Preventive Medicine 95 (2017) S134–S140

Contents lists available at ScienceDirect

Preventive Medicine

journal homepage: www.elsevier.com/locate/ypmed

Quantifying bicycle network connectivity

Michael Lowry [a,*], Tracy Hadden Loh [b]

[a] Department of Civil Engineering, University of Idaho, Moscow, ID 83844, USA
[b] Rails to Trails Conservancy, Washington, DC 20037, USA

ARTICLE INFO

Article history:
Received 28 April 2016
Received in revised form 3 December 2016
Accepted 5 December 2016
Available online 7 December 2016

Keywords:
Built environment
Accessibility
Active transportation
Infrastructure
Neighborhood
Bicycling

ABSTRACT

The intent of this study was to compare bicycle network connectivity for different types of bicyclists and different neighborhoods. Connectivity was defined as the ability to reach important destinations, such as grocery stores, banks, and elementary schools, via pathways or roads with low vehicle volumes and low speed limits. The analysis was conducted for 28 neighborhoods in Seattle, Washington under existing conditions and for a proposed bicycle master plan, which when complete will provide over 700 new bicycle facilities, including protected bike lanes, neighborhood greenways, and multi-use trails. The results showed different levels of connectivity across neighborhoods and for different types of bicyclists. Certain projects were shown to improve connectivity differently for confident and non-confident bicyclists. The analysis showed a positive correlation between connectivity and observed utilitarian bicycle trips. To improve connectivity for the majority of bicyclists, planners and policy-makers should provide bicycle facilities that allow immediate, low-stress access to the street network, such as neighborhood greenways. The analysis also suggests that policies and programs that build confidence for bicycling could greatly increase connectivity.

1. Introduction

More than half of adults in the United States have at least one chronic health condition (Bauer et al., 2014), which, according to the Centers for Disease Control and Prevention (CDC), are responsible for seven out of ten deaths annually and 86% of US health care costs. The CDC recommends 150 min of moderate-intensity aerobic activity per week and muscle-strengthening at least twice a week to improve health (DHHS, 2008). Bicycling for recreation or utilitarian travel can be an excellent means for people to meet the CDC's physical activity guidelines. Bicycling is the eighth-most popular form of exercise among Americans (BLS, 2008) and a growing body of evidence demonstrates that bicycling has substantial health benefits (Hartog et al., 2010; Rojas-Rueda et al., 2011). Furthermore, surveys have shown that 40% of daily travel involves destinations within 2 miles, which for many people could be a reasonable distance for bicycling (FHWA, 2009).

The presence and quality of bicycle facilities has a significant impact on bicycling behavior (Dill and Carr, 2003; Fraser and Lock, 2010; Pucher et al., 2010), especially network connectivity (Cohen et al., 2008; Koohsari et al., 2014; Saelens et al., 2003). In previous research connectivity was typically measured by structural characteristics of the network, such as intersection density (Lowry et al., 2012). However, Mekuria et al. (2012) argued that connectivity should be measured in terms of the continuity of "low-stress bicycling" between origins and destinations. They define low-stress bicycling as bicycling on pathways and streets with low vehicle volumes and speeds; whereas, high-stress bicycling involves traveling on and crossing busy streets such as arterials with high vehicle volumes and speeds. Using the city of San Jose, California as an example, Mekuria et al. (2012) showed how a street network that is structurally well-connected exhibits "islands" of discontinuity because high-stress streets and intersections act as barriers that separate residential areas from important destinations.

Tolerance for vehicle traffic varies among bicyclists; i.e. what one person might consider high-stress bicycling, might be just fine for someone else (Sallis et al., 2013). In an often cited report, Geller (2006) suggested there are four types of people, and later research by Dill and McNeil (2013) estimated a percent for each type as follows:

- *Strong and Fearless* (4%): willing to bicycle under any traffic conditions,
- *Enthused and Confident* (9%): comfortable with minimal bicycle accommodations,
- *Interested but Concerned* (56%): uncomfortable with high vehicle speeds and volume,
- *No Way No How* (31%): not interested in bicycling.

In this study, we used a geographic information system (GIS) based tool to quantify bicycle network connectivity for the three types of bicyclists in Geller's typology. We compared connectivity for 28 neighborhoods in Seattle, Washington under existing conditions and for the proposed bicycle master plan. When complete, the proposed plan will

* Corresponding author.
E-mail address: mlowry@uidaho.edu (M. Lowry).

http://dx.doi.org/10.1016/j.ypmed.2016.12.007
0091-7435/

add over 700 new bicycle facilities throughout the city. Our GIS analysis allowed us to rank the proposed projects in terms of improving connectivity for different types of bicyclists and neighborhoods.

