2 for a base case and several alterative scenarios. The base measurement accounts for one-way restrictions and the need for round trip travel, and uses Method C for associating demand with the network. In the current network, low-stress connectivity was 1.2% of all possible home-based-work trips, whereas with BforE, it was 64%. The low level of

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

	Mileage	Mileage with contraflow
Local one-way	324.3	1.74 (0.5% of local one-way mileage)
Nonlocal one-way	85.6	0.6 (0.7% of nonlocal one-way mileage)
All one-way streets	409.9	2.34 (0.6% of overall one-way mileage)
All streets (one-ways and two-ways)	1,526.6	na

Note: na = not applicable.

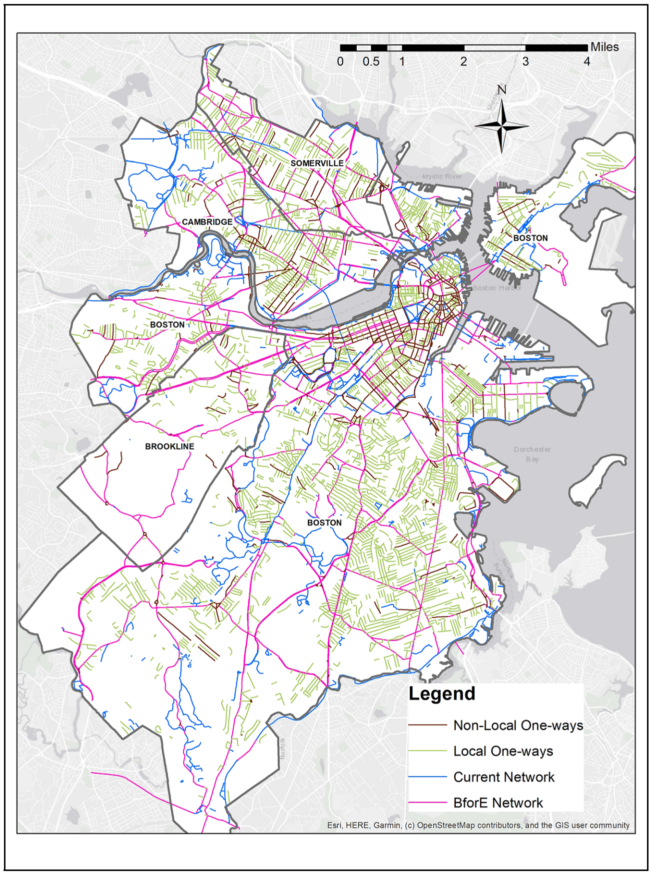

Figure 2. Greater Boston area showing one-way streets overlaid with present day and Bikeways for Everybody (BforE) bike networks.

connectivity in the current network stemmed mainly from the lack of through routes, whereas in the BforE case, it stemmed mainly from small, scattered pockets that were not connected to the through routes.

The results were quite sensitive to the method chosen to associate demand with the network. Although 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 relation to first- and last-block travel conditions. The results for the different demand association methods followed similar trends 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 Bikeways for Everybody 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 confirmed the importance of measuring connectivity in relation to round trips rather than one-way. Connectivity appeared to be 1.8% when travel in only the home-to-job direction was considered, and 2.3% if travel in the opposite direction was considered instead. However, when round trips were considered (base case), connectivity was only 1.2%. Because round trip accessibility had a "weakest link" relationship between outbound and inbound routes for every O-D pair, average round trip accessibility was worse than both average outbound and average inbound accessibility. The distortion from neglecting to consider round trips was not evenly spread across the city, but was 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 there are 90% fewer jobs accessible to area residents via low-stress bicycling because of one-way restrictions. Allowing contraflow on only local streets would undo much of that harm, bringing connectivity back up to

