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A cycling-focused accessibility tool to support regional bike network connectivity

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ABSTRACT

Many cities in the United States are working to become more "bike-friendly" through the provision of new bike infrastructure that is safe and attractive for all types of cyclists, from the timid to assured. These efforts are supported by evidence associating low level of traffic stress facilities with increased cycling activity rates and co-benefits related to the economy, environment, and public health. However, not every mile of bike infrastructure provides the same utility, prompting planning agencies with finite financial resources to search for empirical methods to help evaluate what projects will provide the greatest network connectivity benefit and how disparate projects can complement one another to produce a complete bike network. In this study, we introduce the Cyclist Routing Algorithm for Network Connectivity (CRANC), an accessibility-oriented decision-support tool designed to quantify the benefits of new bike facilities for various populations and neighborhoods. Unlike prior tools, this method simulates the route preferences of different cyclist types and trade-offs in travel time and level of traffic stress to model potential changes in destination accessibility that may result from multiple scenarios of citywide and regional bike network expansion. Here, CRANC is applied to the Boston region's bike network to determine how a proposed shared-use path in Cambridge, Massachusetts will improve accessibility to regional job opportunities and to labor force for employment sites in Cambridge. Our introduced decision-support tool produces unique, meaningful results relevant to a variety of stakeholders, and holds promise as a new resource for transportation researchers and practitioners.

1. Introduction

Many cities across the United States are striving to increase their cycling activity rates in order to create economic, environmental, and health-related benefits for their residents, workers, and visitors. Commonly, the provision of safe bike infrastructure is a key strategy to realize this vision (Pucher et al., 2011, Bigazzi and Gehrke, 2018); with many communities working to become more "bike-friendly" by planning, designing and implementing shared-use paths, cycle tracks, bike lanes, and other missing connections to create a comprehensive "low stress" bike network (Furth et al., 2016). Yet, not every mile of newly created bike infrastructure is likely to be equal: as with roadways, some links (for instance, those connecting major activity centers or portions of a regional

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network) will have higher utility for travelers, while disconnected, redundant, or remote pathways will be useful to fewer current or potential cyclists, and will see lower rates of utilization. The questions for city, regional, and state policymakers, who always have finite financial resources to spend on transportation projects, are (i) which connections will provide the greatest increase in network connectivity and any corresponding co-benefits; and (ii) how could corridor-level projects or grander visions complement each other to make a safer and more complete bike network.

Recently, transportation professionals and decisionmakers have started to evaluate such projects through the lens of destination accessibility, which measures how many important destinations can be reached (by a specified mode of travel) from a particular place with a given level of effort. To support this approach, some researchers have developed bike network connectivity analytic methods (Iacono et al., 2010, Lowry and Loh, 2017, Furth et al., 2018, Kent and Karner, 2019) to help prioritize what bike infrastructure projects may best improve regional bicycle accessibility to activity destinations. In general, these existing bike network connectivity tools use shortest-path algorithms to route potential trips on eligible links and summarize the number of opportunities available in a specified distance. While promising, these planning tools have yet to account for factors other than distance and travel time in cyclist routing choices; they assume zero tolerance for "high-stress" links, no matter how short; and they lack sensitivity to the differential value of nearby versus more distant opportunities.

In response, this study aims to introduce a new decision-support tool that uses a network routing engine to quantify the potential accessibility improvements that could result from the realization of different bike network scenarios. Specifically, this replicable and transferable network connectivity tool estimates the number of additional destinations (e.g., job locations) that could be reached by residents and the number of workers that could access a given employment site.

Our approach differs from prior methods in some important ways: we use a network routing engine that (i) accounts for topography, travel speed, and varying facility preferences for different types of cyclists; (ii) allows less confident cyclists to have some (user-specified) tolerance for higher stress segments; and (iii) calculates travel time as a function of cyclist type as well as facility characteristics. We then assess the portion of each modeled route that is spent on high- and low-stress links and present the results as cumulative opportunity values segmented by travel time as well as share of trip on higher stress links. By then comparing alternative transportation scenarios, the resulting tool is used to quantify the destination accessibility benefits of various bike network improvements. Results are produced at a Census block geography and can be summarized for any given study area. Moreover, in this study, two cyclist types are analyzed: an "interested but concerned" group that prefers traffic separation and an "enthused and confident" group primarily concerned with minimizing travel time, with little aversion to interacting with vehicle traffic.

2. Literature review

2.1. Cyclist types

Typologies are an effective analytic method to help understand how variations in the sociodemographic, economic, and psychosocial characteristics of individuals in a population relate to the effective planning of policies and programs to reach priority populations (Dill and McNeil, 2016, Chaloux and El-Geneidy, 2019). In active transportation research, cyclist profiles derived from anecdotal or more objective evidence have been fashioned to identify possible barriers to increasing cycling activity. Since cyclists react differently to programmatic interventions and infrastructure improvements (Damant-Sirois et al., 2014), an adoption of cyclist types can be insightful to ensure cycling promotion efforts induce desired mode shift among potential cyclists, rather than only benefitting those who are already cycling (Gatersleben and Haddad, 2010).

A widely adopted cyclist typology was proposed by the Bicycle Coordinator of the City of Portland, Oregon in 2006 (Geller, 2006). In "Four Types of Cyclists," Geller (2006) noted three general cyclist categories who express varying sentiment for the personal safety afforded by bicycle transportation ("The Strong and the Fearless," The Enthused and the Confident," and "The Interested but Concerned") and a final category of non-cyclists ("No Way No How"). An empirical examination of Geller's typology found that two-thirds of Portland area residents were classified as either "Enthused and Confident" or "Interested but Concerned" (Dill and McNeil, 2013). Alleviating the safety concerns of the latter cyclist type, who represent an estimated one-half of adult travelers in the United States, will likely have the greatest impact for increasing cycling activity for utilitarian travel (Dill and McNeil, 2016).

2.2. Bike network connectivity

For cyclists unwilling to use roadway links that present too much perceived traffic danger or traffic stress, the connectivity of a network can be substantially improved if high stress links are removed. Accounting for this factor requires methods that use available information about a road segment's vehicular traffic patterns and cycling accommodations to determine the suitability of a road for cycling by different types of cyclists (Sorton and Walsh, 1994, Landis et al., 1997, Harkey and Stewart, 1997, Mekuria et al., 2012).

