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Prioritizing new bicycle facilities to improve low-stress network connectivity

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ABSTRACT

This paper introduces a new method to prioritize bicycle improvement projects based on accessibility to important destinations, such as grocery stores, banks, and restaurants. Central to the method is a new way to classify "bicycling stress" using marginal rates of substitution which are commonly developed through empirical behavioral research on bicyclist route choice. MRS values are input parameters representing bicycling stress associated with the number of lanes and speed limit of a street. The method was programmed as a geographic information system tool and requires commonly available data. The tool is demonstrated on three improvement scenarios that were recently proposed for Seattle, Washington. The full build-out scenario consists of 771 projects that include various new bike lanes, protected bike lanes, and multi-use trails. The tool produces priority rankings based on a project's ability to improve low-stress connectivity between homes and important destinations. The analysis identifies specific areas and neighborhoods that can be expected to exhibit better bikeability. Transportation planners can use the tool to help communicate anticipated project impacts to decision-makers and the public.

1. Introduction

Many cities are currently trying to expand their bicycle network (Buehler and Pucher, 2012). They are devising Bicycle Master Plans that enumerate a wish list of improvement projects such as bicycle boulevards, bike boxes, buffered bike lanes, and cycle tracks (NACTO, 2014). American cities are way behind their European peers in terms of expansive infrastructure for mass bicycling, but there is evidence change is underway (Furth, 2012). In 2010, USDOT Secretary Ray LaHood signed a policy declaring "The establishment of *well-connected* walking and bicycling networks is an important component for livable communities, and their design should be part of Federal-aid project development" (LaHood, 2010 emphasis added). Four years later, his successor, Secretary Anthony Foxx, launched a new initiative to increase federal funding for bicycle improvement projects, which he called "the most innovative, forward-leaning, biking-walking safety initiative ever" (Foxx, 2014). Over the next few decades, cities will need to make strategic capital investment decisions as the federal government, state departments of transportation, local governments, and non-profit organizations such as the Rails-to-Trails Conservancy direct more funding toward bicycle infrastructure.

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Capital investment decisions usually involve two key steps: project appraisal and project prioritization. Project appraisal determines whether there is economic justification for the project based on expected benefits and costs. One approach is to monetize expected impacts over a particular time period in terms of present-value dollars and calculate the benefit–cost ratio to confirm that benefits outweigh costs. It can be fairly easy to estimate costs (Krizek et al., 2006); but, monetizing benefits can be quite difficult. Most benefits from bicycle improvement projects are non-market benefits, meaning the dollar value is not readily apparent. Such benefits are typically indirect or ancillary, meaning the benefit is not directly due to the project, but rather due to incidental impacts from a change in society's behavior. For example, if a community improves their bicycle network, more people might choose to ride their bike rather than drive, which in turn might improve health, reduce emissions, and decrease traffic congestion. Likewise, improvement projects might increase home values or increase community attractiveness. These types of benefits are very difficult to quantify and monetize. Even direct benefits, such as reduced bicycle crashes, can be difficult to quantify (Nordback et al., 2014). Consequently, decision-makers often use professional judgment and the intensity of public opinion to justify bicycle facility improvement projects.

Once projects have been economically justified, the next step is to prioritize them for implementation. There are various prioritization techniques available, and the information used during project appraisal can often be used for prioritization as well. For example, through a process called Incremental Analysis projects can be rank-ordered based on benefit–cost ratios. However, once again, decision-makers face the challenge of monetizing non-market benefits. An alternative approach is to identify performance indicators (also called measures of effectiveness or project selection criteria) to evaluate how well a project is expected to perform with regard to specific goals and objectives. For example, the Seattle Department of Transportation (SDOT) identified five goals and corresponding performance indicators to prioritize candidate bicycle improvement projects. The goals are to increase (1) ridership, (2) safety, (3) connectivity, (4) equity, and (5) livability. They were developed through public involvement activities, stakeholder focus groups, assessment of data availability, review of the literature, and other activities (SDOT, 2013a). Prioritization can be achieved by rank-ordering a single performance indicator, a composite indicator, or through some deliberative process that takes into consideration all the performance indicators simultaneously.

Preferably, the evaluation of performance indicators should involve quantitative analysis. The USDOT notes, "Quantitative information lends objectivity to a decision-making process which might otherwise be dominated by subjective judgment or political considerations" (FHWA, 2011). Quantitative analysis is more likely to be repeatable and transparent. Nevertheless, as already discussed, the benefits associated with bicycle improvement projects are often very difficult to quantify, in which case, qualitative indicators may be the only viable alternative. Qualitative evaluation might consist entirely of narrative description. For example, the City of Portland's bicycle implementation plan involves a series of yes/no and open-ended questions to evaluate seven performance indicators. A quasi-qualitative evaluation might involve subjectively assigning a score to some or all of the performance indicators on a scale of 1–10. SDOT's bicycle master plan notes that project prioritization should use "a variety of qualitative and quantitative methods, recognizing that prioritizing bicycle projects is not a science but rather an art" (SDOT, 2013a, pg. 8).

This paper introduces a new method to objectively analyze "connectivity", a performance indicator commonly used to prioritize bicycle improvement projects. According to a review conducted by SDOT, the cities of Portland, Minneapolis, and Vancouver all include connectivity as one of their prioritization criteria (SDOT, 2013a). A recent USDOT Roundtable called for "more standardized tools…to measure connectivity." (Foxx, 2015).

The new method described in this paper uses network analysis and geographic information system (GIS) software to produce project priority rankings based on a project's ability to connect homes with destinations via low-stress bicycling. The method was programmed as an ArcGIS tool and requires commonly available GIS data: (1) street and trail network, (2) residential land use parcels, and (3) points-of-interest destinations. Transportation engineers and planners can use the tool to help communicate expected project impacts to the public and decision-makers.

The next section of this paper provides background on assessing bicycling stress and measuring connectivity. This is followed by a description of the new method and a case study example involving the Bicycle Master Plan for Seattle, Washington in which the full build-out includes 771 projects.

2. Background

Assessing the stress associated with a bicycle facility can be accomplished through various *bicycle suitability assessment* methods. Callister and Lowry (2013) provide a summary of more than a dozen methods that have been developed since 1987, starting with Davis's pioneering Bicycle Safety Index Rating (BSIR). Each method calculates a *suitability rating* based on different roadway attributes. For example, the method developed by Sorton and Walsh (1994) called Bicycle Stress Level (BSL) calculates five stress ratings from "Very Low Stress" to "Very High Stress" based on three roadway attributes: (1) width of outside lane, (2) vehicle traffic volume, and (3) vehicle speeds. The 2010 Highway Capacity Manual presents a method called Bicycle Level of Service (BLOS) based on ten roadway attributes and produces a letter grade rating from "A" through "F" (TRB, 2011). Mekuria et al. (2012) developed a method called Level of Traffic Stress (LTS) which produces four ratings ranging from LTS 1 to LTS 4 based on three key roadway attributes: (1) number of vehicle lanes, (2) speed limit, and (3) bike lane width (other attributes included in the method are bike lane blockage, parallel parking, and presence of traffic signal).

