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Mapping bikeability: a spatial tool to support sustainable travel

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Abstract. The built environment has been shown to influence active transportation. Although spatial data for the built environment is increasingly available, there has been little effort to use existing data and knowledge to define and map 'bikeability' as an approach to promoting travel by bicycle. Our goal was to build a tool to identify areas that are more conducive and less conducive to cycling. We used empirical research to develop a bikeability index and geographic information systems to map the index across the Metro Vancouver region. Results of an opinion survey, travel behaviour studies, and focus groups were used to identify the components of the index and their relative importance. Pertinent geospatial data layers were scored and combined using a flexible weighting scheme to create a composite map highlighting both high and low bikeability areas. The bikeability index was comprised of five factors shown to consistently influence cycling: bicycle facility availability; bicycle facility quality; street connectivity; topography; and land use. For mapping purposes, we created corresponding metrics: density of bicycle facilities; separation from motor vehicle traffic; connectivity of bicycle-friendly roads (local streets, bicycle routes, and off-street paths); slope; and density of destination locations. Using empirical evidence to combine data layers for these metrics we generated a high-resolution (10 m) bikeability surface for the region, depicting bicycle-friendly areas and areas where cycling conditions need to be improved. Built environment interventions for specific locations are informed by evaluating scores for the five individual component layers. Mapping bikeability provides a powerful visual aid to identify zones where changes are needed to support sustainable travel. This evidence-based tool presents data in a user-friendly way for planners and policy makers. The overall bikeability score and its five component scores can guide local action to stimulate changes in cycling rates. It uses widely available data types, thus facilitating easy application in other cities. Furthermore, the flexible parameters and weighting scheme enable users elsewhere to tailor it to evidence about local preferences and conditions.

Keywords: bicycle, built environment, physical activity, urban planning, GIS, spatial tool

1 Background

Faced with global challenges of congestion, air pollution, climate change, energy scarcity, and physical inactivity, the fields of public health, urban planning, and transportation are collectively focused on strategies to reduce automobile travel and promote active transportation (Frumkin et al, 2004). A growing body of research has explored how the built environment influences physical activity, with findings that people who live in more walkable neighbourhoods walk more, have lower rates of obesity and chronic disease, and travel less by car, even after accounting for demographics and personal preferences (Handy et al, 2006; Transportation Research Board and Institute of Medicine of the National Academies, 2005). Features of these walkable neighbourhoods include high population density, mixed land use, grid-based street networks, and human-scale design (Saelens and Handy, 2008; Saelens et al, 2003). The existing focus on walking is justifiable given that it is the most common form of leisure-time physical activity, with few barriers and no cost. However bicycle travel, being faster and more efficient while nearly as accessible and economical, is a more reasonable substitute for automobile travel when trip distances exceed 1 km (European Commission, 1999). The utility of cycling for transportation has been recognized in model cities such as Copenhagen and Amsterdam, where cycling mode shares are as high as 30%, with little differentiation by age or gender (Pucher and Dijkstra, 2003). The potential of cycling for transportation in North America has yet to be realized, although promising initiatives are taking place in select cities (eg, New York, Portland, and Montreal) and the longer-standing changes in Portland and Montreal have been accompanied by substantial modal shifts (Miller, 2010).

The literature provides some evidence regarding built environment correlates of cycling behaviours, based on both opinion and behaviour-based studies. Surveys have documented cyclists' opinions on factors that motivate and deter cycling, highlighting issues of safety, infrastructure, and the physical environment (Bhat et al, 2009a; Hunt and Abraham, 2007; Winters et al, 2011a). Stated preference studies have quantified trade-offs between such factors, given hypothetical travel situations (Bhat et al, 2009b; Krizek, 2006; Stinson and Bhat, 2003). The initial behaviour-based research drew on aggregated data, and found that cities with more bicycle lanes have higher cycling rates (Dill and Carr, 2003; Nelson and Allen, 1997). Other endeavours have used disaggregate origin–destination data from travel surveys (Cervero and Duncan, 2003) or tracked cyclists' route selections (Aultman-Hall et al, 1997; Dill, 2009; Winters et al, 2010a; 2010b) and found that features of the built environment are associated with both mode choice and route choice.

While the research indicates that environmental factors are associated with cycling, the data have not been used in a systematic way to stimulate changes in cycling rates. Over the past decade government departments and agencies have built spatial databases of environmental features, and the data and the technology to use them have become more accessible. Research on the promotion of walking has drawn on these, using geospatial data to create walkability maps and popular online tools such as WalkScore (http://www.walkscore.com/). Much less has been done to use existing knowledge to define and map 'bikeability'. Existing indices for walkability, sprawl, or urban and suburban built environments (Ewing et al, 2003; 2006; Frank et al, 2009; Moudon and Lee, 2003; Schneider et al, 2006) are comprised of components such as density. Given that walking and cycling are recognized as functionally different (Krizek et al, 2009) and the dimensions of the built environment influencing each mode may differ (Lee and Moudon, 2006; Moudon et al, 2005), there are certain to be differences between a measure for walkability and one for bikeability. There is rising interest in bikeability—as highlighted by several projects led by urban planners and researchers elsewhere that were concurrent with this work. Projects in three other North American cycling cities (Montreal, New York, Portland) (Larsen and El-Geneidy, 2010; Richards, 2010; Voros and Birk, 2010)

Table 1. Concurrent projects using spatial data to capture 'bikeability'.

Reference (location)	Objective	Factors	Unit of analysis
Current paper (Vancouver)	To build a planning tool that identifies areas more conducive and less conducive for cycling, based on the on-the-ground conditions, using widely available data	Bicycle-route density; bicycle- route separation; connectivity of bicycle-friendly roads; topography; and destination density	continuous surface: 10 m grid cell
Larsen and El-Geneidy (2010) (Montreal)	To determine optimal locations for new facilities	Current cyclists' trips; short car trips; suggested routes from local survey; reported bicycle–car crashes	300 m grid
Richards (2010)[a] (New York)	To determine if neighbourhood bikeability predicts body mass index	% cycling commuters; % of streets with bicycle lanes; bicycle lane density; cycling injuries	neighbourhood
Voros and Birk (2010) (Portland)	To help planners assess existing conditions and cycling potential, and maximize return on investment	Cycle-zone analysis: bikeway quality[b]; road-network density; bicycle-network density; permeability; connectivity (connected node ratio); average slope; distance to commercial establishment	homogeneous bicycle zones, defined with expert assessment (36 across Portland)

[a] Abstract only.

[b] Bikeway quality: automobile speed; automobile volume; number of lanes; bicycle-lane drop; difficult transition; bicycle-lane width; jogs; pavement quality; intersection crossing quality; stops.

have also generated composite scores (table 1). Each project was initiated with a different objective and, as is often the case with concurrent efforts, used disparate approaches. The criteria used to determine these indices, where reported, are based primarily on expert opinion or intuition. There have been no publications evaluating these indices.