One early tool developed in the United States to classify links based on the stress imposed on a cyclist by the street network was the Bicycle Level of Service (Landis et al., 1997), which modeled real-world cycling data of nearly 150 cyclists to quantify the suitability of a road for cycling as a function of factors such as vehicle traffic volume, posted speed limits, and surface conditions as well as the width of a bike lane. The Bicycle Compatibility Index (Harkey and Stewart, 1997)—another early tool to incorporate bicycle stress levels—was the result of a Federal Highway Administration sponsored study of video survey data that designated roads with a bicycle level of service akin to Highway Capacity Manual designations for vehicle use.

Furth and colleagues introduced a simpler method that classifies segments by four levels of traffic stress, linked to Geller's cyclist typology (Furth et al., 2016, Mekuria et al., 2012). Stress ratings provided in the initial version of their Level of Traffic Stress method were based on the number of vehicle lanes, speed limit, and bike lane width (Lowry et al., 2016), with the revised version adding average daily traffic as an input for roads in which cyclists are in mixed traffic (Furth et al., 2018). Their method introduced the concept of low-stress network connectivity as the fraction of origin–destination pairs connected on a bike network exclusive of high-stress links, recommending the adoption of such a measure to evaluate low-stress connectivity with and without a slate of alternative bike network improvement scenarios.

People for Bikes (2018) recently introduced the Bike Network Analysis method, as a replicable system for classifying OpenStreetMap (OSM) data that applies a still simpler Level of Traffic Stress scheme for categorizing road segments by two levels of traffic stress (low and high). By adopting road segment stress level assignments from Lowry et al. (2016) and OSM network data in Greater Philadelphia, Moran et al. (2018) calculated millions of shortest-distance routes between Census block centroid pairings to inform bike infrastructure investment prioritization.

Factors other than traffic stress can also affect cyclists' willingness to travel along certain links, and thus affect their connectedness to various activity destinations, including hills and environmental features such as mixed land uses and open space (Chen et al., 2018). Iseki and Tingstrom (2014) show how an aversion to hills can distort accessibility contours, while Broach et al. (2012) demonstrated that cyclists have a limited willingness to detour from the shortest route to avoid high-stress links. Of these additional factors, the Level of Traffic Stress method accounts only for detour limits (Furth et al., 2016).

2.3. Destination accessibility for cyclists

Destination accessibility can be defined as the extent to which land use and transportation systems enable individuals to reach a set of activities or destinations by means of a given travel mode (van Wee, 2016). A handful of studies have examined destination accessibility for cyclists by accounting for how traffic stress can make certain roadway links undesirable or unusable. Lowry et al. (2012) introduced a GIS-based method classifying streets by their level of stress and measured the percent of residents who can reach commercial destinations via low-stress routes under three scenarios with varying magnitudes of bike network expansion. Later studies (Lowry and Loh, 2017, Lowry et al., 2016) extended this method to allow a limited amount of travel on medium-stress segments, though still considering road segments with a high level of traffic stress impassible.

Also using the Level of Traffic Stress method and a shortest-distance algorithm for bike routing decisions, Furth et al. (2018) assessed the connectivity improvements in terms of employment accessibility for six alternative network configurations for a corridor in northern Delaware. Like several previous network connectivity tools, their method measured accessibility in terms of distance without accounting for the differential travel speeds due to cyclist type. In this study, we introduce a destination accessibility tool for evaluating bike network connectivity—similar to the routing engines found in modern navigation apps—that allows for cyclist speed to vary by segment type, makes fuller use of available data sources to inform routing decisions, and treats aversion to high-stress network links that are unsuitable to all cyclist types in a gradual manner instead of an all-or-nothing assignment.

3. Methods

This section details three central components of the Cyclist Routing Algorithm for Network Connectivity (CRANC) tool introduced in this study: its network routing engine for different cyclist types, measures of employment and labor force accessibility, and set of alternative bike network scenarios for comparison.

3.1. Bicycling network routing engine

Graphhopper, an open-source Java library and web service, was used as the base network routing engine for this study. Its codebase was extended in two important aspects to permit this study. First, we defined two cyclist types: "enthused and confident" and "interested but concerned." The former type favors greater travel speeds and route directness, showing only modest disinclination for heavily trafficked roadways or those lacking separated bike facilities. Meanwhile, the "interested but concerned" cyclist prefers streets with safer bike infrastructure (e.g., shared-use paths, cycle tracks). Second, Graphhopper's "overall facilities" module was edited to encode level of traffic stress tag values—based on criteria previously used in the People for Bikes Bicycle Network Analysis (2018) tool—to each link of the OpenStreetMap (OSM) street network and corresponding road segment within the choice set of alternative paths. While the level of stress tag was not used as an explicit variable in the routing engine, this process allowed for a calculation of the distance and duration traveled on low and high stress facilities for each modeled trip.

Regarding the bicycling network routing algorithm, Graphhopper generates an internal representation of the street network as a graph of directed links (or edges) between nodes. For any origin–destination pair, Graphhopper discovers the path between the two trip ends with the lowest overall impedance by assigning impedances to the graph's edges and summing them over all of the edges in a path. A link's impedance is its travel time multiplied by an aversion factor, as shown in Equation (1):

$$W_{ij} = (v_{ij}/l_i) \times a_{ij} \quad (1)$$

where W_i is the weight (or impedance) associated with road segment$i$ for cyclist type j, v_{ij} is the speed along road segment$i$ for cyclist type j, l_i is the length of road segment$i$, and a_{ij} is an aversion factor that is applied to road segment$i$ for cyclist type j.

The speed associated with a road segment is the base speed multiplied by a function of grade, as shown in Equation (2):

$$v_{ij} = v_o(i, j) \times (1 + \beta G_i)^2 \quad (2)$$

Table 1
Base travel speed assignment by road class and cyclist type in the bicycling network routing engine.

Weight Elements and OpenStreetMap Tags	Base Travel Speed (km/hour) per Cyclist Type	
	Interested but Concerned	Enthused and Confident
Road Class or 'Highway' Tag		
Trunk (regional highway)	15	20
Primary/secondary/tertiary (major/minor arterial or collector)	14	20
Residential (local)	12	16
Service (alley, parking lot aisles, etc.)	12	12
Cycleway (bike path)	18	18
Footway/pedestrian (walking path or car-free zone)	10	6

Table 2
Priority index and aversion factors applied to road segments in the bicycling network routing engine.