There is variability within the population regarding tolerance for different levels of traffic stress (Damant-Sirois et al., 2014). Geller (2006) classifies the population into four groups along this line, and later research by Dill and McNeil (2013) measured the proportion of each group in metropolitan Portland, OR as follows:

- *Strong and Fearless* (6%): willing to ride under any conditions.
- *Enthused and Confident* (9%): willing to ride with minimal bicycle accommodations.
- *Interested but Concerned* (60%): uncomfortable negotiating fast, high volume traffic.
- *No Way No How* (25%): no interest in riding regardless of bicycle accommodations.

Mekuria et al. (2012) suggest their LTS ratings correspond to Geller's classification as follows: "strong and fearless" can tolerate high levels of traffic stress, "enthused and confident" can tolerate moderate levels of traffic stress, and "interested but concerned" will only tolerate low-stress roadway segments. Using San Jose, California as a case study, they calculated LTS for every link in the network and show that when only low-stress links are considered, many small "islands" emerge – sets of low-stress streets that are connected within themselves, but are separated from other islands by barriers such as freeways, rivers, and major arterials that lack low-stress crossings.

In other words, they found certain origin and destination pairs lack *connectivity* if bicycling is limited to only low-stress links. This definition of connectivity is used in this paper and is typically what is implied by the general public and transportation practitioners, such as in the quotes in the introduction. This definition is synonymous with *accessibility*, a measure of the ease of reaching important destinations (see Marshall (2004) for a discussion about the subtle difference between classically defined connectivity and accessibility).

Hansen (1959) developed a widely used method to evaluate accessibility for a specified origin point. His method sums, over all potential destinations, a measure of the *intensity* of the destination divided by the *impedance* of travel between the origin and destination. The intensity of a destination is the magnitude of its attractiveness, such as number of employees or floor area. Impedance is a function of travel cost (e.g. distance or travel time).

A few researchers have adapted Hansen's accessibility method for bicycle travel. Lowry et al. (2012) use distance weighted by BLOS as impedance in a GIS tool that evaluates a community's "bikeability". Iacono et al. (2010) developed impedance functions that incorporate "distance decay" for bicyclists to more realistically model the diminishing attractiveness of a destination with greater distance. McNeil (2011) defined a list of essential *destination types* (e.g. restaurant, bank, etc.) and associated point values with each type and then calculated an accessibility score for residential parcels by summing the points within a 20-min bike ride. The Walk Score® website uses a similar method to assess how good a location is for walking on a scale from 0 to 100 (Walk Score, 2014a). A user of the free website enters a street address and a map of the location appears showing nearby amenities and an accessibility score based on the diversity of amenities within walking distance. The creators of the website developed a more sophisticated method to calculate Bike Score™; however, the method is not available as an interactive web application. Instead, the website provides Bike Score™ summaries for over 100 cities (Herst, 2013). The proprietary Bike Score™ method takes into account proximity to bike lanes, nearby hills, and the percent of commuters in the area who travel by bicycle (Walk Score, 2014b).

3. Method

The method developed for this report involves four innovative techniques to (1) determine stress, (2) route shortest paths accounting for a limited tolerance for higher stress links, (3) quantify connectivity and (4) evaluate each link's contribution to overall accessibility. This section describes these innovations mathematically, while the next section outlines steps that an analyst can follow to execute the method.

3.1. Determining stress

First, we introduce a new bicycle suitability method for assigning the stress that a link imposes on cyclists. Our method is based on the concept of marginal rate of substitution (MRS). In economics, MRS is the rate at which a consumer is willing to give up one good in exchange for another good. Hood et al. (2011) and Broach et al. (2012) placed GPS trackers on cyclists and used logistic regression to empirically identify MRS values for various roadway conditions. For example, Hood et al. (2011) found that bicyclists are willing to travel 51% farther in a bike lane than on a similar road without a bike lane. Likewise, Broach et al. (2012) found cyclists are willing to go 140% out of the way to avoid a street where Annual Average Daily Traffic (AADT) exceeds 20,000 vehicles per day.

Researchers and practitioners typically use MRS values for route choice modeling within a regional travel demand model. As far as we know, our method is the first published work to express traffic stress in terms of MRS. We calculate stress using two MRS values: a stress-creating factor reflecting traffic attributes and a stress-reducing factor reflecting bicycle accommodation. The use of only two factors is intentional for simplicity and to minimize data requirements.

For a street and trail network composed of a set of links and a set of nodes, denoted E and V (in graph terminology links and nodes are called edges and vertices, respectively), we define a stress factor for every link $e \in E$ as:

$$F_{stress,e} = F_{roadway,e} * (1 - F_{bikeaccom,e}) \tag{1}$$

where

$F_{stress,e}$ = stress factor for link e,
$F_{roadway,e}$ = roadway stress factor for link e, and
$F_{bikeaccom,e}$ = bicycle accommodation stress reduction factor for link e.

The roadway factor is a function of a road's traffic attributes such as functional classification (e.g. local, collector, arterial), speed limit, and AADT. For our analysis, we defined eleven roadway types, mainly by number of lanes and speed limit, following Mekuria et al. (2012). Stress reduction factors, in turn, were defined for five levels of bike accommodation: a signed bike route with no further accommodation (5% reduction), sharrows (10%), conventional bike lanes (50%), buffered bike lanes (65%), and protected bike lanes (75%). Fig. 1 shows the stress factor for each roadway type and the stress reduction that is possible through various types of bicycle accommodation. The stress factors are marginal rates of substitution with respect to distance bicycling on a multi-use trail. For example, for a 6-lane road with speed limit 35 mph and no bicycle accommodation, the stress factor of 140% implies that a bicyclist would prefer traveling up to 140% farther on a multi-use trail; however, if a protected bike lane is provided, then the stress factor is reduced to 35%.

The MRS values shown in Fig. 1 are based loosely on the work by Hood et al. (2011) and Broach et al. (2012). The two research teams produced more than 40 MRS values for different conditions and types of bicyclists, however, the roadway characteristics they used differed from each other and from the work by Mekuria et al. (2012). Future research should try to produce MRS values that conform to typical roadway classification schemes. Furthermore, the values used in the case study could be improved through research specifically targeting the functional form of Eq. (1).

Fig. 1 also shows how our MRS factors can be grouped into Level of Traffic Stress categories using thresholds for stress factors that correspond to the framework of Mekuria et al. (2012). Categories provide a means to further describe cycling conditions and determine which conditions a bicyclist might deem acceptable, tolerable, or unacceptable. For example, a "strong and fearless" bicyclist would deem all stress levels acceptable, but an "interested but concerned" bicyclist might deem LTS 3 streets merely *tolerable* for short distances, and LTS 4 streets *unacceptable* no matter the distance.

Intersections can also generate traffic stress, depending on characteristics of the cross street such as number of lanes, presence of crossing refuge, speed limit, and traffic volume, the movement through the intersection (i.e. right, left, or through), and any stress reducing bicycle accommodations, such as a traffic signal or bike box.