Our goal was to define bikeability on the basis of empirical evidence, and build a planning tool that identified areas that are more conducive and less conducive to cycling. With the guiding aim of reducing car travel, our focus was on cycling for transportation purposes (ie, for work, school, shopping, or personal business), as compared with recreational or fitness purposes, for which individuals may make different route choices and be less constrained by distance (Wahlgren and Schantz, 2011; Winters and Cooper, 2008). Capitalizing on geospatial data sources, we mapped bikeability as a continuous surface, displaying a continuum of conditions from high to low, using Metro Vancouver, British Columbia as a case study. Our ultimate goal was to build a flexible tool relying on commonly available data to facilitate widespread adoption, and enable it to be tailored to local conditions.

2 Methods

2.1 Case-study setting

Metro Vancouver is an urban region of western Canada comprised of twenty-two municipalities that are home to approximately 2.1 million people (Metro Vancouver, 2006). The region has widely varying neighbourhood characteristics (urban, suburban, rural), transportation infrastructure (neighbourhood streets, arterials, freeways, off-street bicycle paths, on-street bicycle lanes), and topography (flat river deltas, hilly areas, mountains). The climate is conducive to cycling all year, with all monthly average low temperatures above freezing, all monthly average high temperatures below 25 °C, but substantial rainfall (over 1200 mm rain/year) (Environment Canada, 2009). There are over 1350 km of bicycle facilities in the region with about 170 km being off-street paths.

2.2 Identifying components of bikeability
Three previous studies were used to identify components of the bikeability index and their relative importance: an opinion survey; travel behaviour studies; and focus groups (figure 1) (Winters and Cooper, 2008; Winters and Teschke, 2010; Winters et al, 2010a; 2010b; 2011a).

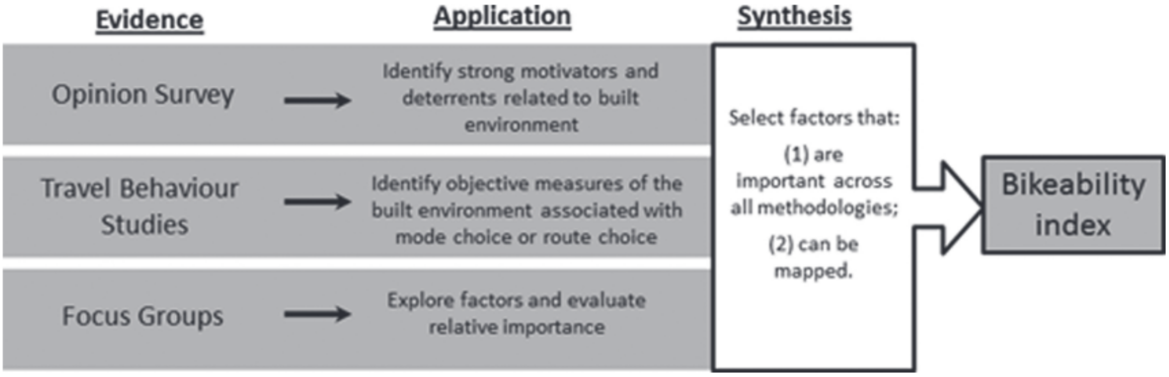

Figure 1. Data sources and methodology for derivation of bikeability index.

2.2.1 *Opinion survey*
We used the findings from a population-based survey we conducted in the region to identify built environment factors that influence cycling. The Cycling in Cities Survey (Cycling in Cities Research Program, University of British Columbia, http://www.cyclingincities.spph.ubc.ca) included 1402 current and potential cyclists from Metro Vancouver. The survey queried the relative importance of seventy-three potential motivators and deterrents, about a third of which were related to the built environment. Survey participants reported that strong influences were bicycle facilities, aesthetics, topography, traffic and trip distance (or speed of cycling relative to other modes) (Winters et al, 2011a). The survey also asked about usage and preferences for sixteen types of cycling infrastructure. Results highlighted the desirability, to all types of cyclists, of off-street or physically separated routes, followed by local street bicycle routes (Winters and Teschke, 2010).

2.2.2 *Travel behaviour analyses*
We identified objective measures of the built environment that are associated with cycling based on two analyses of actual travel. For these analyses we used additional data collected during the Cycling in Cities Survey: two commonly made trips by each participant. The first analysis examined 3280 trips made by car and bicycle to determine which built environment measures were associated with a higher likelihood of cycling versus driving (Winters et al, 2010a). The second analysis used a subset of the data to compare the actual route used with the shortest-distance route between the origin and destination, to understand how the built environment influences route selection (Winters et al, 2010b). The results indicated the importance of the following domains for cycling:

- Bicycle facilities: cyclists detoured en route to use bicycle facilities; and more bicycle-friendly facilities (traffic calming, road markings or bicycle signage, or bicycle-activated crossing signals) were positively associated with the odds of cycling.
- Connectivity: intersection density was positively associated with the odds of cycling; and arterials and highways were inversely associated with odds of cycling.

- Topography: hilliness was inversely associated with odds of cycling.
- Land use: neighbourhood commercial, education, entertainment, and office land-use types were associated with higher odds of cycling.

2.2.3 *Focus groups*

We conducted a series of focus group sessions to provide context on how the built environment contributes to making a neighbourhood bikeable (Winters and Cooper, 2008). The emphasis was on physical environment factors that are modifiable through planning and zoning, as opposed to those beyond the scope of municipal or regional decision making (eg, climate, helmet legislation). On the basis of the results of the Cycling in Cities Survey and existing literature linking walking or physical activity with the built environment (Brownson et al, 2009; Saelens and Handy, 2008), eight broad factors were selected for exploration: topography, distance traveled, environment (ie, air and noise pollution), traffic, street network, bicycle facilities, land use, and population density.

We recruited four groups of eight–ten participants: one group of cycling advocates and three groups of Cycling in Cities Survey respondents. Participants in the latter groups were stratified according to cycling frequency: regular cyclists (who cycled at least once a week); occasional cyclists (who cycled less than once a week); and potential cyclists (who had not cycled in the last year, but were willing to consider cycling in the future).

Participants started by completing questionnaires about how the factors might increase or decrease their likelihood of cycling for a utilitarian trip, and what other factors were important. A moderator then facilitated an hour-long discussion exploring the context in which each factor influenced cycling. Finally, each participant was asked to prioritize their top three factors. The prioritization was not completed by the cycling advocacy group.

The focus groups provided information on the relative importance of built environment factors as indicated in the ranking in table 2. Bicycle facilities were clearly the most important component, scoring about twice the number of points as traffic or the street network.