Priority Index[a]	Aversion Factor	Road Class Application
0 (Worst)	9.00	(none)
1 (Avoid at all costs)	3.00	Non-residential streets without bike facilities
2 (Reach destination)	1.80	(none)
3 (Avoid if possible)	1.26	Footpaths and pedestrian zones
4 (Unchanged)	1.00	Residential streets
5 (Preferred)	0.82	Non-residential streets with bike lanes
6 (Very nice)	0.69	Bike paths and streets with protected bike lanes
7 (Best)	0.60	(none)

Notes. [a] Priority index value of 4 is given to all road segments for the "enthused and confident" cyclist type.

where G_i is the grade (or change in elevation divided by the road segment's length) of road segment i and and $v_o(i, j)$ is the base travel speed for road segment$i$ and cyclist type j. Table 1 provides an overview how these base travel speeds differ based on road segment characteristics and cyclist type. The road segment characteristics were determined using the highway and surface tags in OpenStreetMap (OSM), while elevation data was acquired from the Consortium for Spatial Information. For "interested but concerned" cyclists, β is a value of 5.0 for uphill grades and 2.0 for downhill grades, while β equals zero for the "enthused and confident" cyclist type; an insensitivity that stems from using default values associated with Graphhopper's racing bike profile for this latter cyclist type.

For each cyclist type, a priority index p_{ij}, ranging in value from 0 to 7, was then assigned to each road segment, with 4 representing a neutral preference for cycling on the segment, higher values indicating an increased preference, and lower values signifying an increased aversion. For "interested but concerned" cyclists, priority indices are based on road class and presence of bicycling facilities, as shown in Table 2, with greater preference for bike paths, streets with bike lanes, and residential streets, and with an aversion toward non-residential streets without bike facilities. For "enthused and confident" cyclists, each road class is given a neutral preference.

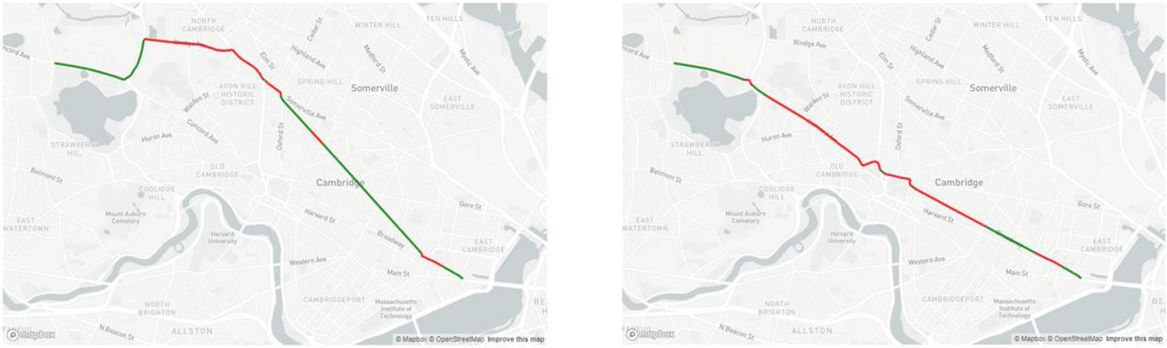
Eq. (3) shows how this priority index was used to calculate an aversion factor a_{ij} for road segment$i$ and cyclist type j. Herein, aversion is essentially priority's reciprocal; however, before performing the reciprocal operation, 0.5 was added to the priority index to avoid division by 0 (Graphhopper allows for a priority index of 0, although it was not adopted for this study). A scaling factor of 4.5 was applied so that neutral priority ($p_{ij} = 4$) would have an aversion factor of 1.0.

$$a_{ij} = 4.5/(p_{ij} + 0.5) \tag{3}$$

Fig. 1 displays the assigned routes for a sampled trip in Cambridge, Massachusetts originating near the northwest corner of the Fresh Pond Reservoir at the city boundary with the Town of Belmont and ending at Kendall Square, for the two cyclist profiles. In this example, under present conditions, the "enthused and confident" cyclist takes a more direct 4.41-mile route with 64% of the chosen route occurring along non-residential streets without bike facilities or high-stress network links depicted in red. In contrast, the "interested but concerned" cyclist selects a less direct route that is over a half-mile in distance but travels along low-stress facilities (depicted in green) for 63% of the sampled trip. As illustrated, the "interested but concerned" cyclist's route is based upon the impedance factors in the bike network routing engine but still enables this more risk averse cyclist type to travel on some high-stress links in the bike network.

3.2. Destination accessibility

For this study, destination accessibility was operationalized as the cumulative sum of opportunities that can be reached from a given zone to all zones within the study area. Accessibility is calculated in "bins" representing a specified travel time range and specified percentage of the trip that uses low-stress road segments. Census blocks were chosen as the zonal system because these spatial units are the smallest geography at which data on employment and population are publicly available. Employment data from



(a) Route for "Interested but Concerned" Cyclist Profile (b) Route for "Enthused and Confident" Cyclist Profile

Fig. 1. Bicycle network routing engine results for two cyclist profiles.

the 2015 Longitudinal Employer-Household Dynamics data set and population data from the 2010 Decennial US Census were used to measure job and labor force accessibility, respectively, using Equation (4).

$$A_{i(k)} = \sum_{j=1}^{n} O_j \delta(C_{ij}, k) \tag{4}$$

where $A_{i(k)}$ is the accessibility to a set of defined opportunities (e.g., jobs, labor force) from zone i for bin k, O_j is the count of defined opportunities in zone j, C_{ij} is the generalized cost of travel from i to j, and $\delta(C_{ij}, k)$ is 1 if the route from zone i to zone j meets the range limitations of bin k, and is 0 otherwise. In this application, bins were defined with three travel time ranges (15 min or less, 30 min or less, and all times) and three ranges for percentage of route that is on low-stress segments (75 percent or more, 50 percent or more, and all routes)—to generate a 3 × 3 time-stress matrix for each zone origin in the study area by cyclist type.

3.3. Study area and bike network scenarios

This study seeks to quantify the improvement in destination accessibility for residents and employers in the City of Cambridge resulting from the realization of different visions for an active transportation future within and beyond its municipal boundary. Cambridge, which neighbors Boston, is the fifth most populous city in Massachusetts and home to Harvard University, the Massachusetts Institute of Technology, and Kendall Square, a major technology and pharmaceutical employment center. Cambridge officials are seeking to bolster the provisioning of safe, off-street bike infrastructure by constructing the Grand Junction Pathway (GJP), a multi-use, off-road, paved path aligned within an existing rail right of way, extending from the City's southern boundary at the Charles River to Kendall Square and northward to the City of Somerville. For the destination accessibility analyses, trips from each Census block within Cambridge (n = 1095) to every block in Cambridge and the 14 other largely urbanized municipalities in the core of the Boston region (Fig. 2) were examined. As such, block-level employment accessibility for modeled cycling from Cambridge blocks to jobs in the 15 municipalities and labor force accessibility for modeled cycling to Cambridge blocks by adults in the 15 municipalities were analyzed. While expansive, the employment and labor force (population over 18 years of age) outside of those 15 municipalities are not included in the counts of opportunities for any scenario or travel time.