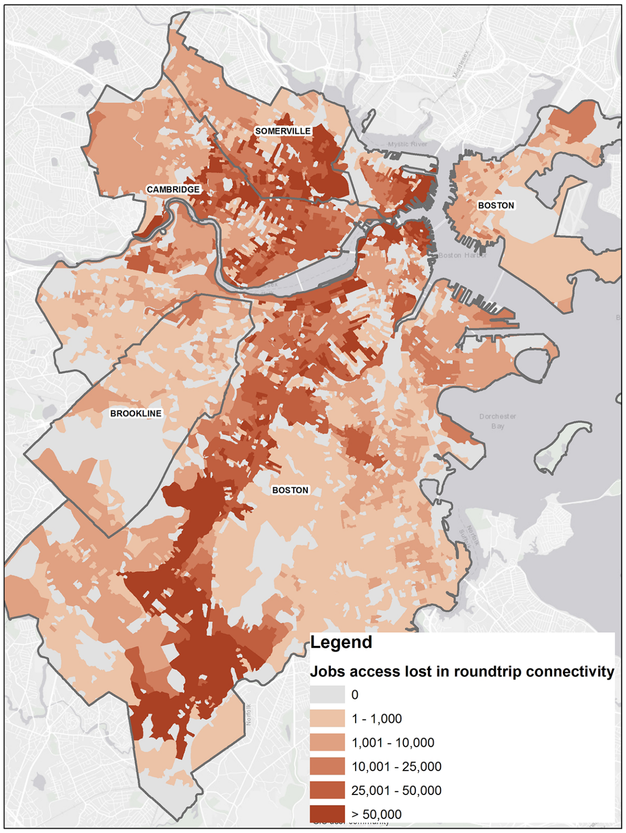

Figure 3. Difference between number of accessible jobs with single direction versus round trip.

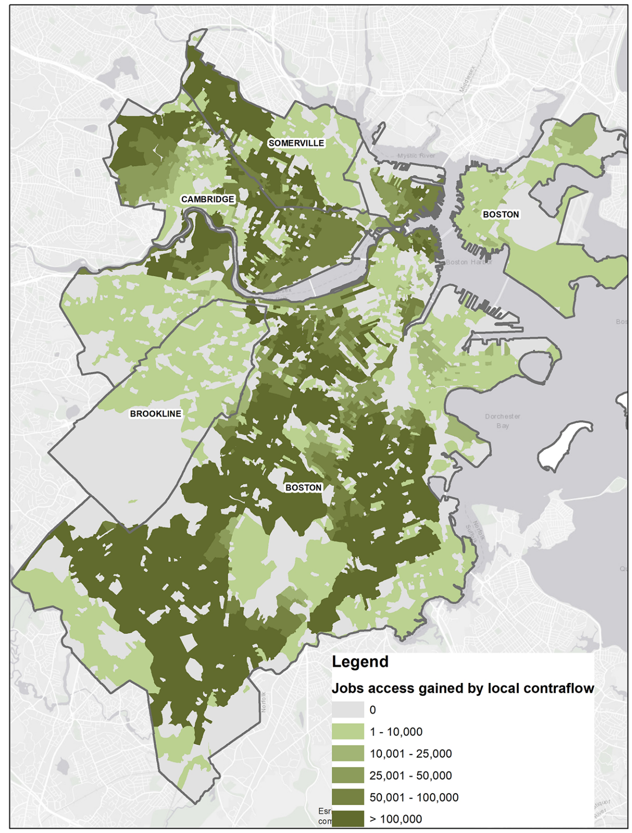

Figure 4. Jobs access gained by adopting local contraflow.

8.7%, giving area residents low-stress accessibility to seven times more jobs than they currently have. Figure 4 shows the geographic distribution of accessibility gains from implementing local street contraflow. Neighborhoods with a lot of one-way streets, such as Dorchester, Roxbury, and much of Somerville would gain low-stress bike access to over 100,000 jobs. Large gains can also be seen in Hyde Park, a neighborhood with few one-way streets, because of new low-stress routes created through adjacent neighborhoods.

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

Table 2 shows a very small impact of contraflow on nonlocal streets in the BforE case. This does not indicate a lack of need for contraflow on nonlocal streets; rather, this result arose only because the BforE network already includes contraflow on critical nonlocal streets.

Prioritizing Streets for Contraflow Conversion

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

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

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

where
$WC(e)$ = weighted centrality of edge (link) e,
O_i = population at origin i,
D_j = jobs at destination j, and
e_{ij} = 1 if edge, e, is on the shortest path from i to j; 0 otherwise.