Table 2. Ranking of built environment factors in focus groups with current and potential cyclists ($n = 23$).

Rank	Factor	Example quote from participant	Score[a]
1	Bicycle facilities	“The more you feel separated from traffic, the safer you feel.”	50
2	Traffic	“The encroaching volume of traffic is rendering the bike lanes inadequate.”	25
3	Street network	“If I’m commuting I find [grid network] much easier, I feel I can progress through much faster.”	17
4	Topography	“Hills are a big problem for me because I don’t have the strength or endurance.”	16
5	Environment	“I just hate it—all types of pollution—I would go a long way out of my way to avoid it.”	12
6	Distance	“If I could ride to work from home in a half hour, I wouldn’t think twice about it.”	9
7	Neighbourhood land use	“I don’t find the suburbs set up for bicycles. It’s not easy to do your everyday chores because of the distances.”	4
8	Population density	[no comments]	2

[a] Factors were prioritized in order of importance to participant. Priority 1 was assigned 3 points, priority 2, 2 points, and priority 3, 1 point. Total points = 135. 23 individuals completed the ranking exercise, and one person assigned only 2 factors.

The participant quotes further highlighted the importance of separated facilities. Conversely, land use and population density were not as highly ranked by participants.

The focus group discussions also gave insight as to how concepts could be operationalized. For example, participants felt that highly connected grid-based road networks allowed for more route choice and efficient travel, but that busy streets with bus, truck, or high car volumes deterred cycling. This suggested that a conventional connectivity measure (intersection density) should be modified for cycling to include only bicycle-friendly roads (eg, local roads and bicycle paths). Another theme was that bicycle routes needed to connect with other bicycle routes, suggesting that a density measure be used instead of a present/absent dichotomous measure.

2.3 Developing the bikeability index

The empirical evidence from the opinion survey, travel behaviour analyses, and focus groups is summarized in figure 2. A comparison of results across studies, looking for consistency and readily mapped features, produced four main domains: bicycle facilities; street connectivity; topography; and neighbourhood land use. These also met the criteria of data availability: topography and road networks exist in national datasets, and bicycle route networks and land-use data (eg, parcel data from tax assessments) are held by most municipalities.

Some synthesis of the results was conducted, on the basis of the focus-group discussions. We integrated the connectivity and road-type measures as ‘connectivity of bicycle-friendly streets’, and the neighbourhood land use and distance concepts as a ‘destination density’ measure. A preliminary index with the four components was presented to local bicycle planners for review. Their qualitative evaluation highlighted the importance of separated bicycle facilities. These practitioners stated that the quality of separated facilities such as bicycle tracks and off-street paths warranted substantial recognition in the index. This guidance resonated with what was reported in both the focus groups and opinion survey, which specified that not all bicycle routes are equally desirable, but that facilities separated from traffic were preferred over others. Therefore we decided to include bicycle route separation from traffic as a fifth factor wherever such data were available (which was usually the case).

The final index is a combination of these factors:

$$\begin{aligned}\text{bikeability} = {} & (B_1 \times \text{bicycle route density}) + (B_2 \times \text{bicycle - route separation}) \\ & + (B_3 \times \text{connectivity of bicycle - friendly streets}) \\ & + (B_4 \times \text{topography}) + (B_5 \times \text{destination density}),\end{aligned}$$

where B_1–B_5 are the weights applied to each layer. The scoring from focus groups (table 2) proposed a higher weighting for bicycle facilities. Where bicycle route density is the only facility measure available, the scoring indicates its weight should be twice the weight of other factors (ie, $B_1 = 2$, $B_3 = B_4 = B_5 = 1$); where both bicycle route density and separation are available, the weighting could be balanced (ie, B_1–B_5 = 1). We conducted a post hoc analysis to compare the original four-component bikeability measure (without the bicycle route separation component) with the five-component measure (with bicycle route separation). The two were highly correlated ($r = +0.96$, $p < 0.0001$) at the census tract level (administrative units with populations of 2000–8000 people). Adding bicycle route separation provided more fine-grained information, with higher scores directly alongside a separated corridor.