For compatibility with the framework employed for segments, every intersection is treated as having a base impedance in units of distance – in the case study we used 30 ft – and then we apply stress factors, which again are marginal rates of substitution with respect to distance traveled, that increase or reduce the impedance in recognition of attributes of the crossing and the subject movement. For simplicity, we formulate intersection stress using two MRS values: a stress creating factor and a stress reducing factor. The calculation can be made for every intersection crossing movement k at intersection $v \in V$ as follows:

$$F_{stress,v,k} = F_{cross,v,k} * (1 - F_{crossaccom,v,k}) \tag{2}$$

where

$F_{stress,v,k}$ = stress factor for crossing movement k at intersection v,
$F_{cross,v,k}$ = cross-street stress factor for movement k intersection v, and
$F_{crossaccom,v,k}$ = crossing stress reduction factor for movement k at intersection v.

The cross street factor depends on roadway type. For the case study we used the same roadway types that were used for calculating stress associated with a link. Intersection bicycle accommodations might include a traffic signal, bike box, median refuge, or two-stage crossing stations. For the case study, the presence of a traffic signal or functional classification priority were used for stress reduction as shown in Fig. 2. The rationale is that crossing a busy street is stressful, but the provision of right-of-way relieves some stress. Functional priority was based on the following hierarchy: principal arterial > minor arterial > neighborhood greenway > collector > local street > multi use trail. Therefore, crossing a collector when traveling on an arterial is not as severe as crossing a collector when traveling on a local street. The assumption is that a bicyclist traveling on a local street who encounters a collector or arterial is faced with a stop sign and then waiting for a gap in the cross-traffic stream, both of which are nuisance for bicycling. Local streets with frequent stop-signs are a nuisance for all travelers, but even more so for cyclists who must exert energy to accelerate. Thus, there is some advantage for traveling on a higher functional classification roadway. However, the advantage might be offset by the high stress along the roadway (link stress).

The functional classifications used in the case study are standard for most US cities and state DOTs, except for neighborhood greenway (also called Bicycle Boulevard). Neighborhood greenways are an increasingly popular new functional classification with low traffic volumes, low vehicle speeds, and priority at intersections with local streets. Neighborhood greenways are attractive for bicyclists because they exhibit low link stress and low intersection stress.

3.2. Routing shortest paths

Bicyclists traveling for utilitarian purposes choose routes that will minimize impedance or generalized cost, which is a combination of distance, traffic stress, and slope. We define impedance for every link $e \in E$ as:

Roadway Number of Lanes	Roadway Speed Limit	Roadway Stress w/out Bicycle Accommodation	Stress Reduction from Bicycle Accommodations: Bike Route 5%	Sharrows 10%	Bike Lane 50%	Buffered Bike Lane 65%	Protected Bike Lane 75%
2 lanes (residential)	Up to 25 mph	10%	10%	9%	5%	4%	3%
2 lanes (residential)	30 mph	15%	14%	14%	8%	5%	4%
2-3 lanes	Up to 25 mph	20%	19%	18%	10%	7%	5%
4-5 lanes	Up to 25 mph	35%	33%	32%	18%	12%	9%
2-3 lanes	30 mph	40%	38%	36%	20%	14%	10%
6+ lanes	Up to 25 mph	67%	64%	60%	34%	23%	17%
4-5 lanes	30 mph	70%	67%	63%	35%	25%	18%
6+ lanes	30 mph	80%	76%	72%	40%	28%	20%
2-3 lanes	35+ mph	100%	95%	90%	50%	35%	25%
4-5 lanes	35+ mph	120%	114%	108%	60%	42%	30%
6+ lanes	35+ mph	140%	133%	126%	70%	49%	35%

Level of Traffic Stress Limits

LTS 1 Limit:	LTS 2 Limit:	LTS 3 Limit:	LTS 4 Limit:
10%	30%	60%	no MRS limit

Fig. 1. Stress in terms of MRS for various types of roadway and bicycle accommodation.

Cross Street Number of Lanes	Cross Street Speed Limit	Cross Street Stress w/out Bicycle Accommodation	Stress Reduction: Traffic Signal or Functional Priority 60%
2 lanes (residential)	Up to 25 mph	10%	4%
2 lanes (residential)	30 mph	15%	6%
2-3 lanes	Up to 25 mph	20%	8%
4-5 lanes	Up to 25 mph	35%	14%
2-3 lanes	30 mph	40%	16%
6+ lanes	Up to 25 mph	67%	27%
4-5 lanes	30 mph	70%	28%
6+ lanes	30 mph	80%	32%
2-3 lanes	35+ mph	100%	40%
4-5 lanes	35+ mph	120%	48%
6+ lanes	35+ mph	140%	56%

Fig. 2. Crossing stress (see Fig. 1 for stress limits).

$$W_e = L_e(1 + F_{slope,e} + F_{stress,e}) \tag{3}$$

where
W_e = impedance for link e,
L_e = length of link e,
$F_{slope,e}$ = slope factor for link e, and
$F_{stress,e}$ = stress factor for link e (see Eq. (1)).

For slope factors, we used MRS values provided by Broach et al. (2012) as follows:

$$F_{slope,e} = \begin{cases} 37\% \text{ if slope } > 2\% \\ 120\% \text{ if slope } > 4\% \\ 320\% \text{ if slope } > 6\% \end{cases}$$

In other words, ascending a moderate upslope is equivalent to increasing travel distance by 37%, and ascending an extremely steep upslope is equivalent to increasing travel distance by 320%. A bicyclist is willing to go 320% farther on level ground to avoid a very steep upslope.

We define the impedance for any movement k through intersection $v \in V$ as:

$$W_{v,k} = L_v(1 + F_{turn,v,k} + F_{stress,v,k}) \tag{4}$$

where
$W_{v,k}$ = impedance for movement k through intersection v,
L_v = base impedance for all intersections = 30 ft,
$F_{turn,v,k}$ = turn factor for movement k through intersection v, and
$F_{stress,v,k}$ = stress factor for movement k through intersection v (see Eq. (2)).

The turn factor represents the perceived increase in distance due to turning (if a turning movement is to occur). For the case study, turn factors were 100% and 200% for right turns and left turns, respectively, and 0 for a through movement. Thus a right turn is equivalent to adding an additional 30 ft to a trip, and a left turn an additional 60 ft, with values based loosely on the empirical findings of Hood et al. (2011) and Broach et al. (2012). The penalty on turns reflects a preference to take a straight route rather than one that zigzags through a grid.

Link stress and intersection stress, as given by Eqs. (2)–(4), are intended to be tractable and parsimonious. They could be modeled with greater detail; we leave that to future research. For example, a left turn from a principal arterial with heavy opposing traffic might exhibit a higher MRS than a left turn from a local street. Likewise, intersection accommodations such as bike boxes, crossing islands, and two-stage queuing boxes could be accounted for. On links, additional factors that could be considered include the presence of parallel parking, vehicle volumes, and bicycle lane width.