2. Method

2.1. Connectivity analysis

The GIS tool used in this study was recently developed by the Rails-to-Trails Conservancy. A detailed description can be found in Lowry et al. (2016). In this paper, we provide a brief summary and describe how the tool was applied in scenario analysis for different types of bicyclists and neighborhoods.

There are five GIS data inputs: (1) bicycle trip origin points, in this case residential parcels with the number of dwelling units for each parcel, (2) selected destination points classified by type, such as grocery stores, banks, and elementary schools, (3) street network with roadway functional class, number of lanes, speed limit, and bicycle facilities, (4) intersection points with traffic signals or other bicycle accommodations, and (5) digital elevation map.

The GIS tool quantifies bicycling stress for every street segment in the network as follows:

$$\textit{bicycling stress} = \textit{roadway stress}^{*}(1 - \textit{bicycle facility reduction factor})$$

where *roadway stress* is a percentage increase in perceived travel distance along a street segment. The value for roadway stress depends on the number of lanes and speed limit. For example, roadway stress is equal to 135% for a 4 lane, 30 mph street. This value means that bicycling across this street will be perceived to be a distance that is 135% of the actual physical distance across that street segment (Note that a pathway has 0% roadway stress). This is what economists call the marginal rate of substitution (MRS) for the street segment (the rate at which the bicyclist is willing to substitute another street or pathway to get to the desired destination). Recent research on bicycling route-choice has produced MRS values through stated-preference surveys and revealed preference GPS tracking (Hood et al., 2011; Broach et al., 2012).

In the equation above, *bicycle facility reduction factors* are MRS values between 0 and 1 for different types of bicycle facilities. For this study we used the tool's default values for roadway stress and bicycle facility reduction, the latter being: neighborhood greenway (10%), bike lane (40%), and protected bike lane (90%). Lowry et al. (2016) discuss issues and limitations related to using MRS values for bicycle route-choice modeling.

The GIS tool identifies the best low-stress route for bicycling between every residential parcel (origins) and every destination by minimizing bicycling stress. However, if bicycling stress along a street segment exceeds certain "stress tolerance parameters", then the route is deemed impassible. For this study, we devised three different sets of stress tolerance parameters to correspond with Geller's types of bicyclists (see Table 1). Our parameters are based on the theoretical work of Mekuria et al. (2012); future research should identify empirically-based stress tolerance parameters. "Concerned bicyclists", i.e. the majority of the population, are only comfortable on low-speed local streets and off-street pathways. "Confident bicyclists" can tolerate higher traffic speeds and more lanes. "Fearless bicyclists" are willing to ride on any street where bicyclists are permitted. Confident and Fearless bicyclists would most likely be comfortable traveling greater distances, yet to focus the analysis on improvements in connectivity due to new bicycle facilities, we used the same travel distance for all three bicyclist types (2 miles maximum).

Table 1
Tool parameters used to define stress tolerance for the case study.

Stress tolerance parameter	Concerned bicyclists	Confident bicyclists	Fearless bicyclists[a]
Comfortable speed limit (mph)	20	30	–
Comfortable number of lanes (number)	2	3	–
Maximum travel distance (miles)	2	2	2
Tolerable number of high-stress city blocks (number)	2	4	–
Tolerable number of high-stress intersections (number)	3	5	–

[a] Fearless bicyclists do not have tolerance constraints.

The tool-user must provide a list of desired destination types, such as grocery stores, banks, and elementary schools. The GIS tool calculates, for every origin, the percent of destination types that can be reached via low-stress routes. This is called the origin's "connectivity" potential. For example, if the tool-user provides a list of ten destination types, and for a particular origin, only three destination types can be reached due to the constraints of the stress tolerance parameters, then tool would calculate a connectivity value of 30% for that particular origin. In other words, someone living at that location could potentially reach 30% of the desired destinations via low-stress bicycle routes. On the other hand, it also means that 70% of the desired destinations cannot be reached, either because of high-stress bicycling barriers (busy streets and intersections) or because there are no destinations of that type within 2 miles.

There is likely a relationship between connectivity and actual bicycling activity. To test this hypothesis, we calculated Pearson correlation to compare the number of trips reported in a recent household travel survey with the *average* connectivity value for different neighborhoods. The survey included >6000 households and 675 bicycle trips (PSRC, 2015).