For this study, we analyzed three pairs of network scenarios (Fig. 2). The first pair is the existing bike network, with and without the introduction of the GJP. The second scenario pair uses the proposed citywide bike network expansion, as envisioned in the City's bicycle plan (City of Cambridge, 2015), with and without the GJP. The third pair of scenarios assumes the citywide network vision is achieved along with a broad regional expansion of cycling greenways (LandLine Vision) proposed by Boston's regional planning agency and its active transportation advocacy partners (MAPC, 2018)–again, with and without the GJP. Comparing accessibility results with and without the GJP yields a measure of the value of the GJP in the current network and in improved future networks.

4. Results

4.1. Employment accessibility

The number of job opportunities in the 15-municipality study area that can be reached by the two cyclist types from every Cambridge Census block was calculated for present cycling conditions and the three different scenarios described above. We then classified the assigned route for each block-to-block pair into one of nine categories based on the estimated travel time (three categories) and percent of the trip spent on low-stress links in the network (three categories). To visualize results, differences in accessibility between the "with" and "without" variation of each scenario pair can be mapped for each block. As an example, Fig. 3 displays each block's increase in employment opportunities reachable in 30 min and with at least 75 percent of the route along low-stress segments when the GJP is added to the existing street network, for "interested but concerned" cyclists. The darker shades indicate Census blocks with the greatest increase in accessibility, either because the GJP provides a speedier trip to certain

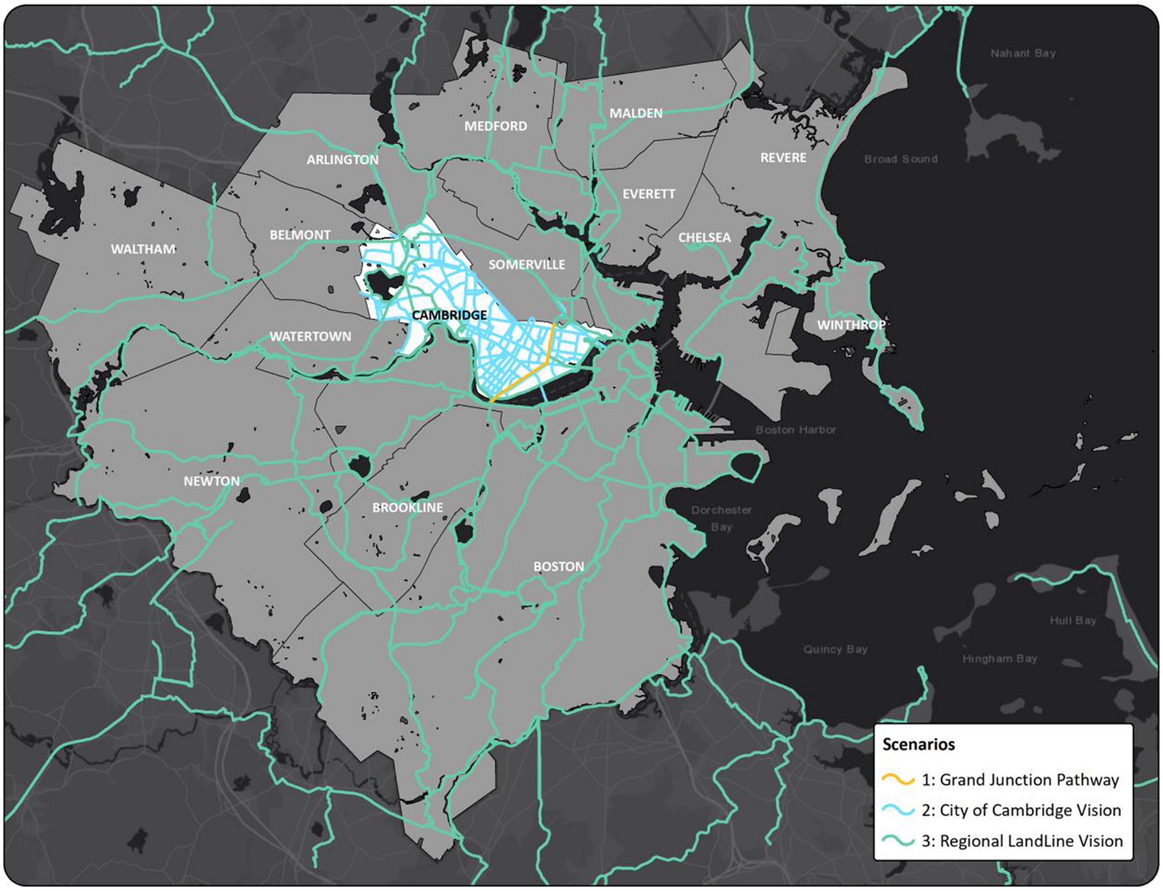


Fig. 2. Map of bike network scenarios, City of Cambridge, and surrounding Massachusetts municipalities.

