

Built Environment Influences on Healthy Transportation Choices: Bicycling versus Driving

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ABSTRACT *A growing body of evidence links the built environment to physical activity levels, health outcomes, and transportation behaviors. However, little of this research has focused on cycling, a sustainable transportation option with great potential for growth in North America. This study examines associations between decisions to bicycle (versus drive) and the built environment, with explicit consideration of three different spatial zones that may be relevant in travel behavior: trip origins, trip destinations, and along the route between. We analyzed 3,280 utilitarian bicycle and car trips in Metro Vancouver, Canada made by 1,902 adults, including both current and potential cyclists. Objective measures were developed for built environment characteristics related to the physical environment, land use patterns, the road network, and bicycle-specific facilities. Multilevel logistic regression was used to model the likelihood that a trip was made by bicycle, adjusting for trip distance and personal demographics. Separate models were constructed for each spatial zone, and a global model examined the relative influence of the three zones. In total, 31% (1,023 out of 3,280) of trips were made by bicycle. Increased odds of bicycling were associated with less hilliness; higher intersection density; less highways and arterials; presence of bicycle signage, traffic calming, and cyclist-activated traffic lights; more neighborhood commercial, educational, and industrial land uses; greater land use mix; and higher population density. Different factors were important within each spatial zone. Overall, the characteristics of routes were more influential than origin or destination characteristics. These findings indicate that the built environment has a significant influence on healthy travel decisions, and spatial context is important. Future research should explicitly consider relevant spatial zones when investigating the relationship between physical activity and urban form.*

KEYWORDS *Bicycle, Built environment, Physical activity, Urban form, Non-motorized transportation*

BACKGROUND

Increasing active transportation is a promising approach to counteract issues at the forefront of both public health and transportation: the obesity and inactivity epidemics, growing congestion, and air and noise pollution.^{1,2} Many cross-sectional

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studies have shown that supportive built environments are associated with increased walking and overall physical activity, reduced vehicle miles traveled, and improved health outcomes.³⁻⁵ Although few studies to date have focused on cycling, the mode warrants more attention. Since bicycle travel is three to four times faster than walking, it may be the better substitute for driving for short-to-medium trip distances. Making some typical utilitarian trips by bicycle, most days of the week, would fulfill the recommended physical activity guidelines for health.⁶

Results from ecological (aggregate) studies,^{7,8} opinion surveys,⁹ stated preference surveys,^{10,11} and focus groups¹² all provide evidence that built environment factors influence cycling. However, few individual-level (disaggregate) studies of travel behavior have explicitly looked at cycling outcomes, and they have found null results for built environment variables after accounting for individual characteristics.^{13,14} These inconsistencies may stem from methodological issues in travel behavior studies that employ GIS-based measures to examine the effect of the built environment on cycling. Specifying “place”, or selecting the appropriate spatial zones for analysis, is a challenge in this research area. In individual-level studies, a common approach is to examine how the characteristics in the area of one’s residence correlate with activity levels. Typically the area is identified by a 1-mile or kilometer buffer around the home postal code, representing the walkable distance from home. Some cycling research has extended the 1 mile distance to 3 or even 5 miles, in recognition that the activity space should be larger to encompass bikeable distances.^{14,15} However, it is now widely recognized that these home-based areas do not accurately represent an individual’s activity space, or the built environment they are influenced by, since physical activity can also occur at other locations such as the workplace, parks or a gym. Furthermore, the extent of one’s activity space varies by demographic characteristics.¹⁶ Some research has tried to address this by defining physical activity outcomes by purpose (transportation, leisure) or type (walking, vigorous activity).^{13,17} An emergent method, though technologically intensive, is to employ GPS to accurately determine where people travel or engage in physical activity (i.e., Dill¹⁸).

To clarify the relationship between cycling and the built environment, methodological refinements tailored to cycling are needed. Factors such as the local availability of sidewalks or land use mix may be primary motivators of walking trips, but decisions on whether to cycle may be influenced by a different suite of factors across spatial areas beyond the trip origin. For example, in a survey querying 73 factors, the top four motivators for making a trip by bicycle were related to routes: being away from traffic and noise pollution, having beautiful scenery, having separated bicycle paths for the entire distance, and having flat topography.¹⁹ The geographic accessibility of destinations (i.e., schools, employment sites, retail) may also affect the likelihood of making trips by bicycle, and since two thirds of cycling trips are under 5 km and 90% are less than 10 km,²⁰ short trip distances are important.

In this study, we investigated the effect of the built environment on healthy transportation mode choices (bicycle versus car) for trips made by 1,902 current and potential cyclists in Metro Vancouver. We addressed the issue of specificity of place by characterizing the built environment at origins, destinations, and along routes for utilitarian trips (to work or school or for personal business or social reasons). We hypothesized that within each of the three spatial zones, different built environment features would influence decisions to travel by bicycle instead of by car.

METHODS

Trip Data

Travel data came from the Cycling in Cities survey, a population-based survey of 2,149 current and potential cyclists conducted in 2006 across the Metro Vancouver region. Details of the survey are published elsewhere.^{9,19} To be eligible, respondents had to be in the “near market” for cycling, defined as having access to a bicycle and having cycled in the past year (current cyclists) or being willing to cycle in the future (potential cyclists). All study procedures were approved by the University of British Columbia Behavioral Ethics Board (Application #H05-80976).