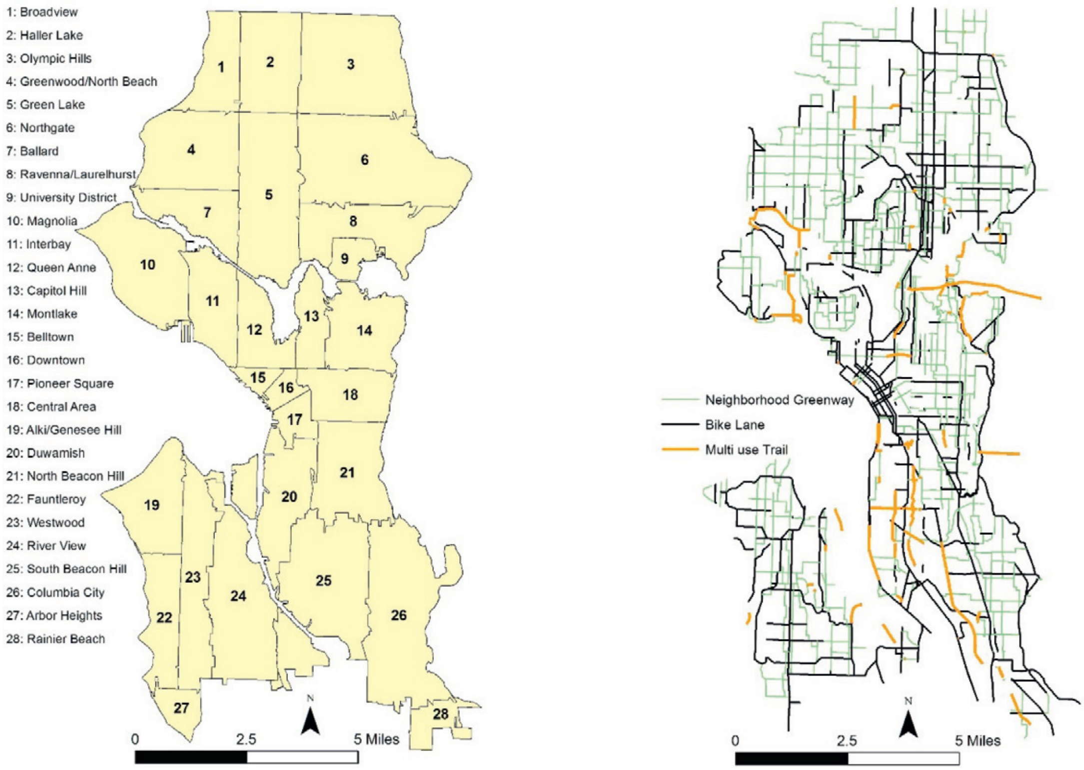
The GIS tool also calculates "network flow" for every link in the network. This metric is determined by counting the number of times a link is included on a route between origins and destinations. Network flow is the total link usage between every origin and every destination. Links with high network flow are important to the network because it means lots of origin-destination pairs rely on that link.

2.2. Case study data

We analyzed connectivity for 28 neighborhoods in Seattle, Washington (population 652,000). In 2014 Seattle Department of Transportation (SDOT) released a bicycle master plan that consists of 771 projects that will provide 141 miles of new bike lanes, 234 miles of new neighborhood greenways, and 30 miles of new multi-use trails. Nearly half of the new bike lanes will be "protected bike lanes" which significantly reduce bicycling stress by providing a horizontal and vertical barrier between the bicyclist and vehicle traffic (FHWA, 2015). Streets that will be designated as neighborhood greenways will have reduced speeds (20 mph) and signs, pavement markings, and vehicle volume management to create low-stress bicycle crossings at busy streets (NACTO, 2014).

For three years SDOT collected public input via email, mail, public meetings, and an on-line interactive map to identify the projects in the proposed plan. They estimate full build-out will take 20 years and cost between $390 million and $525 million. The projects are distributed evenly across Seattle's neighborhoods (see Fig. 1). The city council approved the plan and now SDOT's challenge is to determine the order in which the projects should be completed. There are many constraints and goals that will need to be considered, including choosing projects that will improve low-stress connectivity for Seattle's neighborhoods in an equitable manner. SDOT provided our research team their GIS files for the proposed plan and underlying street network.

The residential parcels were obtained from the metropolitan planning organization (MPO) and neighborhoods were delineated based on US postal zip code (see Fig. 1). A few "neighborhoods" used for the analysis are rather large, and are by some accounts considered districts comprised of smaller neighborhoods, such as Green Lake which includes Phinney Ridge, Fremont, and Wallingford.



(a) (b)

Fig. 1. Seattle (a) neighborhoods and (b) proposed new bicycle facilities.

Table 2
Percent of destination types that can be reached on average via low-stress bicycling.