A link's weighted centrality is dependent not only on the number of shortest paths it is part of but also on the number of pupulation and jobs connected by those shortest paths. Weighted centrality cannot be seen as an exact measure of incremental contribution because any street's contribution to connectivity is dependent on which other streets have contraflow. However, in real networks, these dependencies have a predictable character, and so we believe that as long as the total number of links that can be changed is more than a few, the difference in weighted centrality will be a good measure of contribution in any scheme that reasonably selects links for improvement.

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

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

With local one-way segments having been sorted based on their centrality score, we applied contraflow in increments of 10 mi to the current network, increasing low-stress connectivity as shown in Figure 6. Each 10-mi 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 mi 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 showed that a substantial fraction of the benefit of local contraflow could be realized at relatively little cost.

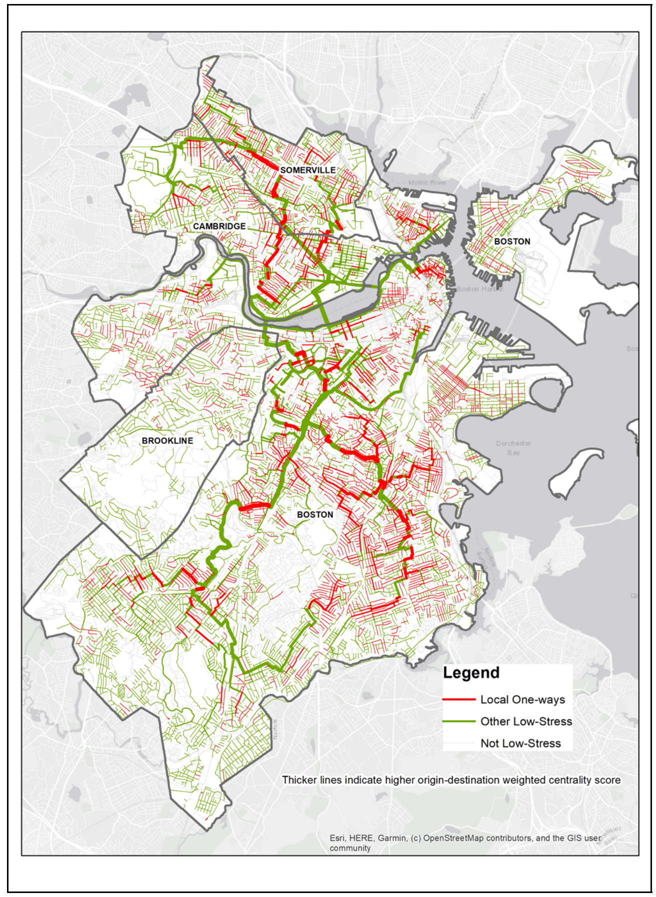

Figure 5. Centrality map of the street network. Thicker lines represent higher centrality.

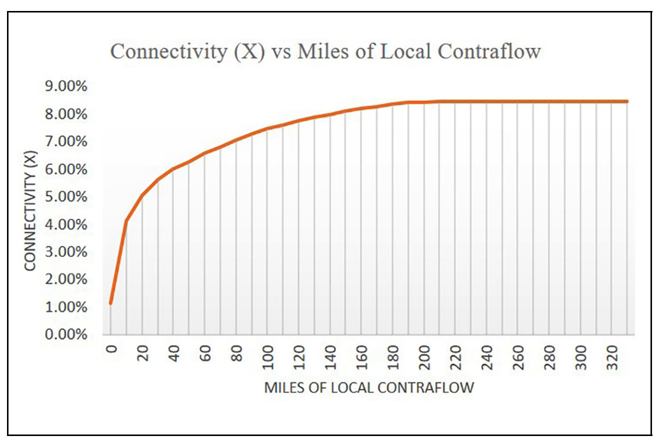

Figure 6. Incremental benefits of local contraflow.

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 from one-ways. Applying contraflow to only 3% of local streets could achieve 40% of the total gain possible if streets were 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 round trip connectivity is accounted for. The method by which demand data, which generally come in polygons, is associated with 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.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: P.G. Furth, T. Putta; data collection: T. Putta; analysis and interpretation of results: T. Putta, P.G. Furth; draft manuscript preparation: T. Putta, P.G. Furth. All authors reviewed the results and approved the final version of the manuscript.

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