In a telephone survey, participants were asked about destination, mode, and trip purpose for two common non-recreational trips. The two trips queried were selected by the interviewer based on reported travel patterns, using the following hierarchy: (1) the most frequent non-recreational bicycle trip (if any), (2) any other non-recreational bicycle trip (if any), (3) the most frequent non-recreational trip by any other mode, and (4) the second most frequent non-recreational trip by any other mode. Data were collected for 4,260 trips. Origin and destination locations were provided by six-digit postal code, specific address or intersection. Geocoding (98% success rate) resulted in 3,897 trips with complete data within Metro Vancouver. As the focus was on decisions to travel by bicycle instead of car, we excluded trips made by transit ($n=328$), walking ($n=260$) or other modes ($n=29$). The analysis dataset consisted of 3,280 trips made by 1,902 individuals.

We generated shortest distance routes connecting each origin and destination pair using FME (Safe Software, Surrey, Canada) and Dijkstra’s algorithm with weighting based on distance only.²¹ The road network dataset for creating shortest routes was the Road Atlas (DRA) centerline street network datafile²² enhanced with off-street cycling paths in the region.

Demographic Variables

Demographic variables collected in the survey are summarized in Table 1. Values were imputed for variables with missing data (response=“don’t know/refused”). For ordinal and nominal variables, the most common response category was imputed, corresponding to age category of 35–44 (five missing), education level of graduated university (seven missing) and household income of 60–89K (648 missing). The mean observed value (= 3) was imputed for ten records missing the number of bicycles in the household.

Respondents were also categorized according to how often they cycled, based on their derived annual trip frequencies: *regular cyclists* (cycled at least weekly, i.e., ≥ 52 trips per year), *frequent cyclists* (cycled at least monthly, i.e., 12–51 trips per year) or *rare cyclists* (cycled <12 times in the past year).

Spatial Analysis Zones

For each trip, we created spatial analysis zones in ArcGIS²³ using buffers for routes, origins, and destinations (Figure 1). To create route zones, we applied a simple buffer of 250 m to each shortest route polyline. In preliminary work, we evaluated the effect of different buffer sizes (100, 250 and 500 m) and found that built environment measures were highly correlated across these sizes (Pearson correlation >0.85). The final choice of 250 m was meant to maximize the variability in measures (using smaller versus larger buffers) while recognizing the imprecision of the routes (shortest routes instead of actual routes). This buffer

TABLE 1 Descriptive characteristics of trip takers ($n=1,902$; before imputation for missing data)

	Number	Percent
Cycling frequency		
Rare ^a (<12 trips per year)	1,138	59.8
Frequent (at least 1 trip per month)	618	32.5
Regular (at least 1 trip per week)	146	7.7
Gender		
Male	925	48.6
Female	977	51.4
Age (4 missing)		
19–24	119	6.3
25–34	296	15.6
35–44	613	32.3
45–54	495	26.1
55–64	262	13.8
65 and older	113	6.0
Education (22 missing)		
Some high school or less	34	1.8
Graduated high school	240	12.8
Vocational/college/technical	532	28.3
Some university	160	8.5
Graduated university	914	48.6
Household income (383 missing)		
<\$30,000	146	9.6
\$30,000–\$59,999	350	23.0
\$60,000–\$89,999	400	26.3
>\$90,000	623	41.0
Employment status (7 missing)		
Working	1,504	79.4
Student	66	3.5
Retired	170	9.0
Unemployed/homemaker/other	155	8.2
Mean number of people in household	3.08	
Has children in household	961	50.5
Access to car	1,831	96.3
Mean number of bikes in household	2.98	
Home residence		
City of Vancouver	494	26.0
Rest of Metro Vancouver region	1,408	74.0

^aThis group comprises both the occasional and potential cyclists from reference ⁹

typically included adjacent streets on each side of the shortest route and thus allowed for a set of plausible alternative routes.

To create the origin and destination buffers, we used methods developed by Oliver et al. for pedestrian travel²⁴ that produce irregularly shaped buffers based on accessibility defined by the transportation network. The methodology addresses limitations of simple buffers, which may not best represent the area experienced by and accessible to users (e.g., land area not adjacent to roads or cycling paths). We used Network Analyst in ArcGIS to identify all line segments within 450 m along the street network and applied a 50-m buffer to this set. We also evaluated 250 and