Now we describe the formulation for determining shortest paths. Let P_{ij} denote the set of all paths between i and j; a path involves a set of links and a set of intersection movements. For every path $p_{ij} \in P_{ij}$, total impedance can be summed across the path as follows

$$w(p_{ij}) = \sum_{e \in p_{ij}} W_e + \sum_{(v,k) \in p_{ij}} W_{v,k} \tag{5}$$

If the physical distance (i.e. total path length) between i and j is too far, then it is unlikely a bicyclist will travel for utilitarian purposes between i and j. The 2009 National Household Survey suggests many commuters won't bicycle beyond 2 miles (Santos et al., 2011).[1] Furthermore, we assert a bicyclist will only tolerate short distances of certain stress levels. We define two stress thresholds: $\bar{\tau}$ and $\bar{\bar{\tau}}$ which we call the "tolerable stress threshold" and "unacceptable stress threshold", respectively. Stress below $\bar{\tau}$ is deemed "acceptable", stress between $\bar{\tau}$ and $\bar{\bar{\tau}}$ is "tolerable" but only for short distances, and stress above $\bar{\bar{\tau}}$ is "unacceptable" no matter the distance.

For every possible path between i and j the following attributes can be summed: (1) length, (2) link length of tolerable stress, (3) link length of unacceptable stress, (4) intersection length of tolerable stress, and (5) intersection length of unacceptable stress. The calculations are as follows, respectively

$$\begin{aligned}
c_1(p_{ij}) &= \sum L_e, \text{ for } \{e \in p_{ij}\} \\
c_2(p_{ij}) &= \sum L_e, \text{ for } \{e \in p_{ij} : \bar{\tau}_e < F_{stress,e} \leqslant \bar{\bar{\tau}}_e\} \\
c_3(p_{ij}) &= \sum L_e, \text{ for } \{e \in p_{ij} : \bar{\bar{\tau}}_e < F_{stress,e}\} \\
c_4(p_{ij}) &= \sum L_v, \text{ for } \{v \in p_{ij} : \bar{\tau}_v < F_{stress,v} \leqslant \bar{\bar{\tau}}_v\} \\
c_5(p_{ij}) &= \sum L_v, \text{ for } \{v \in p_{ij} : \bar{\bar{\tau}}_v < F_{stress,v}\}
\end{aligned}$$

The shortest feasible path p^*_{ij} between i and j can be found, if it exists, by solving

$$p^*_{ij} = \arg\min w(p_{ij}) \tag{6}$$

subject to

$$\begin{aligned}
&c_1(p_{ij}) \leqslant C_1, \\
&c_2(p_{ij}) \leqslant C_2, \\
&c_3(p_{ij}) \leqslant C_3, \\
&c_4(p_{ij}) \leqslant C_4, \text{ and} \\
&c_5(p_{ij}) \leqslant C_5
\end{aligned}$$

Eq. (6) and the accompanying constraints constitute a network optimization problem called the Constrained Shortest Path problem. Santos et al. (2007) provide the binary integer formulation and discuss various solution algorithms. For our analysis, LTS 3 was deemed tolerable and LTS 4 deemed unacceptable. Furthermore, we applied the following constraints: total length, C_1 = 2 miles; total link length of tolerable stress, C_2 = 1800 ft (about two city blocks); total link length of unacceptable stress, C_3 = 0 ft; total intersection length of tolerable stress, C_4 = 90 ft (3 intersections); and total intersection length of unacceptable stress, C_5 = 0 ft.

3.3. Quantifying accessibility

To quantify bicycling-related accessibility for a community, we define $n \in N$ types of destinations that represent a "basket" of important and/or desirable types of destinations. In the case study we defined N to include the following: postal service, department store, grocery store, clothing store, restaurant, drinking place, pharmacy, sporting goods store, bank,

[1] The same summary of the National Household Survey reported that 40% of all trips in the survey, regardless of mode, were 2 miles or less.

barber/beauty salon, physical fitness facility, amusement and recreation, dentist, heath care provider, elementary or secondary school, university, library, child day care, religious organization, movie theater, and public park.

The basket of destination types is analogous to the consumer price index which economists use to calculate the cost of purchasing a collection of essential items such as eggs, milk, and bread. It is possible that some bicyclists would not need certain destinations in the basket, and it is also possible that different bicyclists would have unique preferences for particular destination types, e.g. preference for a particular restaurant. Nevertheless, like the consumer price index, the concept of a basket provides a means to calculate a meaningful metric with objectivity.

We define B as the set of all possible basket destinations in a community, and $b_{i,n}$ as the number of basket destinations that can reached from location i by solving the constrained shortest path problem with i as origin. We set a minimum basket requirement for each destination type and calculate $r_{i,n}$ as the percent of destination types that satisfy the basket requirement. For the case study, the basket requirement was two, in other words, at least two basket items of each basket type must be reachable. This leads to a key metric introduced in this paper: *the percent of residents that can reach a majority of important destinations via low-stress bikeways*. The metric is denoted as R and is calculated as follows

$$R = \frac{\sum_{i \in S} r_{i,n} * M_i}{\sum_{i \in S} M_i} \tag{7}$$

where

S = set of all origins,

M_i = population multiplier for origin i, and

$r(\widehat{R}_i) = \begin{cases} 1, & \text{if } \widehat{R}_i \text{ is } \geqslant 70\% \\ 0, & \text{otherwise} \end{cases}.$

For the case study, the cutoff for "majority of important destinations" was 70%, but an analyst could use a different value. Higher values are more restrictive.

3.4. Evaluating each link's contribution to overall accessibility

The contribution of each link to overall accessibility – and therefore its relative importance in the network – can be evaluated using a metric called *centrality*. McDaniel et al. (2014) used a form of centrality to quantify the relative importance of a link in a bicycle network. Their formulation counted the number of times a link is used on the shortest path between every residential parcel (origins) and every non-residential parcel (destinations). We modify their formula by only considering paths to basket items that satisfy the constrained shortest path problem. Thus, our centrality metric for a link e is

$$C_e = \frac{1}{a} * \sum_{i \in S, j \in B} p^*_{ij}(e) M_i M_j \tag{8}$$

where

$p^*_{ij}(e) = \begin{cases} 1, & \text{if link } e \in p^*_{ij} \\ 0, & \text{otherwise} \end{cases},$

M_i = multiplier for origin i,

M_j = multiplier for destination j, and

a = constant for scaling.

The origin and destination multipliers represent a magnitude of trip potential. For origins, the multiplier is the population, while the destination multiplier is number of employees (see McDaniel et al., 2014 for a discussion of other multipliers that could be used). The constant a is used to scale the centrality value; for the case study we used the population of the study area.

Centrality provides a means to evaluate the relative importance of each link in the network. Improvement projects consisting of multiple links can be evaluated by calculating the length-weighted average centrality across all the links within a project. This is another key metric introduced in this paper that we call Project-Average Centrality and calculate as follows:

$$C_{\overline{X}} = \frac{\sum_{e \in E_X} (C_e * L_e)}{\sum_{e \in E_X} L_e} \tag{9}$$

where $e \in E_X$ are the links within improvement project X. The Project-Average Centrality provides a means to compare the importance of different projects in terms of network connectivity.

4. Case study example

An analyst can follow three steps to execute our new method: Step 1. Identify Improvement Projects and Define Scenarios, Step 2. Prepare Origin and Destination Data, and Step 3. Run the GIS Tool for each Scenario. This section describes these steps for a case study community.