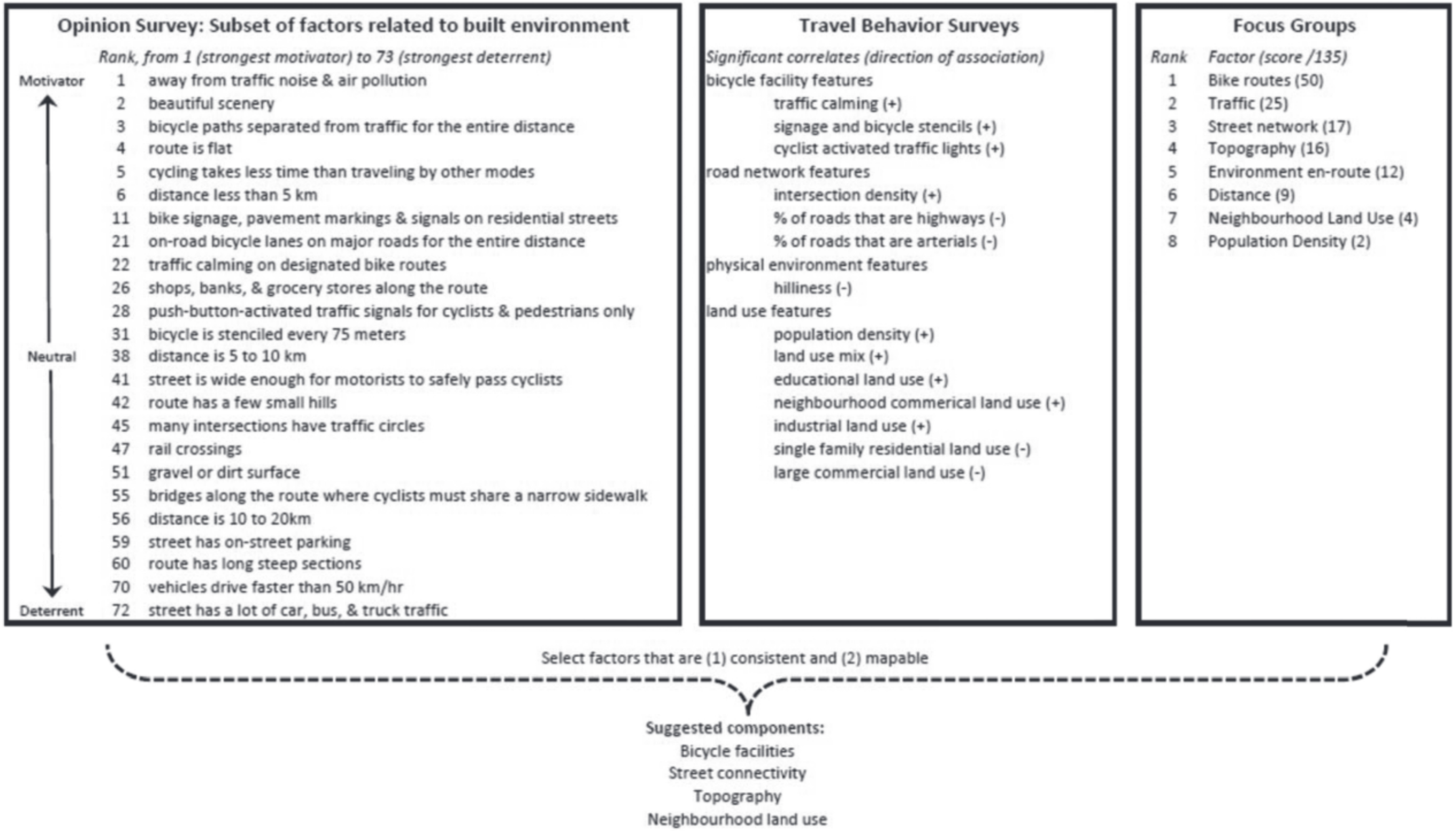

Figure 2. Developing an evidence-based bikeability index.

2.4 GIS procedures

In this section we outline manipulations of the geographical data to create and combine data layers to generate the bikeability map, with sufficient detail that others can repeat analyses and generate an index within their region. In brief, we generated metrics to correspond to the five components and scored them (table 3). All manipulations were done in ArcGIS 9.3 (Esri Inc., Redlands, CA). We worked with 10 m grid-cell raster files in order to generate a high-resolution surface, with the exception of topography where input files were 30 m grids. Where these processes required a search radius we used a 400 m buffer (~1/4 mile). This distance was identified in our previous research as the average distance that cyclists are willing to detour (Winters et al, 2010b).

Table 3. Scoring the components of bikeability to create maps, using empirical data from Metro Vancouver.

Score[a]	Bicycle route density (m of bicycle routes) [b,c]	Bicycle route separation	Connectivity of bicycle-friendly streets (number of intersections) [b,c]	Topography	Destination density (number of bicycle-friendly destinations) [b,c]
1	0	no	0	> 20	0
2	> 0–250		1	10–20	0
3	> 250–450		2–3	7–10	1–2
4	> 450–600		4–6	5–7	3
5	> 600–750		7–10	3–5	4–5
6	> 750–850		11–15	2–3	6–8
7	> 850–1100		16–20	1–2	9–10
8	> 1100–1400		21–25	0.5–1	11–20
9	> 1400–1800		26–30	0–0.5	21–40
10	> 1800–6000	yes	31–60	0	40–300

[a] 1 = low bikeability, 10 = high bikeability.
[b] deciles based on empirical data from the Metro Vancouver area.
[c] in 400 m (1/4 mile) radial buffer.

2.4.1 *Generating component raster files*

Bicycle route density. A shapefile for all designated routes in the region (on-road and off-road) was acquired from the regional transit authority (http://www.translink.ca/en/Cycling/Cycling-Routes.aspx) and updated to include recent additions. This was converted to a density surface by applying the Line Density tool. For ease of interpretation we used Math Tools to convert this raster to have units of 'm of bicycle route' in a 400 m radius circular buffer around a given cell.

Bicycle route separation. To generate an indicator file for high-quality routes we selected all route sections that were physically separated from motor vehicle traffic (ie, off-street paths and bicycle tracks). We applied a buffer of 200 m to each side of these before converting it to a raster file.

Connectivity of bicycle-friendly streets [ie, a local road, an off-street path, or a designated route (Winters and Teschke, 2010). Note: local roads have low motor vehicle traffic: an analysis for Vancouver indicates that volumes are one-tenth of what is observed on major roads]. The Digital Road Atlas (BC Government, 2006) was merged with a shapefile of designated cycling routes. An Esri script (JPtools, Fnode, Tnode) was used to generate a point file with the number of connecting roads at each intersection. The 'select by location' function was used to select all intersections with three or more legs (ie, at least a T-junction) where at least one road was favourable for cycling. We applied the point density tool to create a connectivity raster and used Math Tools to convert to units of 'number of intersections' in buffer.

Topography. A slope raster file was created from the 30 m grid digital elevation model raster file using the 'slope' Spatial Analyst tool with percentage rise (ie, vertical change/horizontal change) as the output. This generates the value of the maximum slope between a cell and its neighbouring cells.

Destination density. Measurement of the domains of density and land use are an area of great discussion in the built environment literature (see Forsyth et al, 2007; Krizek, 2003). Our measure was guided by previous research that indicated specific land-use types that were pertinent to decisions concerning cycling. This destination density was positively correlated with the commonly used proxy of population density (population/land area), with a correlation of $r = +0.74$ ($p < 0.001$) at the census tract level. To construct this, we used 2006 property tax assessment data from BC Assessment (http://www.bcassessment.bc.ca/products/index.asp). We selected those parcels that were potential destinations for cycling on the basis of land uses that were positively associated with cycling in our travel behaviour analysis [neighbourhood commercial ($n = 6986$ parcels), education ($n = 910$), entertainment ($n = 352$), and office ($n = 1754$)]. The polygon file was converted to a point file, and the Point Density tool was used to create a density raster. We used Math Tools to produce units of 'number of destination parcels' in the buffer.

2.4.2 *Scoring and combining component files*

Each raster file was reclassified to a scale of 1–10, where 1 was the least bikeable environment and 10 the most bikeable (table 3). For continuous values (topography layer and density layers) cutoffs were approximated to deciles. The bicycle route separation layer was classified as 10 (present) or 1 (absent). Reclassified raster files were combined using the Weighted Overlay tool. This tool combines layers with a common measurement scale and allows the user to assign relative weighting to the layers. On the basis of the empirical evidence from our earlier research, the five component layers were assigned equal weighting (20% each, to sum to 100%). The importance of bicycle facilities in the previous research was reflected in the fact that they contributed to multiple components of the score.

2.5 Evaluation of the bikeability index

In Canada there is no national travel survey. The best available Canadian travel behavior data are from a question about trips to work asked during the census (Statistics Canada, 2006). The question captures the mode used for the majority of the work trip distance. These data have several limitations: they do not capture multimodal trips, seasonal variation, or modes used for trips other than the commute from home to work (work trips comprise only 30% of the travel in the Vancouver region). Furthermore, each trip is geographically assigned to the home location of the respondent and therefore does not consider the destination or the route in between. The ideal evaluation measure would be geospatial data on cyclist volumes, however these are not available. Therefore, for the evaluation, we extracted cycling-to-work data from the 2006 census at the census tract level. In the study area there were 401 census tracts with mean cycling-to-work modal shares. In GIS we calculated the mean bikeability score for each census tract, and used the Pearson correlation coefficient to describe the relationship between mean cycling-to-work modal share and the mean bikeability score.