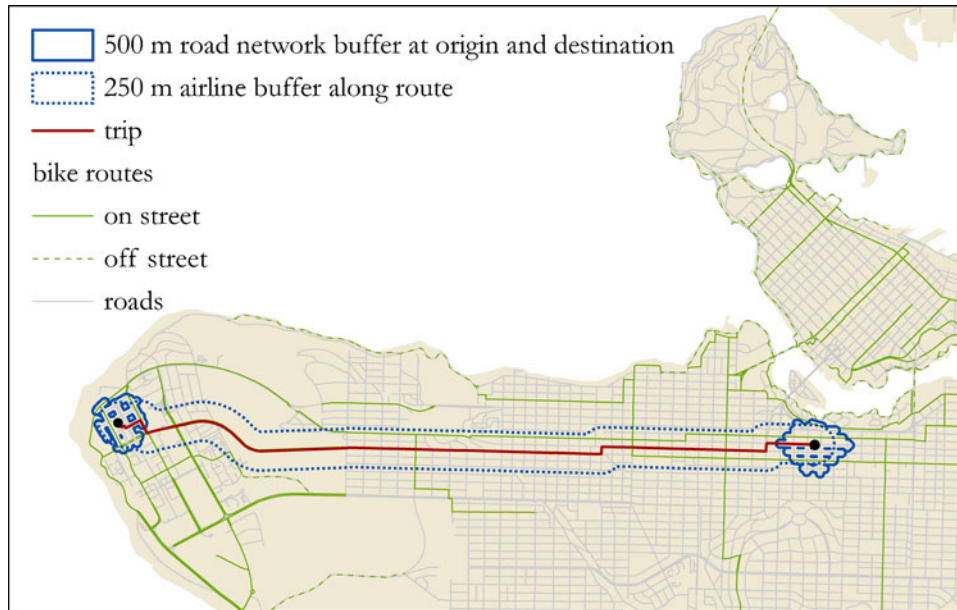


FIGURE 1. Potential zones influencing decisions to cycle: route, origin, and destination zones.

1,000 m distances and found that their built environment measures were correlated with the 500-m measures (Pearson correlation >0.62).

Built Environment Measures

Spatial data sources included the census, academic research projects, the property tax assessment authority, and the regional transit authority. Where possible we sought data from 2006 to match temporally with the trip survey; in practice, the data ranged from 2003 (air pollution model) to 2006 (bicycle facility data).

The selection of measures was guided by literature on the built environment and physical activity (see, e.g., Brownson et al.²⁵ and Forsyth et al.²⁶) or cycling.^{7,9,12,18,19} The measures fell into four general categories: the physical environment, land use, the road network, and bicycle facilities. For each of the built environment variables described below, we generated a priori hypotheses on their direction of influence on cycling and in which spatial zones (origin, destination, route) they might be most influential (Table 2).

Physical Environment

Greenery. The percentage of land area with green cover (defined as street trees, park/forest trees, and grasslands) was calculated from a 5×5 -m raster file where the predominant land cover was assigned based on Landsat data using a classification and regression tree.²⁷

Air Pollution. Traffic-related pollution, measured as the average nitrogen dioxide concentration (in parts per billion), was based on a land use regression model at 10 m resolution.²⁸

Topography. Two measures were created to capture different aspects of topography, both derived from a Digital Elevation Model raster file (30 m resolution).

TABLE 2 A priori hypotheses on built environment measures that may affect the likelihood of making a trip by bicycle, with hypothesized direction of influence and relevant spatial zone

Domain	Built Environment Measure	Metric	Primary spatial zone of influence		
			Route	Origin	Destination
Physical environment	Air pollution	Average NO ₂ concentration	-		
	Greenery	% of land area with green cover	+		
	Topography	Variation in elevation (hilliness) % road segments with slope >5% (steep hills)	-		
Road network	Street connectivity % of road network that is:	Ratio of 4-way intersections to all intersections	+	-	-
		Highway	-		
		Arterial road	-		
Bicycle facilities	% of road network that is:	Local road	+		
		Off-street path	+		
	Presence of:	Designated bike route	+		
		Traffic calming features	+		
		Road markings or signage for cyclists	+		
		Crossings with cyclist-activated traffic lights	+		
Land use	Density	Population per hectare		+	
	% of land area that is:	Land use mix		+	
		Single family residential		-	
		Multifamily residential		+	
		Commercial			+
		Educational			+
		Entertainment			+
Office			+		
	Park		+		

+ higher values are expected to be associated an increased likelihood of making a trip by bicycle versus car, - higher values are expected to be associated with a decreased likelihood of making a trip by bicycle

“Hilliness” was measured as the standard deviation of the elevation for the grid points within each buffer zone. “Steepness” was measured for routes only as it was a polyline-based method. The ArcGIS RunningSlope script was used to split each route polyline into 100-m segments and output the slope for each segment. We then calculated the percentage of route segments with slope >5% along a given route. This cutoff slope was selected based on the Transportation Association of Canada guidelines for bicycle route design.²⁹

Land Use

Population Density. Gross population density was measured as the total census population based on dissemination area data from 2006 Census,³⁰ divided by the total land area in the buffer, excluding water bodies. Where buffer boundaries intersected dissemination area boundaries, the population was apportioned according to the area included.

Specific Land Uses. Property tax assessment data from BC Assessment³¹ includes 203 land use categories. These were aggregated to eight land use types (commercial, education, entertainment, industrial, office, park, single family residence, and multifamily residence). Land uses not hypothesized to influence cycling were excluded (e.g., agricultural, vacant, transport/utility). The land use measure used was the percentage of total land area with land use X equal to the sum of the area of all parcels with land use X divided by the total land area in the buffer. After preliminary analyses, we also reclassified commercial land use parcels according to the lot size, using a threshold of 1 ha to differentiate between large commercial and neighborhood commercial parcels.