4.1. Step 1. Identify improvement projects and define scenarios

Our case study is the Bicycle Master Plan (BMP) for Seattle, Washington (population 652,000). Bicycling is a popular and increasingly common mode of transportation in Seattle. A recent survey of found nearly one third of the population ride bicycles occasionally and about fifteen percent are regular riders, riding a few times a month or more (SDOT, 2013b). The Seattle Department of Transportation was the primary author of the plan which consists of more over 450 miles of new or upgraded bicycle facilities broken up into 771 projects. Fig. 3 shows bicycle facilities for the existing conditions and BMP.

The projects in the BMP were identified through extensive public involvement activities over a three year period and adopted by city council April 2014. The cost of full implementation ranges from $390 million to $525 million and is anticipated to occur incrementally over the next 20 years. The BMP makes the assumption that individual projects are economically justified, with the expectation of conducting project prioritization every few years to allocate funding for a selected number of projects.

For the case study we defined Scenario 1 as the full build-out of the BMP. Scenario 2 is what SDOT has identified as "backbone" projects that would create the foundation for a citywide network. The backbone projects primarily involve building new Neighborhood Greenways and Protected Bike Lanes. Scenario 3 is a set of projects SDOT has identified for implementation in the near future.

SDOT provided GIS files for the projects and underlying street network. Data processing was performed to fix errors in topology and other issues. The street and trail network consisted of 24,324 links. We augmented the network with links to represent intersection movement (left, right, and through) and reverse direction links for every two-way street and trail. The final network consisted of 168,671 links.

4.2. Step 2. Prepare origin and destination data

Residential parcel data for the case study was obtained from SDOT. The number of dwelling units for each parcel was multiplied by 2.2 to estimate parcel population. Hoovers business data (Hoovers, N.D.) were used as destinations. Hoovers Inc., a subsidiary of Dun & Bradstreet Inc., maintains a database of more than 80 million companies, with information about industry type, street address, number of employees, facility square footage, annual revenues, and other business information. Hoovers business data can be purchased through a subscription service or directly through their website by choosing specific database filters, such as zip code and Standard Industrial Classification (SIC) code.

For the case study, Hoovers business data was obtained for companies within city limits and with SIC codes corresponding to these basket destination types: postal service, department store, grocery store, clothing store, restaurant, drinking place, pharmacy, sporting goods store, bank, barber/beauty salon, physical fitness facility, amusement and recreation, dentist, heath care provider, elementary or secondary school, university, library, child day care, religious organization, and movie theater. The Hoovers business data was geocoded for GIS analysis. Fig. 4 shows the case study residential parcels and Hoovers business data points. Public parks were appended to the destination file after using a standard GIS tool to create one random geocoded point per acre within park boundaries. The multiplier used for destinations was the number of employees at each location (provided by Hoovers) and number of acres for public parks. There were 162,057 origins and 21,723 potential basket destinations.

4.3. Step 3. Run GIS tool for each scenario

The method described in this paper was coded for ArcGIS® using open-source Python. The tool prompts the user for three GIS files and their relevant attributes. The GIS files are: (1) street and trail network, (2) residential land use parcels, and (3) potential basket destinations. The tool also prompts for the basket list of desired destination types.

The output includes one new attribute for each parcel (percent of basket reached), two new attributes for each link (impedance and centrality), network-wide measures of accessibility, and the Project-Average Centrality for each project.

The analysis was conducted for the existing conditions and the three improvement scenarios. The execution time on a standard, workstation-class laptop was about 3 h for each scenario (Lenovo w500 with 4 GB memory and Intel Core 2 Duo 3.06 GHz processor). However, using multi-core processing on a 4-core workstation-class desktop the execution time was reduced to about 30 min per scenario.

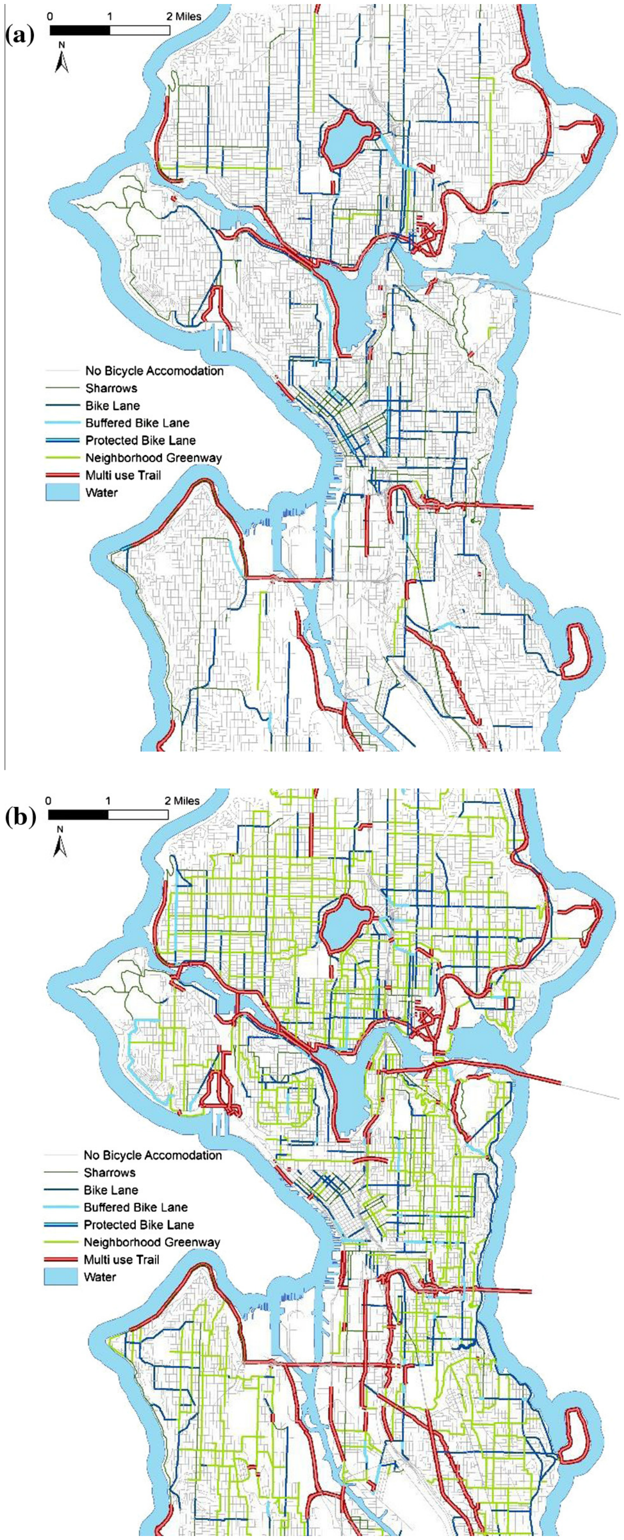

Fig. 3. Bicycle accommodations for (a) existing conditions and (b) BMP full build-out.

Fig. 4. Case study (a) origins and (b) basket destinations.

5. Results

The analysis produces three key results concerning low-stress cycling: (1) a metric to quantify accessibility to important destinations, (2) metrics of each link's contribution to overall accessibility, and (3) project rankings for prioritization. This section describes the results for the case study.