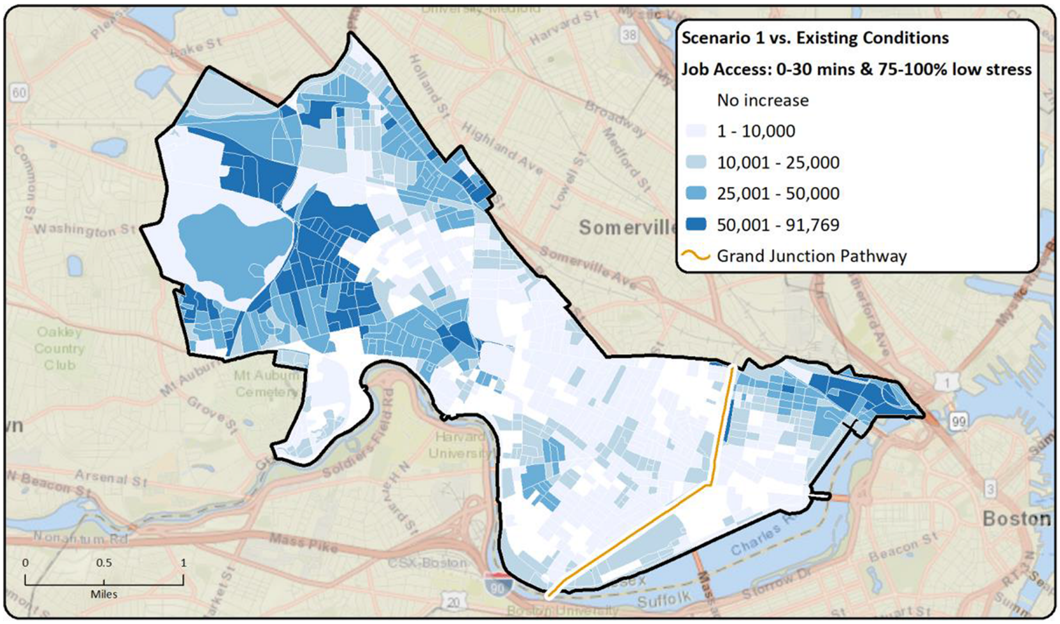


Fig. 3. Change in employment accessibility for “interested but concerned” cyclists resulting from Scenario 1.

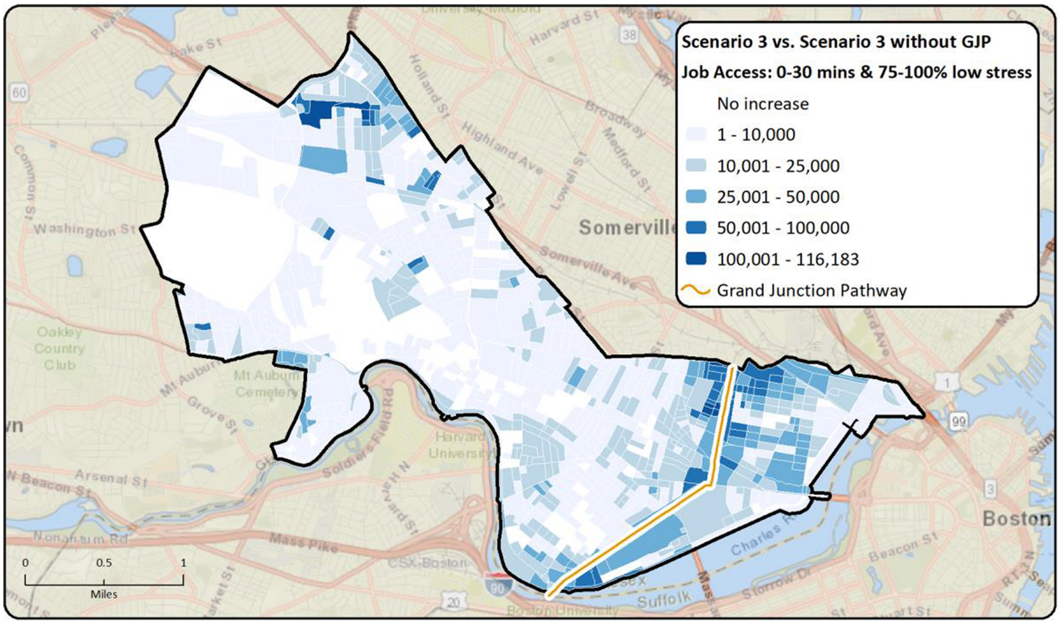


Fig. 4. Change in employment accessibility for “interested but concerned” cyclists from adding the Grand Junction Path to Scenario 3.

employment areas or allows cyclists to reach employment sites via routes that are now at least 75% low-stress. Lighter shades indicate fewer increases in job accessibility. The map shows that while Census blocks immediately adjacent to and northeast of the GJP demonstrate a marginal improvement, the greatest benefits accrue to residents of neighborhoods located one to two miles northwest of the GJP, for whom the GJP introduction enables off-street travel to destinations in job-rich Kendall Square in addition to Boston’s West End and Downton Crossing areas.

The map also identifies in the lightest color those blocks where the introduction of the GJP will not increase job accessibility in the specified thresholds. For some cases, the model estimates no increase in the number of jobs available within 30 min using routes that are more than 75% low stress. This is attributable to the model’s specifications for the “interested but concerned” cyclist type, which assumes a strong preference for off-street facilities; therefore, the introduction of the GJP may cause some trips to be assigned to less direct and lower stress routes with longer travel times. As a result, some blocks that were accessible within 30 min under present conditions are now expected to take longer than that time threshold given the assumption that the most cautious cyclists will strongly prefer off-street facilities even at a considerable expense in travel time.

Fig. 4 shows the potential block-level employment accessibility changes that could be attributed to the GJP if the citywide and regional bike network visions (Scenario 3) are realized. That is, Fig. 4 shows changes in accessibility between Scenario 3 with the GJP and Scenario 3 without it. As expected, this map reveals that residents of Census blocks immediately adjacent to the GJP are likely to experience improvements in job accessibility via cycling. This is especially notable for households with “interested but concerned” cyclists who reside near the northern stretch of the GJP, which in this scenario now connects to existing and planned bike facilities at either end of the GJP. Interestingly, another pocket of improved access to employment opportunities appears in North Cambridge, whose residents would now be able to cycle to the Kendall Square employment center with fewer potential points of motorist conflict, via an existing off-road facility in Somerville (the Community Path) and its planned extension that will connect this facility to the GJP.

The potential benefits for the “enthused and confident” cyclist assumed to have a higher tolerance for mixed traffic and a stronger preference for more direct routes and faster cycling speeds can also be mapped. Fig. 5 shows the block-level change in accessible employment for this cyclist type within 30 min and on routes that are at least 75% low-stress from adding the GJP to Scenario 1 (existing network). Benefits are especially strong in West Cambridge adjacent to the Charles River, for whom the addition of the GJP complements existing bike paths along the Charles River to give those “enthused and confident” cyclists a mostly low-stress yet very direct route to jobs in Kendall Square and beyond.

To assess the aggregate benefits of these potential bike infrastructure improvements, the number of job opportunities accessible to each Census block under the set of combinations in travel time and level of stress—for each of the three scenarios—can be averaged. Fig. 6 is a visualization of the mean number of job opportunities that an “interested but concerned” cyclist can access in nine combinations of travel time and level of traffic stress thresholds. The values in the top left corner indicate average access to employment in the shortest travel time (less than 15 min) and lowest levels of stress (less than 25% high-stress routes), with rows representing increased travel times and columns representing a greater portion of the route on high-stress links. The individual plots depict the number of jobs accessible for each scenario under the specified thresholds (i.e., values are the cumulative sum of those plots above and to the left).