Land Use Mix. Land use mix was calculated with an entropy measure (Shannon Index)³²: $-\sum_k(p_i) \ln(p_i)/\ln(k)$, where p_i is the proportion of each of four land use types (in this case: residential, commercial, entertainment, and office) and k is the number of different land uses included. This widely used measure captures the overall evenness of distribution of key land uses²⁵ but does not address the spatial grain of land use mix or whether the mix is complementary from a travel perspective.^{33,34}

Road Network

Road Types. Road type measures were based on the Digital Road Atlas centerline file.²² We aggregated road class to four categories (highway, arterial, collector, local) and excluded non-accessible road types (private, trail, etc.). The lane kilometers of each road type in a buffer zone were calculated using Hawth’s tools “Sum line lengths in polygons” and divided by the total lane kilometers of roads in the zone to give the percentage of road network of type X. A lane kilometer counts facilities on each side of the road. For example, 1 km of a two-way bikeway would count as two lane-kilometers.

Connectivity. Intersection density was calculated as the number of intersections with three or more connecting road segments divided by the area of the zone in hectares. An ESRI script (JPtoolsFnode_Tonode) was used to determine the number of connecting roads, and the output cleaned to correct intersections with boulevard

roads, which would otherwise be considered as multiple intersections.²⁶ This measure has been widely used in walking and cycling research and is correlated with other connectivity measures.³⁵

Bicycle Facilities

Bicycle Routes. The Metro Vancouver region has about 1,400 km of designated cycling routes that are along major roads, local roads, or trails with bicycle-specific facilities; over 350 km of these are off-road paths. For the cycling route analysis, the Digital Road Atlas was merged with a digital file of designated cycling routes to produce a single transportation network file that included line segments for off-street cycling paths. The calculation of the percentage of bicycle routes within the analysis zones was analogous to the road type analysis described above, using only line segments coded as cycling routes in the numerator.

Bicycle Facilities. Bicycle facilities were measured using Hawth's tools "Count Points in Polygon" tool to sum the following features from detailed shapefiles of facilities: the number of traffic calming features (e.g., roundabouts, barriers that divert traffic), bicycle road markings or bicycle route signs, and traffic crossings with cyclist-activated traffic lights.

Statistical Analysis

Descriptive summaries of built environment measures within each of the zones were calculated. Histograms were used to identify highly skewed variables or bimodal distributions. We examined correlations between built environment measures within each zone (route, origin, destination) and across zones to ensure that co-linear variables were not included in the multivariable models. The only measures with Pearson correlation exceeding 0.7 were land use mix and percent land in office use within the route zone, land use mix and percent land in commercial in the origin zone, and percent arterial roads and percent local roads in the destination zone.

Because we had clustered data with up to two trips per person, we conducted multilevel logistic modeling using PROC GLIMMIX in SAS Version 9.1 (Cary, NC, USA) to model the outcome that a trip was made by bicycle versus by car. All built environment characteristics were first tested in bivariate models for their association with cycling or driving. We then ran three separate multivariable models, one for each zone (route, origin, destination). We also created a fourth multivariable model to examine the a priori hypotheses (Table 2): This final model included measures from every zone. In multivariable modeling, variables that were significant at $p < 0.10$ in bivariate regressions and in the direction of the a priori hypotheses were offered to the models. The parsimonious models included all factors significant at $p < 0.05$. Demographic variables for gender, age, education, and income were added as a block to the parsimonious models to assess if these modified the effect of the built environment on the odds of cycling. Trip distance was included in all models. For continuous variables (e.g., population density, intersection density), the odds ratios are expressed as the change in odds for a change in the interquartile range of the built environment measure. This allows comparison of effect sizes across measures with different variability. For dichotomous variables (e.g., presence of traffic calming features), the odds ratio represents the change in the odds of cycling if the feature is present within the buffer.

RESULTS

Table 1 summarizes the demographic characteristics of trip takers. The population was highly educated (48.6% with university degrees) and came from households with relatively high incomes (41.0% over \$90,000 annually). Nearly all (96.5%) had access to a car. The population was comprised of 7.7% regular cyclists, who cycled at least once a week. The majority of participants (59.8%) were rare cyclists, cycling less than once a month.

Thirty-one percent of the trips were made by bicycle (1,023 of 3,280). For bicycle trips, the most common purpose was to work or school (31%), then social reasons (28%), shopping (22%) and personal business (19%). Proportionally more car trips were for work or school (43%) and shopping (23%) and proportionally less for social reasons (21%) or personal business (13%). Table 3 summarizes the trip characteristics by mode of travel. Bicycle trips were typically shorter than car trips (mean distances 4.7 versus 10.2 km, respectively), though the longest trips for each mode were similar (bike=52.7 km, car=56.1 km). Table 3 also provides the dimensions of the three spatial zones. The area included within the route zones was highly variable due to the broad range of trip distances. The land area also differed within the origin and destination zones, for two reasons: we used network-based origin and destination buffers instead of airline buffers, and we excluded water areas. The differences in spatial extent between zones and within zones required that all built environment metrics be normalized (e.g., percentages, densities) as opposed to raw measures (counts, kilometers of bike routes).