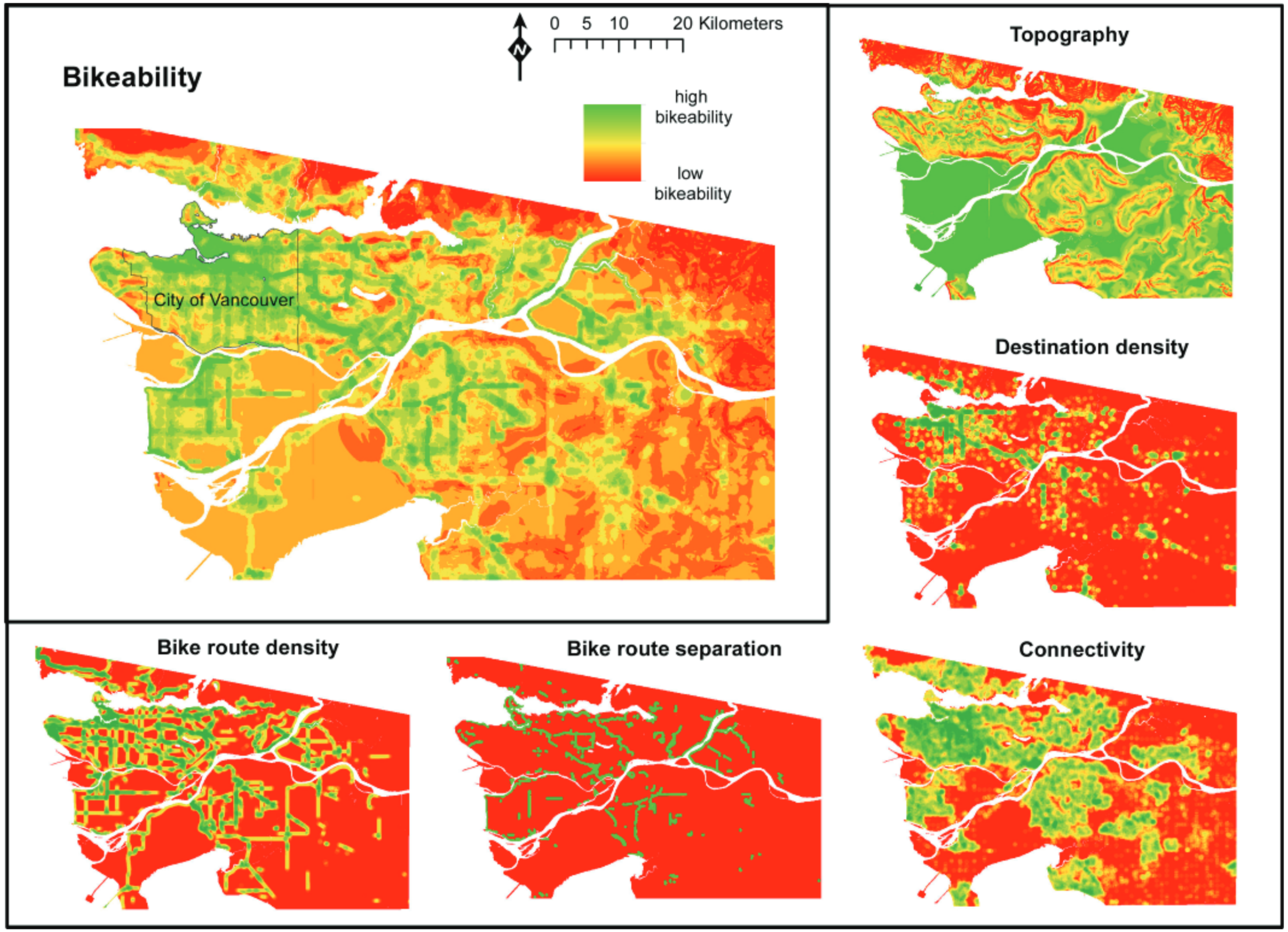

Figure 3. [In colour online.] Bikeability and component maps for Metro Vancouver. Bikeability = Bicycle route density + Bicycle route separation + Connectivity + Topography + Destination density.

3 Results

Figure 3 shows the bikeability surface for Metro Vancouver where bicycle-friendly areas are in green, and areas where cycling conditions need to be improved are in yellow to red. The map provides a regional overview and illustrates the great diversity of cycling conditions.

This composite map is most powerful when used in combination with the individual component maps also included in figure 3. Built environment interventions for specific locations can be informed by evaluating scores for the component layers. For example, certain areas had high scores for topography (no hills) and a reasonably high density of shops and other destinations, but scored low in terms of the density of bicycle facilities. Such areas could be prioritized for new bicycle routes.

Figure 4 shows the mean values for the bikeability index and the component layers for each municipality in the Metro Vancouver region. It illustrates marked differences in local planning policy: the cities of Vancouver, Burnaby, and New Westminster had denser bicycle infrastructure compared with other municipalities. Richmond had excellent topography for cycling, but scored lower for the more modifiable factors that support cycling. Rural areas such as Delta also had good topography but low scores for destination density, reflecting land-use practices that do not encourage utilitarian trips by bicycle.

There was not just between-city variability, but also within-city variability. Figure 5 shows mean values for neighbourhoods within the City of Vancouver, demonstrating the scalable nature of this tool and its flexibility in delineating boundaries. While Vancouver scored well for bikeability in comparison with other municipalities (figure 4), figure 5 shows there is variability between neighbourhoods within the city. Downtown scored well for separated bicycle facilities, and Downtown and the surrounding neighbourhoods also scored well for bicycle route density. However, areas to the southeast (Kensington-Cedar Cottage, Renfrew-Collingwood) had good connectivity and destination density, but lower scores for bicycle facilities. This illustrates that there is room to improve cycling conditions within Vancouver, and these maps suggest area-specific strategies to achieve improvements.

Cycling-to-work mode shares ranged from 0% to 11.9% in census tracts across the region, with a mean of 1.6%. The data were positively skewed, with 73 of the 401 census areas reporting 0% of work trips by bicycle. The mean bikeability scores of the census tracts ranged from 1.5 to 8.5, with a mean of 4.7. There was a significant positive correlation between the two measures ($r = 0.42$, $p < 0.001$), indicating that the proportion of work trips by bicycle increases with the bikeability score. Figure 6 is a scatterplot showing the proportion of work trips by bicycle against bikeability. It shows that no census tracts with bikeability scores under 4 have high bicycle modal shares (ie > 4%), suggesting that low bikeability puts an upper bound on the share of cycling trips. It also shows that areas with bikeability scores over 7.1 all reported at least 1% bicycle modal share, suggesting that high bikeability is motivating and puts a lower bound on the share of cycling trips.

