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Quantifying bicycle network connectivity

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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

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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.