Built environment factors differed between route, origin, and destination zones. Comprehensive tables are available from the authors, but we include key examples here. Destination zones had the least green cover (mean=19.1%) as compared to origin zones (23.7%) and route zones (30.1%). It is intuitive that destination zones (at workplaces, shopping places) may have less greenery than origin zones (residential areas), but these results also indicate that the travel corridors had more green cover than either. Origin zones, not surprisingly, had a higher percentage of land used for single family residences (48.6%) than route zones (34.7%) or destination zones (27.2%). Designated bicycle routes covered, on average, 10.8% of the road network in origin zones, compared with 12.9% in route zones and 14.3% in destination zones. These numbers highlight that the route, origin, and destination zones represented different types of built environments and underscored the importance of considering each of these spatial zones, as opposed to only the trip origin.

Bivariate Comparison of Built Environment Characteristics of Bicycle versus Car Trips

Table 4 contrasts the built environment characteristics of the route zones for car trips and bicycle trips. Based on *t* tests of the mean values, most factors differed between car and bicycle trips and in the expected direction (e.g., bicycle trips were routed through areas that were less hilly, had more grid-based road networks, and had lower density of highways). However, two factors trended in the direction opposite to a priori hypotheses. One was green cover: route zones for bicycle trips had less green cover than those for car trips (25.0% average green cover versus 32.4%). Perhaps the unexpected result reflects areas where cyclists were limited to travel in order to make short trips or to use direct routes. The other factor was the average air pollution, which was higher in bicycle trip route zones than in car trip

TABLE 3 Trip distance and spatial analysis zone dimensions, by mode

	Car trips (<i>n</i> =2,257)					Bike trips (<i>n</i> =1,023)				
	Mean	Median	Standard deviation	Min	Max	Mean	Median	Standard deviation	Min	Max
Trip distance (km)	10.21	6.02	10.50	0.04	56.10	4.65	2.47	5.96	0.04	52.72
Land area (ha):										
Route zones	518.8	312.5	518.9	21.6	2,797.8	245.1	136.0	293.8	21.4	2,648.3
Origin zones	26.2	24.8	10.7	0.9	51.0	30.9	31.2	11.8	0.9	50.3
Destination zones	34.6	34.1	9.8	3.7	54.4	38.1	38.9	9.7	5.6	56.0

TABLE 4 Descriptive statistics for built environment measures for route zones, by trip mode

	Car trips (n=2,257)			Bike trips (n=1,023)			t test
	Mean	Standard deviation	Interquartile range	Mean	Standard deviation	Interquartile range	
Physical environment							
% of land area with green cover	32.4	15.4	19.8	25.0	15.7	21.6	*
Average air pollution (ppb NO ₂)	29.4	8.4	11.2	31.2	9.9	12.7	*
Variation in elevation (standard deviation of elevation points)	23.9	21.7	24.5	14.4	13.6	15.1	*
% of road segments >5% slope	10.9	13.5	15.3	9.6	13.2	14.5	*
Road network							
Intersection density (# intersections/ha)	0.4	0.2	0.2	0.5	0.2	0.2	*
% road network: highway	4.1	7.9	4.5	1.2	4.4	0.0	*
% road network: arterial	22.5	11.3	15.6	19.1	12.3	17.2	*
% road network: local road	57.1	13.2	18.1	63.3	13.5	18.8	*
Bicycle facilities							
Presence of traffic calming features	0.5	0.5	1.0	0.5	0.5	1.0	
Presence of road markings or signage	0.8	0.4	0.0	0.8	0.4	0.0	
Presence of cyclist-activated traffic lights	0.4	0.5	1.0	0.5	0.5	1.0	
% road network: designated bike route	12.9	8.8	11.1	12.8	9.5	13.7	
% road network: off street	2.4	3.1	3.8	2.2	3.6	3.3	
Land use							
Population density (population/ha)	0.2	0.5	0.2	0.5	0.8	0.5	*
% of land area with the following use: ^a							
Single family residence	34.2	12.8	17.7	35.7	14.7	22.2	*
Multifamily residence	2.8	3.7	2.9	3.4	4.2	4.4	*
Neighborhood commercial	2.1	2.1	2.3	2.9	2.5	3.5	*
Large commercial	2.2	2.7	2.7	1.6	2.8	2.1	*
Education	2.2	2.8	1.8	2.4	3.7	2.6	*
Entertainment	0.2	0.2	0.2	0.2	0.2	0.2	
Industrial	4.0	4.8	5.7	3.0	4.8	3.7	*

TABLE 4 Continued

	Car trips (<i>n</i> = 2,257)			Bike trips (<i>n</i> = 1,023)			<i>t</i> test
	Mean	Standard deviation	Interquartile range	Mean	Standard deviation	Interquartile range	
Office	1.4	2.1	1.5	1.6	2.3	2.1	*
Park	9.2	6.4	6.9	8.0	7.2	7.3	*
Land use mix	0.3	0.2	0.3	0.3	0.2	0.3	

* $p < 0.05$, significant result in *t* test for difference in mean value between car trips and bike trips

^aGeneralized land use categories that were not hypothesized to influence cycling were excluded from analysis (e.g., agricultural, vacant, transportation/utility)

route zones (31.2 ppb NO₂ versus 29.4 ppb), although a mean difference of 1.6 ppb is unlikely to be meaningful. Given that these two built environment factors did not conform to a priori hypotheses and therefore may be surrogates for other built environment features, they were not considered in multivariable models.