ID	Neighborhood	Destination density (per sq. mile)	Concerned bicyclists[a]			Confident bicyclists[a]		
			Existing conditions (%)	Proposed plan (%)	Difference (%)	Existing conditions (%)	Proposed plan (%)	Difference (%)
1	Broadview	44	2	20	18	80	82	2
2	Haller Lake	170	8	23	15	77	80	3
3	Olympic Hills	145	5	17	12	73	80	7
4	Greenwood	102	2	31	29	92	93	1
5	Green Lake	228	5	38	33	92	94	2
6	Northgate	139	3	20	17	83	91	8
7	Ballard	280	9	35	26	91	94	3
8	Ravenna	293	6	23	17	79	88	9
9	University District	120	31	45	14	78	78	0
10	Magnolia	74	2	14	12	81	89	8
11	Interbay	203	5	16	11	79	86	7
12	Queen Anne	423	5	10	5	87	92	5
13	Capitol Hill	390	6	30	24	88	94	6
14	Montlake	194	3	28	25	84	90	6
15	Belltown	1511	21	25	4	49	84	35
16	Downtown	4137	14	20	6	60	76	16
17	Pioneer Square	2329	15	30	15	71	80	9
18	Central Area	412	6	33	27	92	94	2
19	Alki	176	5	20	15	82	83	1
20	Duwamish	62	3	14	11	86	95	9
21	North Beacon Hill	158	4	22	18	89	92	3
22	Fauntleroy	86	3	13	10	84	87	3
23	Westwood	78	3	29	26	88	91	3
24	River View	57	2	15	13	74	84	10
25	South Beacon Hill	65	3	8	5	70	82	12
26	Columbia City	100	2	16	14	76	83	7
27	Arbor Heights	39	1	6	5	64	84	20
28	Rainier Beach	63	2	3	1	49	66	17
	All neighborhoods	202	6	23	17	81	87	6

See the text for the list of 22 desired destination types.
[a] See Table 1 for definitions.

The destinations used in the analysis were geocoded from Dun and Bradstreet's Hoovers business data. Twenty-two destination types were defined based on SIC codes: amusement and recreation, bank, beauty salon and barber shop, child care, clothing and accessory store, colleges and universities, computer and electronics store, drinking place, eating place, elementary and secondary schools, general retail store, grocery store, health care provider, insurance, legal services, library, movie theater, office and home furnishings store, public park, pharmacy, physical fitness facility, and postal service.

3. Results

The results show different levels of connectivity across neighborhoods in Seattle. Table 2 shows the percent of destination types that can be reached via low-stress bicycling on average for each neighborhood. For most neighborhoods it is currently not possible to reach more than one or two of the selected destinations types via low-stress bicycling.

Every neighborhood would see an increase in connectivity due to the proposed plan; however, some neighborhoods more so than others. For concerned bicyclists, the greatest increase would be for Green Lake, while the smallest increase in connectivity would occur for Rainier Beach. Green Lake is more affluent, has better bicycle facilities, and offers more destination potential.

Connectivity to specific destination types are shown in Table 3 for Green Lake and Rainier Beach. Since there is only one destination type for this analysis, then "connectivity" in Table 3 represents the percent of the population that can reach the specific destination via low-stress bicycling. The table includes the results under different distance constraints (one mile and 2 miles).

We calculated a composite connectivity score for each neighborhood i as follows:

$$composite\ connectivity_i = population_i * (0.56 * concerned_i + 0.09 * confident_i)$$

where $concerned_i$ and $confident_i$ are the connectivity values for each neighborhood shown in Table 2 under the existing conditions. The weights 0.56 and 0.09 are the percent of each type of bicyclist reported by Dill and McNeil (2013). We calculated the correlation between the number of bicycle trips reported in the travel survey with neighborhood (1) composite connectivity, (2) population, and (3) destination density. The number of bicycle trips reported in the travel survey has a positive Pearson correlation with the composite connectivity values for the neighborhoods ($r = 0.72$, p-value < 0.05), which is larger than the correlation with neighborhood population ($r = 0.58$, p-value < 0.05) and destination density ($r = 0.25$, p-value < 0.05). The relationship with composite connectivity is shown in Fig. 2.

Another key output from the GIS tool is network flow from origins to destinations. Network flow is the total link usage between every origin and every destination. For example, Fig. 3 shows the change in flow between the existing conditions and the proposed bicycle plan for the southern portion of Green Lake. Project importance and rankings can be determined by calculating the difference in flow through a project location with and without the proposed bicycle facility. If a project has a significant increase in network flow, then it is more important. Rankings are determined by sorting all projects by change in network flow. Table 4 shows the types of bicycle facilities among the top twenty-five for different types of bicyclists.