The “time-stress accessibility matrix” graphic shows that if the focus is on jobs accessible within 30 min on a 75% majority low-

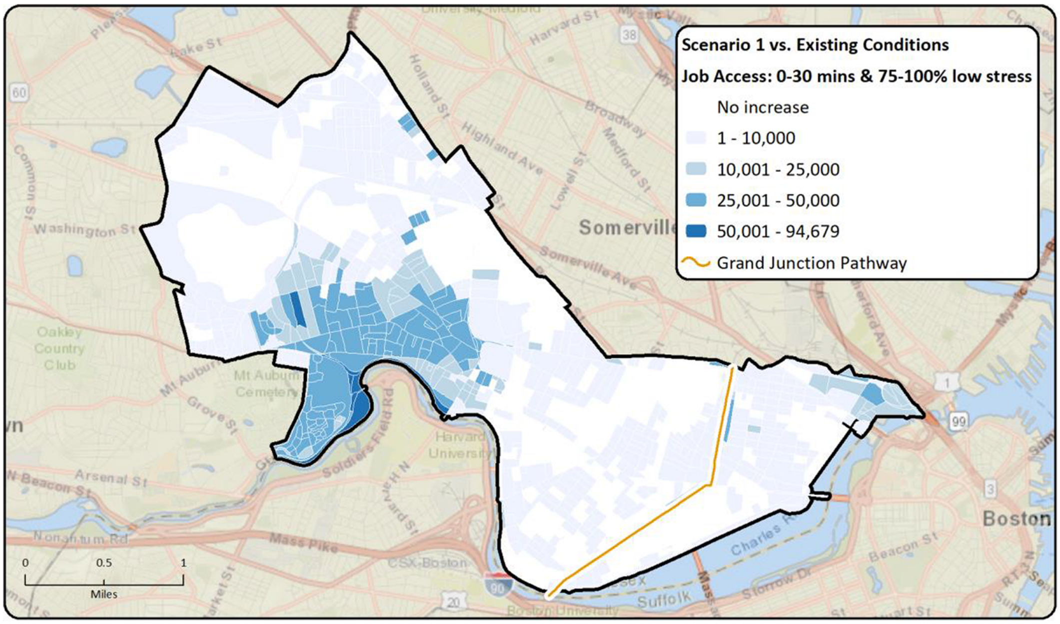


Fig. 5. Change in employment accessibility for "enthused and confident" cyclists resulting from Scenario 1.

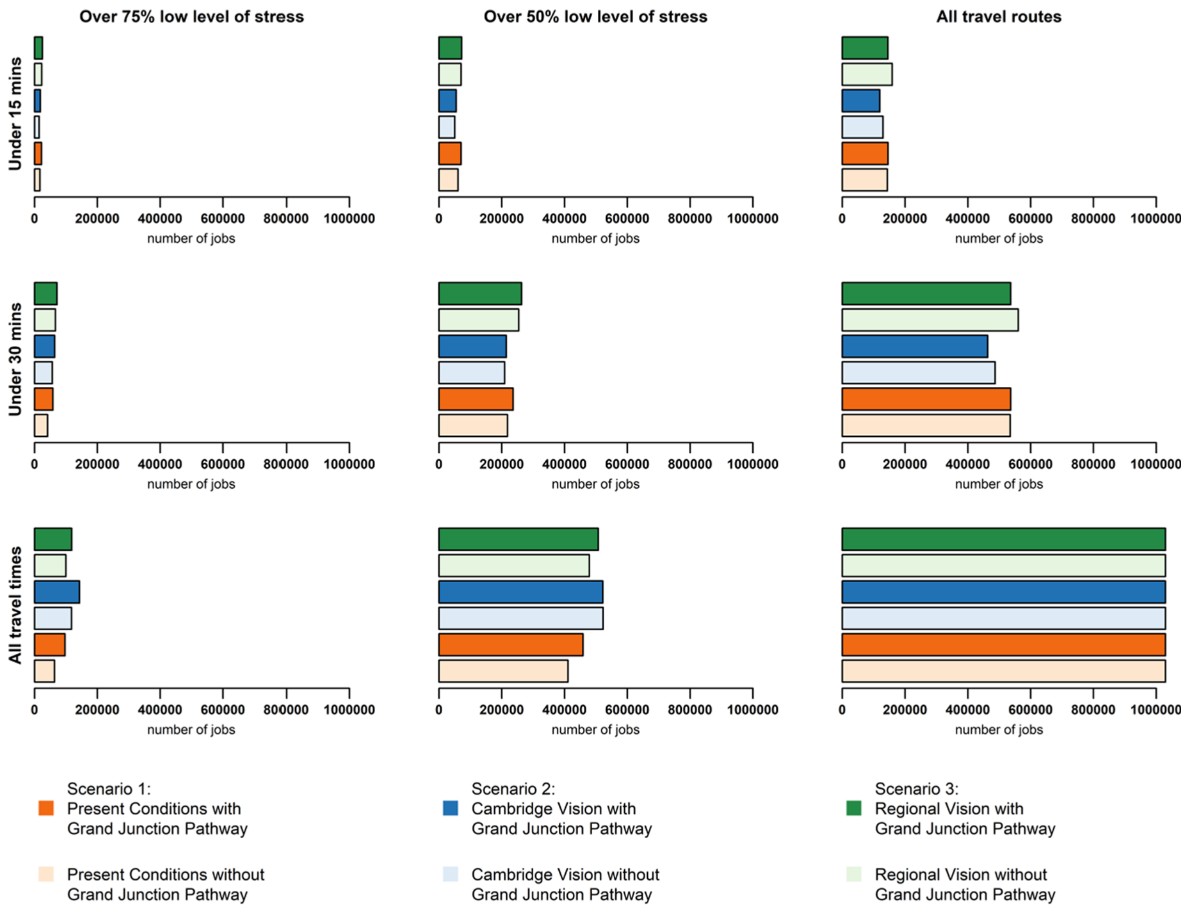


Fig. 6. Time-stress matrix of accessibility to employment opportunities for "interested but concerned" cyclists across scenarios.