In preliminary analyses, the association between commercial land use and the likelihood of cycling was also counter to a priori hypothesis. Bivariate models suggested people were less likely to bicycle to a destination that had a high percentage of commercial land, even though these are likely destinations for utilitarian travel. We refined the commercial land use variable, to separate large “big box” or shopping mall retail from smaller, neighborhood retail, using a threshold of 1 ha lot size. With this differentiation, higher neighborhood commercial land use at the destination was associated with a higher likelihood of making a trip by bicycle (unadjusted OR=1.15, 95% CI 1.01–1.31) and more large retail land use with a lower likelihood of cycling (unadjusted OR=0.81, 95% CI 0.75–0.87; Figure 2).

Multivariable Models for Built Environment Characteristics of Bicycle versus Car Trips

Parsimonious models for each of the three zones, adjusted for trip distance and demographic variables, are presented in Table 5. Trip distance was significant in all three models, with shorter trip distances strongly associated with higher odds of cycling. Demographic factors also played an important role in mode choice. In all models, women were less likely to cycle than men, with their odds of cycling around 0.6. Younger people were more likely to cycle than older people, with those in the 19–24 age group having five times higher odds of making a trip by bicycle than those 65 and older. Those with higher education were more likely to cycle than those without, while those from households with lower incomes were more likely to cycle than those from higher income households. The odds ratios for the demographic variables changed little between models.

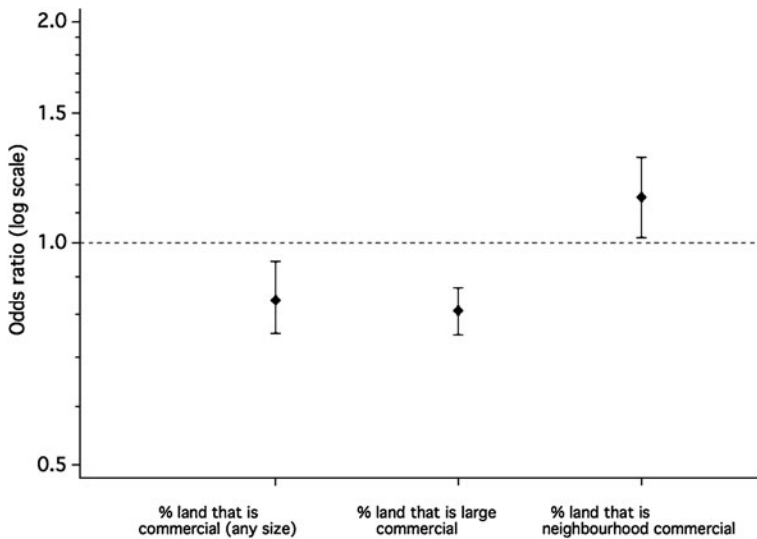


FIGURE 2. Differential effect of large commercial and small commercial land use on likelihood that a trip is made by bicycle instead of car.

TABLE 5 Results of multilevel logistic models for effect of built environment measures on the likelihood that a trip is made by bicycle instead of car

	Route (model 1)		Origin (model 2)		Destination (model 3)	
	OR ^d	95% CI	OR ^d	95% CI	OR ^d	95% CI
Physical environment						
Variation in elevation (standard deviation of elevation points)	0.59	0.49	0.72			
Road network						
Intersection density (# intersections/ha)	1.54	1.32	1.80	1.31	1.38	1.57
% of road network that is highway	0.93	0.88	0.98			
% of road network that is arterial	0.75	0.64	0.89		0.81	0.97
Bicycle facilities						
Presence of traffic calming features ^a				1.95	1.25	1.54
Presence of road markings or signage ^a						
Land use						
Population density	0.74	0.63	0.87		1.09	1.19
% land area that is single family residential						
% land area that is neighborhood commercial land use					1.22	1.43
% land area that is large commercial land use	0.75	0.63	0.90		0.81	0.89
% land area that is educational land use					1.04	1.07
% land area that is industrial land use				1.01		
Land use mix (entropy measure)				1.14		
Trip distance (km) ^b	0.61	0.50	0.74	0.39	0.38	0.44
Demographics						
Gender (ref: male)						
Female	0.57	0.47	0.70	0.57	0.57	0.70
Age (ref >65)						
19–24	6.07	3.28	11.22	2.95	6.41	11.87
25–34	2.89	1.71	4.89	1.57	3.46	5.82
35–44	2.77	1.69	4.53	1.54	3.08	5.03
45–54	2.83	1.72	4.67	1.59	3.07	5.06
55–64	1.72	1.01	2.94	0.94	1.81	3.08