4 Discussion

We developed a bikeability index to characterize and map a region's suitability for cycling. Evidence from a series of studies suggested that the index should be a composite of five factors: bicycle route density, bicycle route separation, connectivity of bicycle-friendly roads, topography, and density of destinations. The index is positively correlated with cycling-to-work modal share. Creating maps of the index, we demonstrated its utility as a planning tool, as the overall bikeability score and its five component scores can guide local action to improve cycling environments and stimulate changes in cycling rates.

Our focus was to develop a new measure specific to cycling conditions, based on empirical evidence. This bikeability index differs from existing walkability or sprawl indices (Ewing et al, 2003; Frank et al, 2009). For example, the walkability index that has been applied to

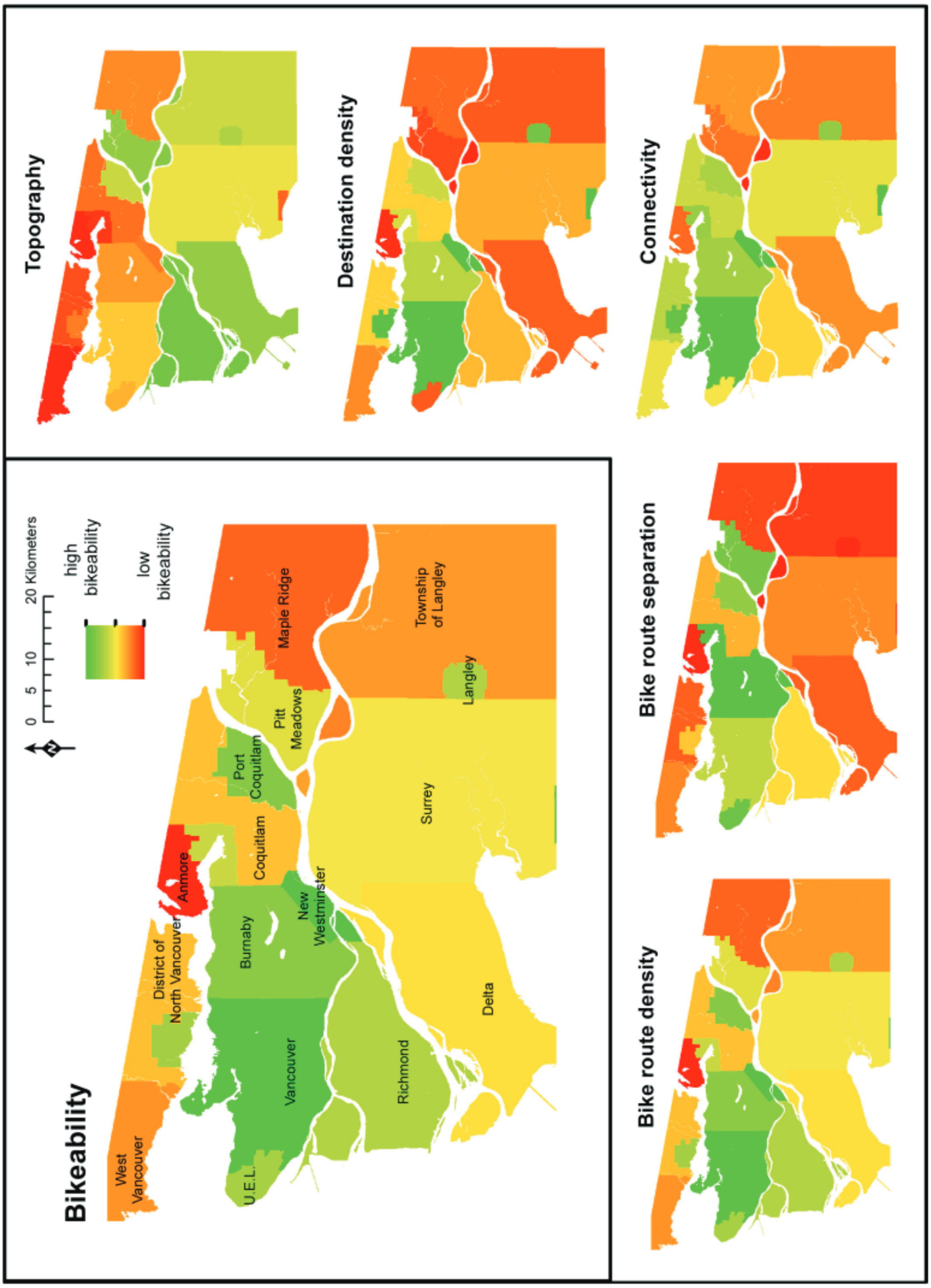

Figure 4. [In colour online.] Mean bikeability and component values for Metro Vancouver municipalities.