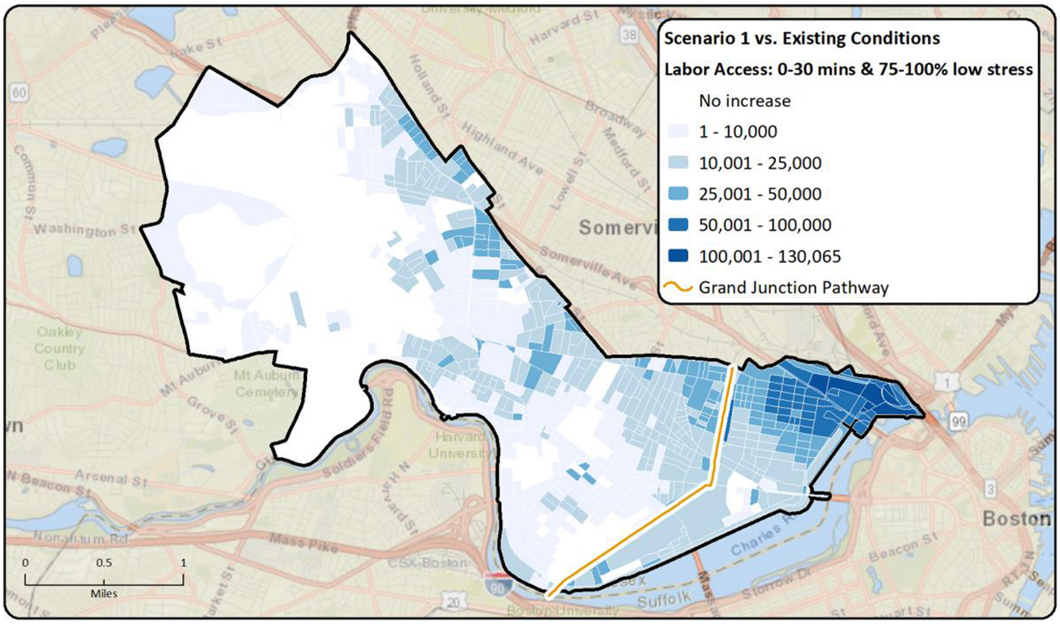


Fig. 7. Change in labor force accessibility for "interested but concerned" cyclists resulting from Scenario 1.

stress route, then each of the three scenarios performs progressively better for the average Census block. The number of jobs available within these thresholds is 73% greater in Scenario 3 (complete regional LandLine vision) than under present conditions without the GJP. However, it can also be noted that the results are not uniformly better across all travel time and traffic stress combinations, as the availability of lower-stress but more indirect routes causes some trips to shift over to longer travel times, as discussed previously. Nevertheless, this presentation of the destination accessibility results for the "interested but concerned" cyclist type helps to illuminate how the different scenarios could benefit Cambridge residents differently based on their personal tolerance for travel times and traffic stress.

4.2. Labor force accessibility

In addition to estimating the improved accessibility to jobs for Cambridge residents, this study also sought to estimate to what extent employers in Cambridge would realize greater access to labor force throughout the entire 15-municipality study area. Rather than calculating how many jobs could be accessed within a specified travel time and level of traffic stress, the number of adult residents in the region who could reach each Census block in Cambridge within a specified time-stress threshold was also assessed. As with the job accessibility analysis, this labor force accessibility analysis was conducted for two cyclist types under existing conditions and the three alternative bike infrastructure scenarios. Fig. 7 provides a block-by-block visualization of the change in labor force accessible to employment locations in Cambridge for the "interested but concerned" cyclist type via a 30-minute-or-less commute along a three-quarter majority low-stress route under Scenario 1. Blocks near the northern stretch of the GJP and to the envisioned path's northeast exhibited the greatest increase in labor force accessibility, with most of those blocks now accessible to an additional 25,000 commuters via an under-30-minute, 75% low-stress cycling route. For those employers increasingly concerned with attracting and retaining talent in a congested area with crowded or unreliable transit services, this study finding demonstrates how the provision of a regional bike network can offer greater multimodal options that make Kendall Square an attractive place for workers interested in a relatively short, low-stress bike commute. As with the analysis of job accessibility, the improvements were less substantial for the "enthused and confident" cyclist type (Fig. 8) because the routes for these cyclists are less affected by citywide and regional bike network improvements.

5. Discussion

This study introduces a new, comprehensive, and multidimensional approach to examining improvements in destination accessibility for cyclists that advances previous efforts in several ways. First, we use a network routing tool that accounts for topography and preferences of various cyclist types while also allowing less confident cyclists to have some (user-specified) tolerance for higher stress segments, making it more behaviorally representative than models using shortest-path routes on a defined set of permissible roadways. This approach offers transportation planners a transferrable tool for evaluating the accessibility benefits of bike infrastructure projects for both "interested but concerned" and "enthused and confident" cyclists, so that infrastructure can be targeted to induce mode shift among potential cyclists. By measuring the associated accessibility benefits of bike infrastructure improvements to "interested by concerned" cyclists, our decision-support tool offers city planners an alternative performance metric to forecasted

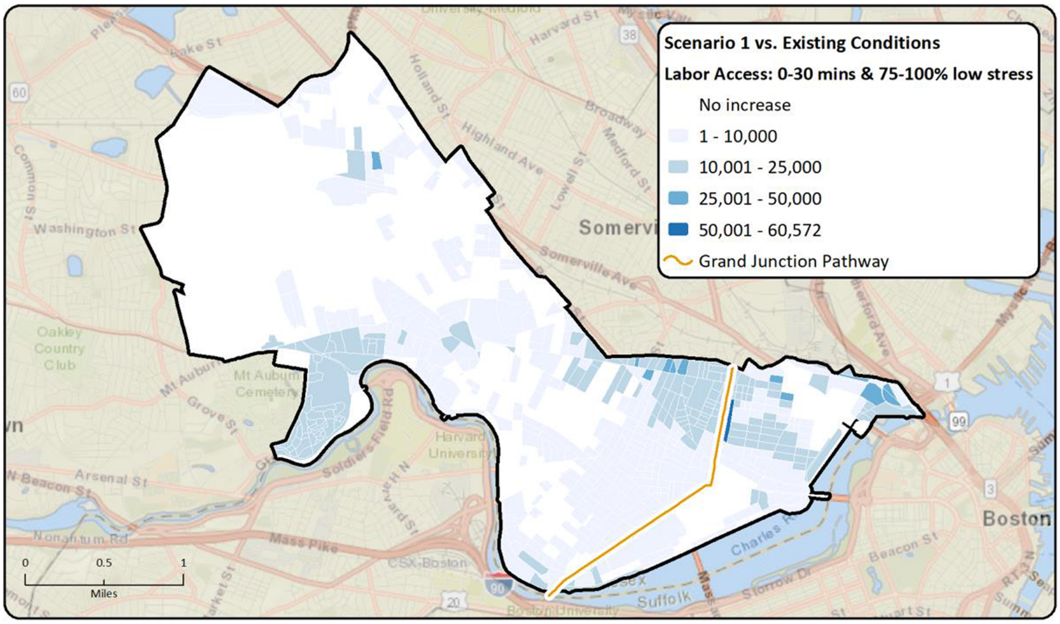


Fig. 8. Change in labor force accessibility for "enthused and confident" cyclists resulting from Scenario 1.

cycling demand when prioritizing project investments. This provision of new bike facilities attractive to individuals who are curious about cycling but require comfortable facilities to do such—a large share of the population (Dill and McNeil, 2016)—is needed to further motivate urban cycling and increase bike mode shares (Bigazzi and Gehrke, 2018).