Education (ref: vocational) ^c											
Some high school or less	1.05	0.73	1.49	1.03	0.72	1.47	1.01	0.70	1.44		
Graduated high school	1.38	1.08	1.75	1.41	1.11	1.80	1.29	1.01	1.64		
Some university	1.88	0.90	3.95	1.91	0.91	4.02	1.73	0.82	3.62		
Graduated university	1.22	0.82	1.84	1.20	0.80	1.79	1.19	0.79	1.78		
Household income (ref >\$90,000)											
<\$30,000	2.00	1.35	2.97	1.87	1.26	2.77	2.10	1.42	3.11		
\$30,000–59,000	1.59	1.20	2.09	1.42	1.08	1.87	1.59	1.20	2.09		
\$60,000–89,000	1.58	1.22	2.04	1.50	1.16	1.93	1.62	1.25	2.10		

OR odds ratios, 95% CI 95% confidence interval

^aOR for cycling facilities is the odds associated with it being present in buffer

^bOR is for a change in 10 km, approximately the interquartile range (9.5 km)

^cEducation is only $p=0.059$ in route model; $p=0.18$ in destination model

^dOdds ratios are the change in odds for a change of the interquartile range of dependant variable

TABLE 6 Cross-zonal multilevel logistic models (adjusted for gender, age, and household income; results not presented here because odd ratios were very stable across models, as shown in Table 5)

Zone	Built environment feature	All trips (model 4; $n=3,280$)		Short trips <5 km (model 5; $n=1,737$)		
		OR for change in IQR		OR for change in IQR		
		OR ^a	95% CI	OR ^a	95% CI	
Origin factors						
Destination factors	Population density (population/ha)			1.09	1.00	1.19
Route factors	% of land area that is educational land use	1.05	1.02	1.08		
	Variation in elevation	0.61	0.50	0.73	0.64	0.87
	Intersection density (intersections/ha)	1.74	1.51	2.01	1.19	1.72
	% of the road network that is arterial	0.83	0.73	0.97	0.66	0.95
	Presence of cyclist-activated traffic lights			1.70	1.27	2.26
Trip distance (km)		0.59	0.49	0.71	0.52	0.79

^aFor built environment measures, OR is the change in odds of bike associated with a change in the interquartile range of the variable, with these exceptions: For cyclist-activated traffic lights, it is the odds associated with it being present in zone; for trip distance in model 4, it is the odds associated with a change in 10 km distance (approximate interquartile range=9.5 km); and for trip distance in model 5, it is the odds associated with a change in 2 km distance (approximate interquartile range=2.1 km) for effect of built environment on the likelihood that a trip is made by bicycle instead of car, for all trips, and for short trips only

Built environment factors influenced the likelihood of cycling, even after controlling for trip distance and demographic factors. Within the route zone (model 1), measures significantly associated with a higher likelihood of cycling were less hilliness, higher intersection density, a lower percentage of the road network categorized as highway or arterial roads, higher population density, a lower percentage of the land used for single family residential or large commercial use. One of these same variables was significant in the origin zone (model 2): higher intersection density. Additionally, the presence of traffic calming features, a higher percentage of land in industrial uses, and a higher land use mix were associated with a higher likelihood of cycling. In the destination zone (model 3), land uses were also important: a higher percentage of educational or neighborhood commercial land uses and less large commercial use were associated with a higher likelihood of cycling. Other significant factors in the destination zone were higher population density, less of the road network as arterials, and the presence of road markings or signage along bicycle routes.

The cross-zonal model (model 4) offered variables according to the a priori hypotheses (from Table 2) about the zone in which they might influence cycling (Table 6). Of four factors offered from the origin zone, none were significant, and of six offered from the destination zone, only educational land use was important. The greatest number of factors hypothesized and offered (12) was from the route zone. Of these, less hilliness, higher intersection density, and a lower density of arterial roads were associated with higher odds of cycling.

While avid, experienced cyclists may have no issue making long trips, trip distance was a significant influence on cycling in our models. Indeed, distances under 5 km have been found to be a strong motivator for cycling¹⁸ and could be considered a threshold for new or casual cyclists. Model 5 (Table 6) used the subset of trips which were under 5 km (53% of the full dataset) where cycling may be a very reasonable substitute for driving. Results were fairly consistent with the cross-zonal full dataset model 4, with the exception that population density at the origin and the presence of cyclist-activated traffic lights along the route were both retained in the model and educational land use at the destination was not.

City planners and health practitioners have a specific interest in understanding how to motivate reluctant cyclists to cycle more. To determine whether such cyclists might be differently influenced by the built environment, we conducted two sub-analyses of the cross-zonal model (model 4): one restricted to the rare cyclist group and one for frequent and regular cyclists combined. All odds ratios in these models were in the same direction as model 4, although not all remained significant (as expected given the smaller sample sizes). In the model for rare cyclists, comprised of 1,930 trips with 15% by bicycle, trip distance was a stronger deterrent (OR=0.32, 95% CI 0.23–0.43) than in model 4. Other significant variables highlighted connectivity as a motivator (intersection density OR=1.28, 95% CI 1.05–1.57) and arterial roads as deterrents (OR=0.76, 95% CI 0.62–0.94). In the model for frequent and regular cyclists (1,350 trips, 54% by bicycle), hilliness, intersection density, and trip distance were significant influences, all with odds ratios similar to model 4.