4. Discussion

4.1. Connectivity

The results suggest significant disparity in connectivity between "concerned" and "confident" bicycling. For most neighborhoods, it seems confident bicyclists can already reach a majority of the selected destinations and, for a few, the proposed bicycle master plan would only provide minor improvement. There were, however, neighborhoods that showed poor connectivity even for confident bicyclists, such as Belltown and Rainier Beach. The former is surrounded by diverse destinations but amidst busy downtown streets, while the latter lacks destinations and lacks good bicycle facilities. For these neighborhoods, the bicycle master plan would improve connectivity for both concerned and confident bicycling. Planners and decision-makers might consider prioritizing the projects that help these neighborhoods first.

Low connectivity was associated with the downtown neighborhoods. This is because nearly all streets downtown are 30 mph and most are 4 lanes or more. So despite the many destinations, riding a bicycle downtown is primarily for the strong and fearless. In other words, accessibility in downtown is a transportation issue rather than a land use planning issue. The University District, with low-speed, two-lane streets exhibits very good connectivity under existing conditions and even better with the proposed plan.

The analysis showed that if destinations are beyond comfortable bicycling distances then there is only so much that can be achieved through better bicycle facilities. Planners and decision-makers should consider how land use policy and market forces impact the availability of various destinations for bicyclists. Likewise, policy-makers should consider providing education programs that build confidence with bicycling, because for many people, connectivity is constrained by aversion to heavy traffic, as well as, willingness (or ability) to travel long distances (see Table 3).

The strong relationship between connectivity and the number of bicycle trips from the survey is promising and future research should investigate improving the model. The results for neighborhoods 9 (the University District) and 3 (Olympic Hills), which under-predict and over-predict the number of trips, respectively, suggest there are other explanatory variables in addition to connectivity that could explain additional variance in bicycling activity, such as household car ownership rates, median income, and median population age. Furthermore, the travel survey included all bicycle travel, including recreational and commute trips longer than 2 miles, but the tool was focused on utilitarian trips < 2 miles. Through further development of the tool and method, planners might one day be able to use connectivity to predict and model bicycle trips.

Table 3
Percent of population currently connected to specific destinations for selected neighborhoods.

Type of bicyclists	Max distance (miles)	Green Lake (population = 49,000)			Rainier Beach (population = 7200)		
		Grocery store (%)	Elementary school (%)	Public park (%)	Grocery store (%)	Elementary school (%)	Public park (%)
Concerned	1	4	0	5	1	2	1
	2	6	2	5	2	2	1
Confident	1	92	90	45	53	81	44
	2	97	96	96	69	88	77
Fearless	1	100	99	100	61	87	59
	2	100	100	100	96	100	100

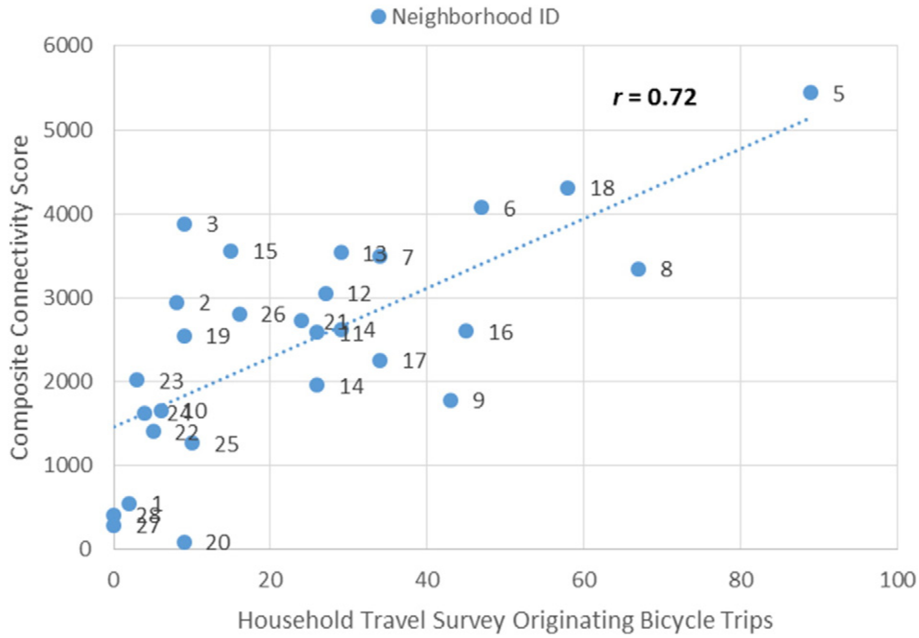


Fig. 2. Composite connectivity score vs. reported bicycle trips in one day.