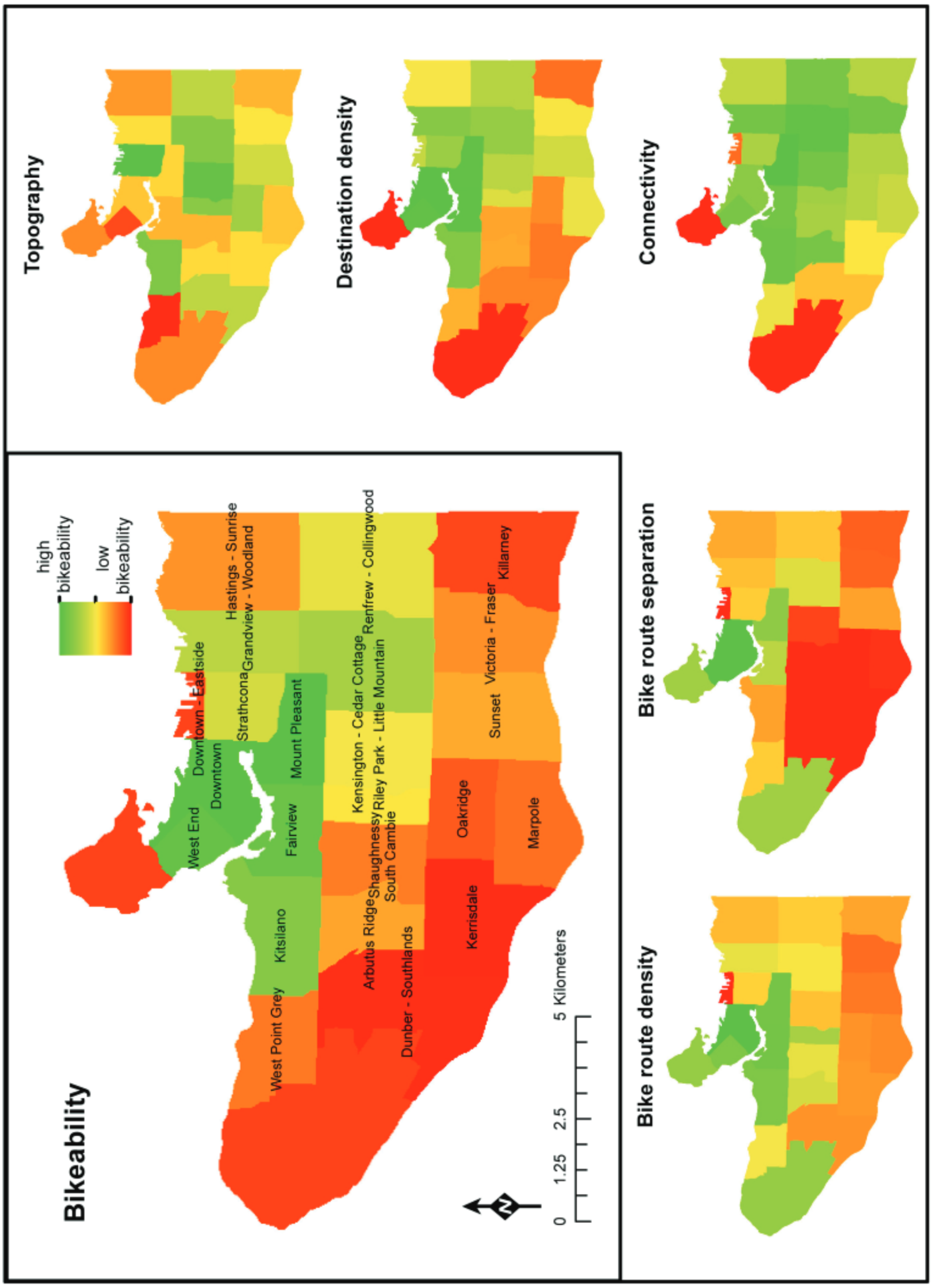

Figure 5. [In colour online.] Mean bikeability and component values for City of Vancouver neighbourhoods.

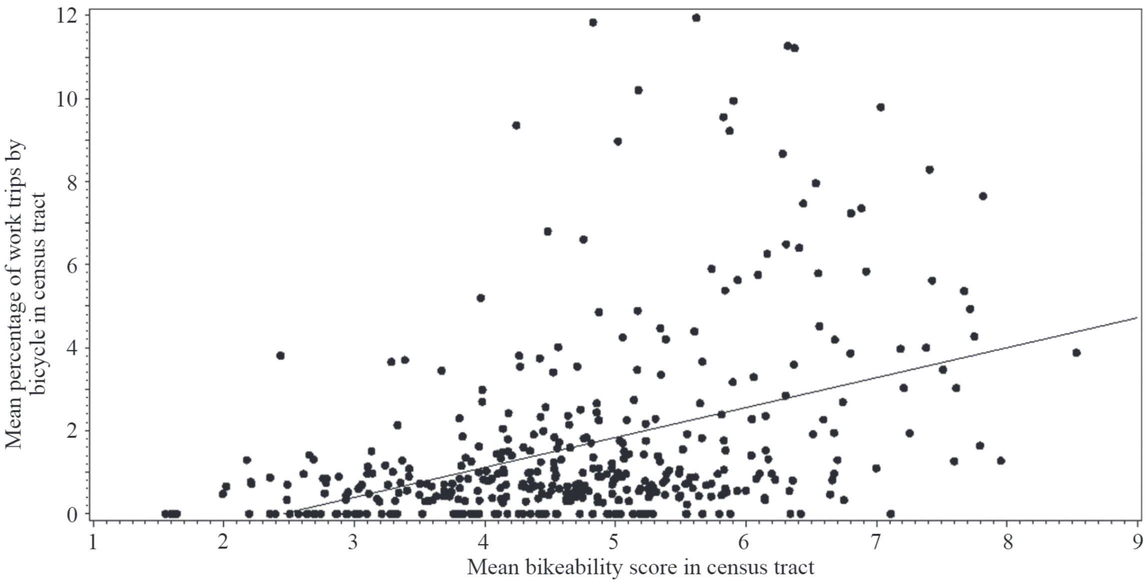

Figure 6. Mean journey-to-work bicycle modal share versus mean bikeability index, by census tract.

Vancouver, Atlanta, and Seattle has four components: residential density, land-use mix (an entropy measure), street connectivity, and retail floor-area ratio, with connectivity weighted double the other factors (Frank et al, 2009). In comparison, our bikeability index also includes a connectivity component (although modified to focus on bicycle-friendly streets) and a measure of land use (accessibility instead of entropy). The topography and bicycle facility-related components are unique. This work highlights that factors that are important to walking and cycling differ. A comparison of a walkability index for Metro Vancouver and our bikeability index (both referenced to the postal-code level—approximately a block) showed a moderate correlation ($r = 0.58$) (Winters et al, 2011b). Only 13% of the region was both highly walkable and highly bikeable.

We designed a system that relies on widely available spatial data to increase utility and facilitate widespread implementation. Our focus was on existing physical conditions, and used data for bicycle network, road network, topography, land use. Given this focus, our index has components that differ from other recent definitions of bikeability, outlined in table 1. Larsen and El-Geneidy (2010) incorporated travel behaviours and cyclists' opinions about each area. This adds a dimension of demographic data and local input, but requires data that are not necessarily attainable in many locations. Both Larsen and El-Geneidy (2010) and Richards (2010) included crash and injury data. Unfortunately this type of data (where available) is subject to reporting bias and typically lacks adjustment for exposure to risk (eg, cyclist counts) (Aertsens et al, 2010; Aultman-Hall and Hall, 1998; Elvik and Mysen, 1999). The cycle-zone analysis of Voros and Birk (2010) had a similar focus to ours, that is, on existing conditions; however, their bikeway quality index component requires very rich facility-specific data (eg, pavement quality, lane width, stop signs). While we used regionally generated data in our case study, future applications of the tool could be built using open data sources, such as those that exist for street networks (http://www.openstreetmap.org), topography (http://www.maps.nrcan.gc.ca/ topo_e.php), and location density (from Google Local Search API, as is used in the Walk Score, http://www.walkscore.com). Bicycle-network data are the only data that would need to be contributed by participating municipalities.