5.1. Access to important destinations

A key output from the analysis is an assessment of accessibility to important destinations. Fig. 5 shows the percent of important destinations that can be reached using low-stress bike routes for each parcel in the south-west quadrant of Seattle. This area of Seattle is economically deprived and underserved. The analysis confirms that many residential parcels in that area exhibit poor accessibility by bicycle to important destinations under the existing conditions (Fig. 5a). In fact, many of the parcels cannot even reach half of the basket destination types. Accessibility is especially poor in the industrial areas (south-east section Fig. 5a). The neighborhoods along the waterfront exhibit relatively better accessibility because they can more directly access a multi-use trail and are in closer proximity to a variety of basket destinations.

The results shown in Fig. 5b show how improvement projects that provide low-stress bicycle opportunities can significantly increase accessibility to important destinations. The proposed bicycle accommodations would allow most of the residential parcels to access a majority of the basket destination types. The BMP proposes neighborhood greenways, protected bike lanes, and multi-use trails for that area. Analysts could use maps like these to visualize how improving low-stress connectivity might help various areas of the community and specific population segments. Additional analysis could investigate equity concerns.

Across the community a full build-out of the BMP would increase the percentage of residents that can reach a majority of important destinations via low-stress bike routes from 42% to 67%. Table 1 summarizes the scenarios and shows that Scenario 2 and Scenario 3 would increase the percentage to 60% and 47%, respectively. These scenarios would not involve as many improvements and are considerably less expensive. Additional scenarios could be analyzed with other combinations of projects or individual projects could be analyzed one at a time; however, piecemeal analysis would not reflect the interaction between projects.

5.2. Network connectivity

The results also provide a means to evaluate the role individual links play in overall network connectivity. The tool labels each link acceptable, tolerable, or unacceptable based on the stress limits. For the case study, arterials with multiple lanes and high speeds are unacceptable barriers for travel. Consequently, although there are numerous potential basket destinations downtown, very few are reachable. The tool also enumerates how often basket destinations are deemed reachable from the residential parcels. In the case study, destinations in bicycle friendly neighborhoods, such as Ballard and Laurelhurst, were deemed reachable from numerous residential parcels, while destinations downtown were not reachable. Indeed, these results reflect the reality that the bicyclists who venture downtown tend to be "strong and confident".

Fig. 6 shows each link's centrality for the existing conditions and the full build-out scenario. The calculation of centrality can be thought of conceptually as gauging the *potential flow* from residential parcels to all nearby important destinations. The categories used in the figure represent the natural log of centrality divided by Seattle's population because the raw centrality values range into the millions (see Eq. (8)). The highest centrality values are concentrated along the Burke-Gilman Trail that snakes along Lake Washington in the upper-right portion of Fig. 6, serving as a low-stress route connecting many origins and destinations. Moderate centrality values are pervasive on the local streets throughout the residential neighborhoods. This is because the residential parcels are the source from where the flow is emanating. On the other hand, high stress streets have low centrality or zero centrality. The full build-out scenario (Fig. 6b) shows more expansive centrality flow and fewer islands of constrained travel. An analyst could further examine the GIS attribute table to gain a better understanding of how the concentrations of centrality changed from scenario to scenario.

The stress limits, shortest path constraints, and basket requirements used in the case study were rather restrictive. Consequently, the existing conditions exhibit inescapable barriers of stress and islands of constrained travel. Improvements were made for the BMP, but the analysis is still quite restricted. The intent or our analysis was to evaluate a strict definition of "low stress" connectivity. An analyst could explore the effect of relaxing these parameters. Indeed, we found, for example, that slightly increasing the threshold that defines unacceptable stress, doubling the distance of tolerable moderate stress, and requiring only one basket item per basket type resulted in 98% of residents reaching the basket destinations in the full build-out scenario.

5.3. Project rankings

Another way to compare the scenarios is to examine the Project-Average Centrality for each project. A high Project-Average Centrality for the existing conditions suggests that the links belonging to a given project are already an important route for bicycle travel, despite potentially being in need of improvement. For a future scenario such as full build-out of the

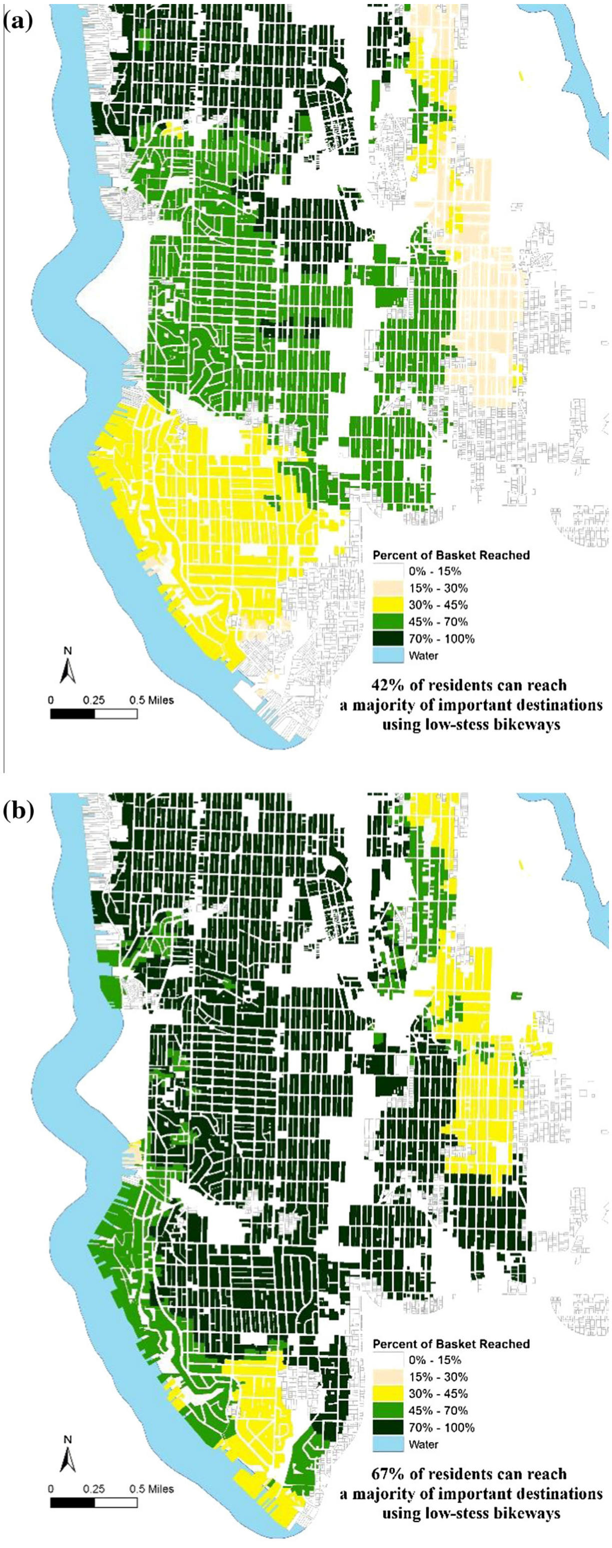

Fig. 5. Accessibility to important destinations for (a) existing conditions and (b) BMP full build-out.