4.2. Network flow and project rankings

As described in the Method section, network flow is a synthetic metric calculated by counting the number of times a link is included on the routes between every origin to every destination. The analysis showed that stress-reducing bicycle facilities *concentrate* network flow. For example, significantly more flow would be expected to cross the University Bridge after the installation of a proposed protected bike lane (see lower right corner of Fig. 3). Likewise, new facilities were shown to *expand* connectivity potential from origins to destinations.

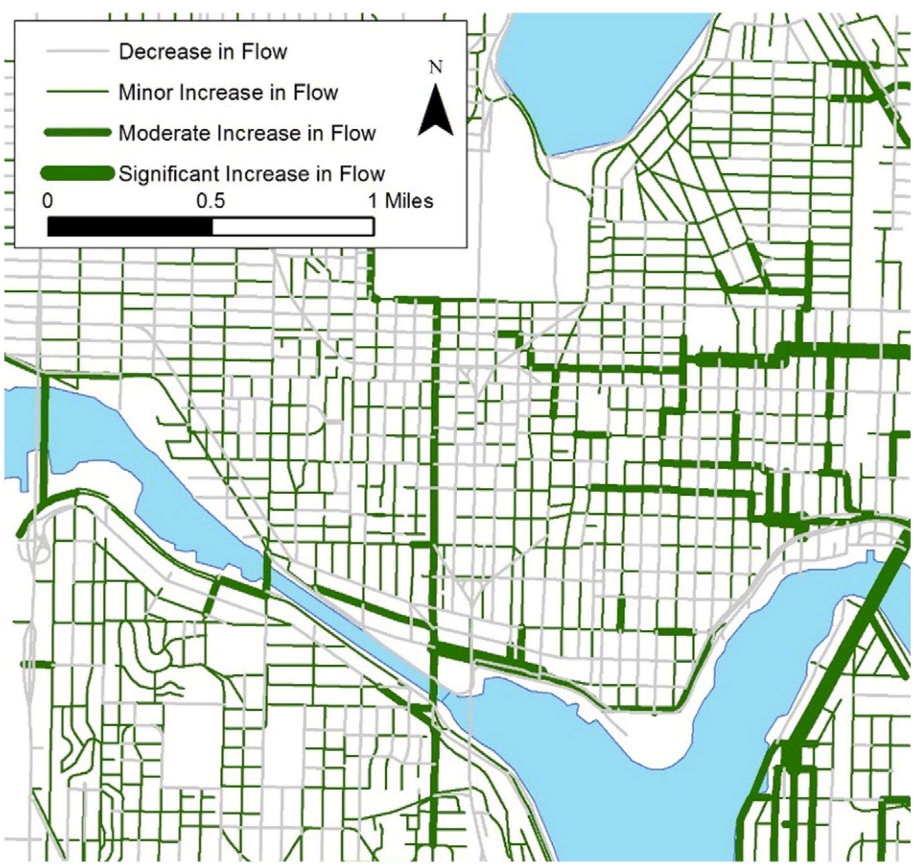


Fig. 3. Change in flow between existing conditions and the proposed plan.

Table 4
Twenty-five top-ranked projects for each bicyclist type.

Bicycle facility	Concerned bicycling	Confident bicycling	Fearless bicycling
Bike lane	0	1	3
Protected bike lane	2	19	9
Multi-use trail	0	1	8
Neighborhood greenway	23	4	5
Cost for top 25 projects	$10 million	$19 million	$30 million

Project rankings were based on change in network flow between the existing conditions and the proposed plan.

As expected we found project rankings differed neighborhood by neighborhood. But to our surprise we also found considerable difference in project rankings depending on type of bicycling (Table 4, χ^2 (6) = 52.2, $p < 0.01$). The top twenty-five projects for concerned bicycling are neighborhood greenways, while none of the multi-use trail projects were top-ranked for this type of bicyclist. This suggests the most important thing policy makers can do to facilitate concerned bicyclists is to provide a means to begin low-stress bicycling the moment someone walks out their front door in their neighborhood. Confident bicyclists, on the other hand, are already willing to bicycle on neighborhood streets, even without the accommodations of a greenway. So for them, connectivity is improved most through protected bike lanes which typically are located on busy streets where there is an abundance of destinations. Likewise, fearless bicyclists are willing to go wherever, so for them, new multi-use trails which often provide new shortcuts to destinations are the most beneficial (fearless bicyclists would most likely prefer and derive benefit from better facilities as well, but this analysis does not capture those benefits). Certainly, concerned bicyclists highly value multi-use trails, but not necessarily in terms of connectivity to destinations, but rather in terms of recreational bicycling. Indeed, it is possible that many concerned bicyclists would drive their car to a multi-use trail, while confident and fearless bicyclist would overcome the high-stress streets between their home and using multi-use trails for recreation.