Second, unlike prior planning tools, CRANC offers an accessibility-based metric and accompanying visualizations that account for route-specific travel times and the levels of traffic stress experienced by each cyclist type in reaching a set of defined activity opportunities. The tool's capability to assess this time-stress trade-off allows less confident cyclists to exhibit some user-specified tolerance for high-stress segments—which is more behaviorally sensitive and perhaps realistic than restricting their travel to only routes without a "missing" low-stress link—and for their travel impendence to be measured as time, not distance. For walk accessibilities, distance is a suitable measure that readily combines travel time and level of effort; however, for other travel modes, time is generally a much better measure of perceived travel impedance and input into accessibility metrics (Miller, 2018). In our analysis, travel time for a chosen route is a function of cyclist ability (cyclist type) as well as characteristics of the network and physical geography.

Third, our analysis not only examines job accessibility to Cambridge residents, but it also assesses the benefits of bike network improvements to employers looking to provide their labor force with an additional means of convenient and sustainable travel. Our two-pronged strategy to study accessibility to employment opportunities and the labor force is a more robust framework for understanding the functional connection between local and regional transportation investments and local and regional land use (Deboosere et al., 2018). Moreover, the measurement of the labor force accessibility benefits of a proposed bike infrastructure project may offer planners a way to attract private financial investment and supplement finite public resources.

Taken together, our study tested multiple different scenarios to identify how the GJP fits within a larger regional vision for bike network connectivity. Despite its theoretical and empirical contributions, our study has certain caveats in need of future considerations. In terms of data, the 2010 population information used for this analysis were not temporally congruent with the present-day bike network that was utilized, nor do these data reflect more recent land use changes that have occurred in the study area. Similarly, the tested network visions do not account for anticipated land use changes or residential and business development decisions that would likely accompany the buildout of a fully-realized citywide and regional low-stress bike network.

Additionally, the binary level of traffic stress designation used to classify the links in our OSM network is a replication of previous work (PFB, 2018) and could likely be improved through a manual, ground-truthing effort of study area facilities as well as a greater distinction in categories (Furth et al., 2018). Finally, while the selection of a zone-to-zone travel route is informed by known facilitators and barriers to cycling activity, the mode choice algorithm has not been fully calibrated and does not include some variables known to be significant to cyclist preferences (Broach et al., 2012).

Future work will seek to refine the cyclist routing algorithms by incorporating observed cycling patterns—GPS data from dockless bikeshare trips in the Greater Boston Region—into an improved route choice model for each cyclist type. Further refinement to the bicycling network routing engine can also be made by utilizing the capabilities of Graphhopper to incorporate travel impedances related to intersection control and turning movements. The summary metrics for destination accessibility may also be improved by using population-weighted aggregation, which will also enable the calculation of summary statistics for specific populations of concern (e.g. minority, low-income, or car-free residents). Our cycling-focused destination accessibility metric could also easily be extended to the availability of other opportunities (e.g., parks, schools) or assessed across different subsets of the population, including priority populations who would potentially benefit most from improvements to the present bike network. Further, the accessibility metric could be augmented with a more robust integration of travel time and level of stress that produces a single metric accounting for these separate aspects simultaneously in lieu of creating a time-stress matrix that is admittedly daunting to the casual reader. Despite these limitations, we believe this study has produced a state-of-the-art decision-support tool that addresses many limitations of previous methods, and which can serve as the basis for future improvements.

6. Conclusion

A massive shift in travel choices from automobiles to nonpolluting transportation modes is essential for cities and regions seeking to reduce greenhouse gas emissions and improve air quality. Rapid expansion of safe, convenient, low-stress bicycle facilities is a key strategy to enable and accelerate this mode shift. However, the public resources and political capital needed to implement new bike infrastructure are both scarce resources. Achieving the intended benefits while securing durable political support necessary for expanded funding requires strategic investments prioritized for maximum impact. A new class of accessibility-based decision support tools for bicycle facilities has emerged in recent years, and the tool described herein is an important contribution to that ecosystem. Just as importantly, planners, researchers, and practitioners must find ways to incorporate these tools into infrastructure planning efforts, which are often as politically opportunistic as they are objectively driven. In the case of the GJP, the application of our accessibility tool provided results that help to build a stronger political base for the proposed facility: we demonstrate that benefits will accrue to neighborhoods at some distance from the actual path, helping to build citywide support; we quantify the benefits for talent-hungry employers who might have otherwise considered the path to be only a resident amenity; and we illustrate how a regional approach to improving bicycle infrastructure yields far greater benefits, thereby facilitating multi-municipal advocacy for state resources and investments. Yet, until accessibility metrics such as the one put forth in this study have been adopted to evaluate different infrastructure investments, the supporters of more robust bike networks will remain unable to provide decisionmakers with a reasonable target for what is the incremental accessibility benefit one can expect to receive from their financial investment. Moreover, any proposed bike infrastructure and network improvement must be paired with other bike-supportive programs and policies (i.e., secured bike parking, access to bikeshare systems, etc.) to ensure that optimal destination accessibility outcomes are in fact achieved. Additional efforts linking state-of-the art technical analysis to personal, business, and political interests are needed to build a stronger case for the types of transformative transportation investments needed to create more sustainable cities and regions.

CRediT authorship contribution statement

Steven R. Gehrke: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Investigation, Writing - original draft, Writing - review & editing. **Armin Akhavan:** Software, Validation, Data curation, Investigation. **Peter G. Furth:** Resources, Writing - review & editing, Supervision. **Qi Wang:** Resources, Supervision. **Timothy G. Reardon:** Conceptualization, Resources, Supervision.

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