BMP, a high Project-Average Centrality suggests that the links belonging to a given project will be very important after the improvements are made. Decision-makers could use the values for existing conditions and improvement scenarios to help

Table 1
Scenarios and accessibility results.

Item	Scenario 0: Existing Conditions	Scenario 1: Full build-out of BMP	Scenario 2: Backbone projects	Scenario 3: Near-term projects
Sharrows (miles)	30	7	0	0
Bike Lane (miles)	68	33	8	20
Buffered Bike Lane (miles)	3	14	0	0
Protected Bike Lane (miles)	1	102	99	34
Neighborhood Greenway (miles)	4	234	66	56
Multi use Trail (miles)	2	30	18	2
Number of Projects	NA	771 projects	282 projects	146 projects
Low Cost Estimate ($ million)	NA	$390	$223	$94
High Cost Estimate ($ million)	NA	$525	$279	$123
Percent of residents that can reach important destinations via low-stress bikeways (%)	42	67	60	47

Note: Scenarios 1–3 list the additional miles that would added to existing conditions.
NA – Not applicable. BMP – Bicycle Master Plan.

identify the most important projects. They could also look at the *change* in Project-Average Centrality between the existing conditions and proposed scenarios. Table 2 lists the top 20 projects ranked by change in Project-Average Centrality (the centrality values have been scaled by dividing by the population of the study area). The greater the change between the existing conditions (Before) and BMP (After) signifies a higher *connectivity impact*.

The first-ranked project is an overpass that would traverse Interstate 5 and provide a critical connection between East and West Seattle. The centrality for the existing conditions is zero because this proposed multi use trail currently does not exist. This project is an ambitious idea that many Seattle residents have requested; it is also one of the most expensive projects among the 771 projects in the BMP. It would probably cost several million dollars to construct. Nevertheless, the results from the analysis confirm that it would be a very important project in terms of network wide connectivity. Indeed, the centrality of this link after construction is the highest and dwarfs the centrality of all other projects.

Five of the top 20 projects (as ranked by change in Project-Average Centrality) are new multi use trails. These projects, like the first-ranked project, exhibit zero centrality for the existing conditions, which helps them rise to the top when sorting by change in centrality. On the other hand, there are other new multi use trails that exhibit poor rankings (e.g. the 418th and 737th ranked projects). These projects rank poorly because they are located away from urban activity, i.e. basket destinations, and/or because improvements elsewhere opened up opportunities for more direct routes from homes to destinations. While it is possible these projects might be important for recreational travel, the analysis suggests they would do little to improve connectivity for utilitarian travel.

Other projects that rank very well when sorting by change in Project-Average Centrality are those that involve protected bike lanes. There are eight protected bike lane projects within the top 20 projects listed in Table 2. These projects attract centrality flow because they offer low-stress bicycling along direct routes where existing parallel low-stress routes are lacking For example, the second-ranked project is a protected bike lane across the University Bridge that connects to the commercial area near the University of Washington. On the other hand, projects that do little to minimize stress, such as sharrows, generally ranked poorly. In fact, nine projects (out of 771) showed adverse change in Project-Average Centrality, meaning there was a decrease in potential flow for the full build-out scenario, because other nearby projects are more effective at offering low-stress connections and therefore would attract away some of the existing flow.

There are projects that show high centrality in the full build-out scenario, yet exhibit only a small change in Project-Average Centrality. For example, a Neighborhood Greenway project (ranked 193rd) that feeds into the Burke-Gilman Trail exhibits only a small change in Project-Average Centrality because, it has high centrality value in both existing and full build-out scenarios. That is, the current local street is already providing an important low-stress connection even without the enhancement of converting it to a neighborhood greenway. Projects that are very important to connectivity (high centrality) before *and* after, should be evaluated based on change in stress. This Neighborhood Greenway, for example, would significantly reduce stress for a half a mile distance through reduced speed limit and intersection priority.

It is also important to recognize the interdependency of centrality rankings within a given scenario. For example, for the full build-out scenario, the 5th ranked project in Table 2 is a protected bike lane that would feed into the first-ranked overpass project mentioned earlier. If the expensive first-ranked project is not funded, then the protected bike lane project would almost certainly not be as important as is suggested in Table 2.

6. Discussion

The case study provides an opportunity to discuss a few strengths, caveats, and limitations with the analysis method presented in this paper. One key strength is the minimal data requirements. Many communities already have the required GIS data: (1) street and trail network with a limited set of attributes including speed limit, number of lanes, and functional classification; (2) residential land use parcels; and (3) points-of-interest destinations. (The latter can be obtained at moderate

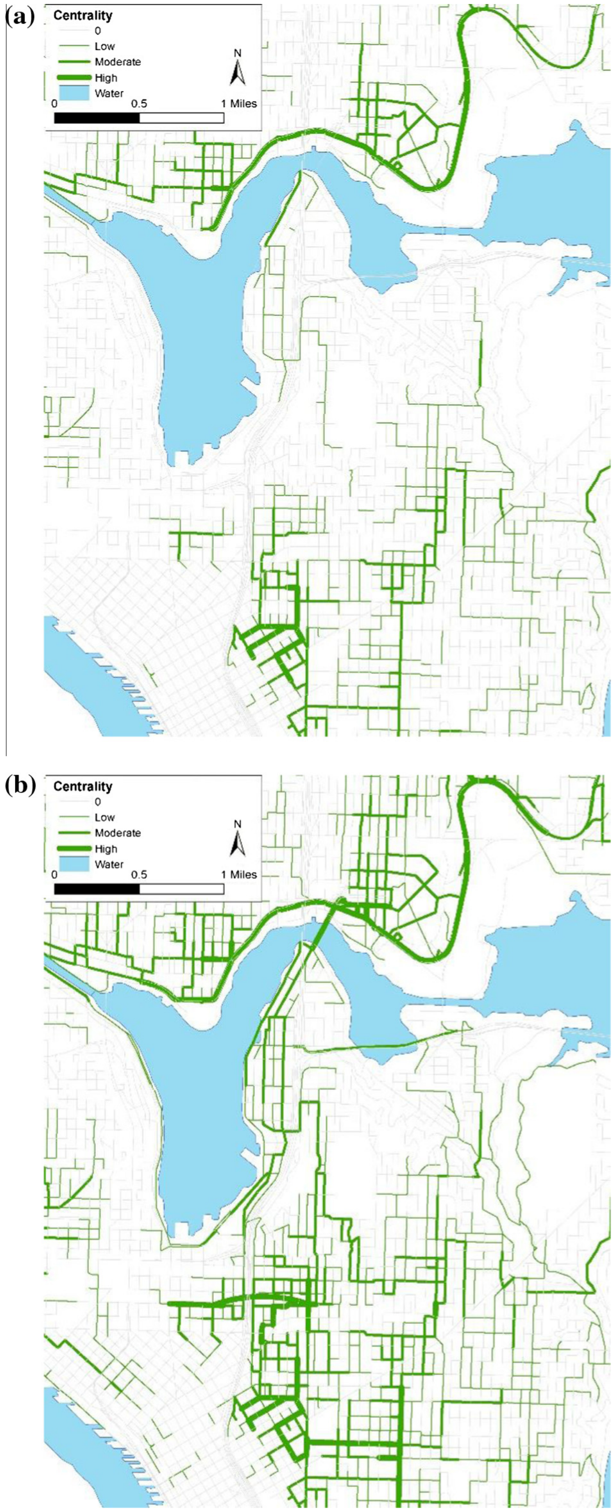

Fig. 6. Centrality for (a) existing conditions and (b) BMP full build-out.

cost from private sources.) Another strength is the quick execution time. Engineers and planners could easily run several scenarios within a day. Other strengths are that the method is straight forward and the output is easy to understand. The general public and decision-makers can easily review maps of centrality and the percent of basket reached to gain a better

Table 2
Top 20 projects ranked by change in project-average centrality.