4.3. Study limitations and strengths

This was a case study using a simplified model of the real world, so the results might not be transferable to another city. However, the findings appear reasonable and provide anecdotal insight that would most likely hold elsewhere. As discussed by Lowry et al. (2016), the output from the GIS tool is sensitive to the input parameters, including bicycle route-choice calibration (i.e. MRS values), so like all modeling tools the results should be considered in the context of inherent tool limitations. For example, it should be noted that different stress reduction factors for protected bike lanes, neighborhood greenways, etc. might produce different flow through the network and possibly different project rankings and connectivity results. Likewise, the bicycle network connectivity measure is influenced by not only bicycle facilities themselves, but also street and land use conditions. The same types of projects, when applied to different neighborhoods with different street or land use conditions, or even in the same neighborhood but at different locations, will possibly generate different results.

Moreover, the analysis made no distinction about the quality and choice of the destinations, for example connectivity to “grocery stores” (Table 3) includes all businesses that report an SIC code in that category, even convenience stores. A more thorough analysis might focus on grocery stores with fresh, healthy food (Bower et al., 2014) or public parks with certain amenities (Cohen et al., 2010).

5. Conclusion

This study used a novel GIS tool to quantify the connectivity improvements anticipated from a proposed bicycle master plan that will build >700 new bicycle facilities. The tool provided a means to rank the projects for different types of bicyclists and for different neighborhoods. Existing baseline connectivity was shown to vary across neighborhoods and the proposed plan showed improvement in connectivity for some neighborhoods more than others. Actual bicycle trips are strongly positively correlated with the connectivity metric used in this study. The results suggest that if planners and policy-makers seek to reach the “interested but concerned” majority of cyclists, they should consider prioritizing new bicycle facilities that would provide households with immediate, low-stress access to the street network, such as neighborhood greenways. These projects are also typically relatively low-cost. This study focused on local utilitarian travel (i.e. doing errands); it is possible that connectivity analysis for inter-neighborhood and regional destinations (i.e. commuting), or recreational travel (i.e. bicycling for the sake of bicycling), would favor new facilities that provide long, unimpeded travel, such as multi-use trails.

Connectivity that supports bicycling for transportation is a combination of five elements: (1) destination potential, (2) physical network structure, (3) continuity of low-stress bikeways, (4) tolerance for traffic stress, and (5) willingness or ability to travel farther distances. The first can be improved through land use policy, the second is largely due to urban planning and geographic constraints, the third concerns better facilities, and the latter two might be addressed through education programs. In this study, the results showed destination potential and network structure were not limiting factors for most neighborhoods (1 and 2 above). Instead the results suggest much can be gained from policies that provide more low-stress bicycle facilities and build confidence for bicycling (3, 4, and 5).

The tool used in this study could be applied in a variety of ways to extend this research or assist practitioners. Future research should continue to explore the relationship between connectivity and mode share. Likewise, research should examine the relationship between network flow and observed bicycle volumes. The tool might be improved by analyzing a broader range of distances, or perhaps incorporating a distance decay function that weights the multiplier with diminishing value as distance increases. Practitioners could use the tool with focused analysis for specific destinations or origins, such as identifying project rankings and connectivity for student access to schools or low-income access to high-quality grocery stores (food desert analysis).

Conflict of interest

The authors declare there is no conflict of interest.

Acknowledgments

This research was supported by a grant from the Rails-to-Trails Conservancy.