There have been recent complementary approaches to capturing bikeability that rely on commuter perceptions or experiences, rather than objective spatial data. Researchers in Stockholm have developed the active commuting route environment scale (ACRES) (Wahlgren et al, 2010) wherein cyclists self-report their experience on their commute route, according to eighteen items related to the physical environment, traffic environment, and social environment. Using self-report data enables the inclusion of items such as perceived safety, conflicts, and beauty. Indeed, while our opinion survey and focus groups found that 'beautiful scenery' and 'environment' were influential, these perceptions vary between individuals, and could not be measured using GIS to include in the bikeability index. The ACRES tool produces an average score for a route, and has been used to compare inner urban and suburban environments (Wahlgren and Schantz, 2011), but does note enable a fine-grain spatial evaluation. Another earlier project is the 'bicycle level of service' (Landis et al, 1997). This road-segment audit tool is a measure of perceived safety and comfort of a hypothetical cyclist with respect to motor vehicle traffic, and relies exclusively on motor vehicle-related measures: traffic volumes and mix; speed limits; and lane widths. There is little overlap between our approach and bicycle level of service, although there are some complementary outcomes: our connectivity measure excludes heavy-traffic roads that would have a low level of service, and facilities with no traffic also received good scores in the bicycle facility-separation component.

Our bikeability index was developed on the basis of studies of the opinions and behavior of Metro Vancouver cyclists, as well as input from local planners. We developed it with a straightforward methodology with flexible parameters, with the goal of it being suitable for application elsewhere, and the ability to tailor it to evidence about local preferences and conditions. The stepwise data manipulations detailed here rely on tools available in ArcGIS. This differs from the scoring procedures in the cycle-zone analysis of Voros and Birk (2010) and allows for routine updating of the tool by planners rather than developed de novo from time to time at considerable expense. We used a flexible methodology to score and combine factors, and have provided cut-off values that can be replicated or used as comparators in other locations. For example, a given municipality could alter the weighting if topography was not an issue, or could leave out the bicycle route separation component if data were not available on the separation of facilities. Alternatively, a municipality with particular interest in attracting the next wave of cyclists could put more emphasis on factors especially important to potential cyclists, perhaps using subanalyses from the opinion survey (Winters and Teschke, 2010) or the focus groups (Winters and Cooper, 2008) to guide weighting.

Finally, our methodology produces a bikeability surface that reduces the biases generated by data aggregation. The modifiable areal unit problem is a persistent geographical-analysis issue whereby the boundaries (ie, municipalities or cycle zones) selected to aggregate spatial data can affect findings (Flowerdew et al, 2008; Horner and Murray, 2002; Jelinski and Wu, 1996). This can result from not only the size of spatial units but also the shape of zones. For example, destination-density values will be different depending on whether a zonal boundary falls along a major road (ie, the center of a main shopping district) or between major roads. While practical applications of our tool may entail aggregation, as demonstrated in figures 3 and 4, it can be done post hoc and can be tailored to the question at hand, whether it is a particular transportation corridor, neighbourhood, or municipality. Other projects have used various units of analysis, from a reasonably small 300 m grid, to neighbourhood-based or larger cycle zones.

4.1 Limitations

In this paper we present a novel planning tool for Metro Vancouver which can be adapted for other locations. As we used evidence from local research to derive the bikeability index, some might argue that these results are location specific and not generalizable to other places. However, while the built environment of Vancouver is reasonably dense, the cycling rates are relatively high [journey-to-work mode share of 3.8% in the city and over 10% in some neighbourhoods (Statistics Canada, 2006)] and substantial investments have been made in cycling, the Metro region includes suburban and rural areas with very different cycling conditions (as shown in figures 3 and 4), and the car remains the dominant transport mode across the region. In previous articles we have situated our findings in the broader context of cycling literature (Winters and Teschke, 2010; Winters et al, 2011a) and found consistencies across geographical locations in what constitutes bicycle-friendly design. Moreover, the flexible nature of the tool allows users to supplement it with locally available data. For example, the discussions from our focus groups could be augmented with local insight to apply weights to any additional layers (Winters and Cooper, 2008).

Our focus was on existing conditions. While the maps represent conditions at a snapshot in time, the straightforward methodology that we utilized means that users can easily incorporate new data as they become available. The tool can test the impact of proposed changes on bikeability scores (eg, adding a new connection on the bicycle network) but it is not designed to predict resultant changes in cycling rates. Determining the latent demand for cycling, or the direct effect of interventions on cycling rates, remains a sizeable challenge (Barnes and Krizek, 2005).

Several assumptions were made in the creation of this model. First, the GIS procedures employed required decisions on categories for each component and on a method for combining the components. We selected decile cut-off values as a reasonable starting point for a regional model and provided these cut-offs (table 3) for clarity. While this decision was admittedly somewhat arbitrary, it was vetted by local planners. For example, an earlier categorization for topography (eg, only round numbers) resulted in maps that did not resonate with local municipal staff. Note that this categorization step is flexible and can be modified if evidence exists to guide selection of specific cut-offs, or if location-specific conditions suggest nonlinear relationships between density and cycling conditions (eg, extremely high-density commercial areas may be poor cycling environments). We also made the decision to build the index as an additive model, similar to existing walkability and sprawl indices. While other methods to combine component scores exist (ie, multiplicative models), the additive approach is a reasonable one since this tool allows users to examine the results of the index and each of its components separately. Additionally, we used 400 m search buffers to calculate density measures, on the basis that in our previous research that was the average distance cyclists were willing to detour. There is little information to guide selection of buffer sizes (Brownson et al, 2009) but a sensitivity analysis could be done with a range of values. Buffer size is a balance of sensitivity—larger buffers attenuate metrics toward a zone's average whereas smaller buffers show potentially important variability in the local context. Finally, our land-use measures are derived from tax-assessment parcel-based data, and thus each parcel reflects one lot, but not the number of individual offices or stores in a given lot. This is a common limitation of land-use data.

5 Conclusions

Mapping bikeability provides a powerful visual aid and a quantitative metric for identifying zones that can be improved to support sustainable travel. This is an evidence-based tool that presents data in a user-friendly way for planners and policy makers. This tool has a number of potential applications. It can be used to identify and prioritize locations for new infrastructure for cycling. It can also be used for research, to select areas of high and low bikeability for studies on health disparities related to physical activity and the built environment. It can be used to engage the public in planning processes for the promotion of cycling. Its regional focus is suited to population-level planning, and it complements the growing number of travel-planning tools targeted at individuals (eg, Vancouver's http://www.cyclingvancouver.ubc.ca, Portland or Milwaukee's http://byCycle.org, and Los Angeles' http://opt.berkeley.edu/). In future studies we hope to extend the bikeability index to other metropolitan areas in Canada and evaluate its association with interregional differences in cycling-mode shares. We also plan to integrate walkability and bikeability maps, to capture overall conditions for active transportation.

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