Rank	Project	Current facility	Proposed bicycle Accommodations	Miles	Project avg. centrality[a]		
					Before	After	Change
1	508	–	Multi use Trail	0.58	0	786	786
2	368	–	Multi use Trail	0.40	0	103	103
3	626	Principal Arterial	Protected Bike Lane	0.35	0	89	89
4	627	Minor Arterial	Bike Lane	0.08	0	62	62
5	385	Minor Arterial	Protected Bike Lane	0.57	0	47	47
6	636	Collector	Protected Bike Lane	0.46	7	50	43
7	423	Local Street	Neighborhood Greenway	1.21	3	44	42
8	625	Collector	Neighborhood Greenway	0.41	4	45	41
9	121	Minor Arterial	Protected Bike Lane	0.51	0	33	33
10	306	–	Multi use Trail	1.01	0	32	32
11	391	–	Multi use Trail	1.36	0	31	31
12	392	–	Multi use Trail	0.13	0	29	29
13	137	Principal Arterial	Protected Bike Lane	0.49	0	28	28
14	466	Principal Arterial	Protected Bike Lane	0.63	0	27	27
15	685	Principal Arterial	Protected Bike Lane	0.47	0	25	25
16	585	Minor Arterial	Bike Lane	0.36	0	24	24
17	100	Minor Arterial	Protected Bike Lane	0.58	0	24	24
18	149	Local Street	Neighborhood Greenway	1.80	15	38	24
19	271	Local Street	Neighborhood Greenway	0.25	2	25	23
20	837	Local Street	Neighborhood Greenway	1.46	3	25	22

[a] Centrality divided by 652,000 (Seattle's population). Before = S0 Existing conditions. After = S1 Bicycle Master Plan.

understanding of project impacts. The method also provides a meaningful and flexible way to incorporate public input into the prioritization process through the definition of the "important" destination types represented in the basket.

The output can aid the selection of which projects should receive funding. A community could choose to fund projects based on rank order of Project-Average Centrality or the rank order of change in Project-Average Centrality. For example, if a community has a budget of $10 million they could fund the top ranked projects until all available funding is exhausted. Another approach might be to select projects so as to fund as many as possible while maximizing total centrality. The output can also help identify inferior projects that are very costly and do not enhance connectivity. Nevertheless, the selection or rejection of projects should include consideration of other performance indicators the community has devised, such as equity and safety. A comprehensive evaluation that considers a robust set of performance indicators can help identify tradeoffs between projects.

The method can also be applied to benchmark progress on plan implementation, or to measure progress related to specific policy priorities that can be articulated as particular origins and "important" destinations, such as Safe Routes to School (households with school-aged children and school facilities). In the long term, the method could also be applied in the land use planning context, including identifying parcels with high bicycle accessibility, and related transportation planning contexts, such as improving bicycle access to transit and siting bikeshare stations. Furthermore, the method could be combined with other spatial analysis techniques that look at a proposed projects relationship to crash data or volume data (Larsen et al., 2013).

As previously mentioned, an important caveat concerns the interdependence of projects. The analysis for a scenario produces results for "full-build-out" of the scenario. If budget constraints prevent full implementation, then centrality values and project rankings might not be as meaningful. A planner should analyze a variety of scenarios, including single project scenarios, to gain a better understanding of project impacts. Likewise, the analyst might want to run scenarios with not-existing but proposed residential parcels and destinations to represent expected future conditions.

The MRS values have a few shortcomings, some of which might be improved through future research and others which might be inconsequential. First, a person's actual MRS values are probably more complex than our method suggests. In reality, a bicyclist would probably not substitute a bike lane with an off-street path at a linear rate (i.e. the tradeoff rate would be different for a one mile trip compared to a 10 mile trip). Economists call this the law of diminishing marginal rate of substitution. Likewise, the interaction between facilities and bicycle accommodations is probably more complex than Eqs. (1)–(4) (e.g. a bike lane probably does not reduce stress on an arterial at the same rate as on a collector). In fact, there are a variety of interactions at play, such vehicle speeds, bike lane width, number of vehicle lanes, etc. Likewise, the model for intersection stress could be more sophisticated with more interaction between turn movements, facility types, and bicycle accommodations.

Various bicycle suitability assessment methods that have been developed in the last few decades, such as BLOS and LTS, are an attempt to quantify this interaction. Our intent was to produce a simple and practical model for which GIS data is commonly available. Most communities do not have detailed information beyond functional classification and bicycle facility type (Callister and Lowry, 2013).

Furthermore, actual MRS values differ from person to person and might be better generalized according to characteristics such as sex, age, bicyclist type, and geographic region (Hunt and Abraham, 2006). A confident bicyclist from Seattle would have a different perception of bicycling on an arterial compared to a concerned bicyclist from a small rural town. A community could certainly develop their own MRS values and future research should investigate these complexities; however, in practical terms these issues are probably inconsequential. The method presented in this paper, like other models used by practitioners, is intended for decision-support, just as economists commonly use simplified MRS values and theoretical constructs like the consumer price index to analyze complex phenomena. The method presented in this paper does not rely on specific MRS values nor on a specific typology of bicyclists, instead the analyst using our tool can and should use local parameters, if available, to define stress. The values in the paper are for illustration and case study. In practice, an analyst would spend some time "calibrating" the tool against the existing conditions because the tool is sensitive to the MRS values and threshold for defining "tolerable" and "unacceptable" stress.

7. Conclusion

This paper introduced a new method for prioritizing bicycle improvement projects based on low-stress network connectivity. The novel GIS tool is easy to use, requires commonly available data, and has reasonable execution time. The tool was successfully used for a case study to produce meaningful project rankings for more than 750 projects that have been proposed as part of Seattle, Washington's Bicycle Master Plan. The analysis showed how the proposed plan would increase the percent of residents able to access a majority of important destinations from 42% to 67% if the full plan is implemented. Two additional less costly scenarios also demonstrated an improvement in accessibility by bicycle. Engineers and planners can use the new method and GIS tool in a similar manner to analyze scenarios for their community. The output can help to prioritize projects and convey connectivity impacts to the general public and decision-makers.

The current method assesses connectivity for utilitarian travel; future research should investigate how to incorporate connectivity for recreational travel. Future research should also seek to advance the method with improved marginal rate of substitution values. Research could also explore the impact of running the tool with different basket specifications (i.e. the list that defines which destinations are important). Finally, additional research should develop strategies for analyzing project interdependencies.

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