References

Bauer, U., Briss, P., Goodman, R., Bowman, B., 2014. Prevention of chronic disease in the 21st century: elimination of the leading preventable causes of premature death and disability in the USA. Lancet 384:45–52. http://dx.doi.org/10.1016/S0140-6736(14)60648-6.
Bower, K., Thorpe, R., Rohde, C., Gaskin, D., 2014. The intersection of neighborhood racial segregation, poverty, and urbanicity and its impact on food store availability in the United States. Prev. Med. 58:33–39. http://dx.doi.org/10.1016/j.ypmed.2013.10.010.
Broach, J., Dill, J., Gliebe, J., 2012. Where do cyclists ride? A route choice model developed with revealed preference GPS data. Transp. Res. A Policy Pract. 46:1730–1740. http://dx.doi.org/10.1016/j.tra.2012.07.005.
Bureau of Labor Statistics, 2008. Spotlight on statistics: sports and exercise. http://www.bls.gov/spotlight/2008/sports/ (accessed February 26, 2016).
Cohen, D., Sehgal, A., Williamson, S., Golinelli, D., McKenzie, T.L., Capone-Newton, P., Lurie, N., 2008. Impact of a new bicycle path on physical activity. Prev. Med. 46:80–81. http://dx.doi.org/10.1016/j.ypmed.2007.07.022.
Cohen, D., Marsh, T., Williamson, S., Derose, K., Martinez, H., Setodji, C., McKenzie, T.L., 2010. Parks and physical activity: why are some parks used more than others? Prev. Med. 50:S9–S12. http://dx.doi.org/10.1016/j.ypmed.2009.08.020 (Supplement).

Dill, J., Carr, T., 2003. Bicycle commuting and facilities in major U.S. cities: if you build them, commuters will use them. Transportation Research Record: Journal of the Transportation Research Board 1828:116–123. http://dx.doi.org/10.3141/1828-14.

Dill, J., McNeil, N., 2013. Four types of cyclists? Transportation Research Record: Journal of the Transportation Research Board 2387:129–138. http://dx.doi.org/10.3141/2387-15.

FHWA, 2009. National Household Travel Survey. http://nhts.ornl.gov/ (accessed February 26, 2016).

FHWA, 2015. Separated Bike Lane Planning and Design Guide. Federal Highway Administration, Washington, DC.

Fraser, S., Lock, K., 2010. Cycling for transport and public health: a systematic review of the effect of the environment on cycling. The European Journal of Public Health 21, 738–743.

Geller, R. 2006. Four Types of Cyclists. Portland Bureau of Transportation, Portland, OR, available at: www.portlandoregon.gov/transportation/article/264746.

Hartog, J.J.d., Boogaard, H., Nijland, H., Hoek, G., 2010. Do the health benefits of cycling outweigh the risks? Environ. Health Perspect. 118, 1109–1116.

Hood, J., Sall, E., Charlton, B., 2011. A GPS-based bicycle route choice model for San Francisco, California. Transportation Letters 3:63–75. http://dx.doi.org/10.3328/TL.2011.03.01.63-75.

Koohsari, M., Sugiyama, T., Lamb, K., Villanueva, K., Owen, N., 2014. Street connectivity and walking for transport: role of neighborhood destinations. Prev. Med. 66: 118–122. http://dx.doi.org/10.1016/j.ypmed.2014.06.019.

Lowry, M., Callister, D., Gresham, M., Moore, B., 2012. Assessment of communitywide bikeability with bicycle level of service. Transportation Research Record: Journal of the Transportation Research Board 2314, 41–48.

Lowry, M., Furth, P., Hadden-Loh, T., 2016. Prioritizing New Bicycle Facilities to Improve Low-stress Network Connectivity. Transportation Research Part A, Policy and Practice.

Mekuria, M., Furth, P., Nixon, H., 2012. Low-stress Bicycling and Network Connectivity. Mineta Transportation Institute.

NACTO, 2014. Urban Bikeway Design Guide. National Association of City Transportation Officials. Island Press.

PSRC, 2015. Puget Sound Regional Travel Study 2014. Puget Sound Regional Council Available at:. http://www.psrc.org/data/transportation/travel-surveys/2014-household.

Pucher, J., Dill, J., Handy, S., 2010. Infrastructure, programs, and policies to increase bicycling: an international review. Prev. Med. 50:S106–S125. http://dx.doi.org/10.1016/j.ypmed.2009.07.028 (Supplement).

Rojas-Rueda, D., de Nazelle, A., Tainio, M., Nieuwenhuijsen, M.J., 2011. The health risks and benefits of cycling in urban environments compared with car use: health impact assessment study. BMJ 343, d4521.

Saelens, B., Sallis, J.F., Frank, L.D., 2003. Environmental correlates of walking and cycling: findings from the transportation, urban design, and planning literatures. Ann. Behav. Med. 25, 80–91.

Sallis, J.F., Conway, T.L., Dillon, L.I., Frank, L.D., Adams, M.A., Cain, K.L., Saelens, B.E., 2013. Environmental and demographic correlates of bicycling. Prev. Med. 57:456–460. http://dx.doi.org/10.1016/j.ypmed.2013.06.014.

US Department of Health and Human Services, 2008. 2008 physical activity guidelines for Americans. http://www.health.gov/PAGuidelines (accessed February 26, 2016).