DISCUSSION

This study found that the built environment had a significant influence on the decision to use the active mode of transport, bicycling, instead of driving. For

utilitarian travel, features of the physical environment—the road network, bicycle-specific facilities, and land use—were all associated with the likelihood of cycling, even after accounting for personal characteristics and trip distance. The following features promoted cycling: less topographical variation, traffic calming and cyclist-activated traffic lights along bicycle routes, higher route connectivity (intersection density), local roads instead of highways and arterials, higher population density, and neighborhood commercial, educational, and industrial land uses.

Our findings for the common constructs of connectivity, land use, and residential density were congruent with existing literature on cycling and physical activity. Higher intersection density was associated with a greater likelihood of cycling. Connectivity, as measured by a variety of different but related constructs,³⁶ has been significant in other studies of cycling using objective built environment measures,^{37,38} as well as in studies that include both walking and cycling.³⁹ Higher population density at the destination was associated with a higher likelihood of cycling. Population or residential density, while often considered a proxy for other unmeasured features, is pervasive in the built environment literature as the data are widely available.^{25,40,41} No previous cycling-only studies have explicitly considered population density. A study examining transportation-related physical activity included residential density, but it was not significant.³⁹ Density and its variability differ from place to place (e.g., New York City versus Atlanta), and thus, its impact might be expected to vary between geographical regions.

We used an entropy measure for land use mix and found that a more balanced mix of residential, commercial, entertainment, and office land uses around the origin was associated with a higher likelihood of cycling. In a San Francisco study, this land use mix measure was one component of a land use diversity index that predicted walking but not cycling.¹⁵ The use of this entropy measure was supported by empirical research on walking and obesity.^{40,42} However, the specific mix of land uses typically included may not be the ideal for cycling, where land uses such as green space may be more highly valued.^{13,19} Limitations of this land use mix measure have been discussed elsewhere.^{33,34,43,44} Other measures have been applied empirically in cycling research such as Moudon et al., who considered an extensive array of proximity-based land use measures, but found few were associated with cycling.¹⁴ Thus, to enhance the land use analysis, we also looked at intensity-based land use measures and found that zones with more neighborhood commercial, educational or industrial land uses were associated with a higher likelihood of cycling, and those with more single family residential or large commercial land uses were associated with a lower likelihood of cycling.

While retail destinations are important trip attractors, we found that the lot size of commercial land use affected the direction of the influence on mode choice. Where there were more large commercial lots (greater than 1 ha), trips were less likely to be by bicycle. Where there were more neighborhood commercial lots, trips were more likely to be by bicycle. Neighborhood commercial lots may be characterized as human settings with easy access to multiple storefronts, in contrast to the vast parking lots that typically abut malls or big-box retail shops. While there have been efforts to measure the urban design characteristics of such micro-scale environments,⁴⁵ the literature linking this to physical activity is still evolving.

We also included built environment factors that might be specifically important to cycling. Hilly topography, as measured by variation in elevation, was an important deterrent to cycling. This concurs with results of surveys¹⁹ and focus groups¹² where cyclists mentioned hilliness as a barrier. Studies that use perceived

measures of hills have also found negative associations with cycling.⁴⁶ However, results from prior studies using objective measures have been mixed. Quartiles of average slope did not correlate with cycling in Portland,³⁷ but a dichotomized average slope variable did in Bogota.³⁸ A variable for the presence of a steep hill did not predict cycling in one study⁴⁷ but predicted recent rail trail use in another.⁴⁸ Based on these discrepancies, we developed new constructs for topography for the current work: the variation in elevation and the proportion of steep road segments along the route. The steepness measure was created based on cyclist's input¹² but was not significant in the models, whereas the variation in elevation was. As a whole, this collection of findings relating topography to cycling is not contradictory but rather may provide detail on the specific qualities that affect cycling. For example, it may not be the presence of a single short steep hill that deters cycling, since it could be avoided with a detour or seen as a physical challenge, but instead constant up and down along a route as indicated in this analysis. Given that certain areas of Metro Vancouver are very hilly, the region provides good variability in this "hilliness" measure. This new construct warrants application in other geographical locations to test its generalizability to predict cycling.

Certain aspects of bicycle facilities and the road network were significantly associated with cycling. Traffic calming around the origin, road markings or signage around the destination, or cyclist-activated traffic lights en route were associated with cycling. The current study had highly detailed spatial data on the locations of bicycle road markings, signage, traffic calming measures, and cyclist-activated traffic lights. We found no studies that had comparable detail on such amenities. As these features are relatively rare across the region, the skewed count data required that we employ dichotomous variables (present/absent). These dichotomous variables were an accurate description of exposure for smaller zones (i.e., origin or destination), but in the larger route buffers, the frequency of such facilities may have been a better measure. The measures for the three types of bicycle amenities were only moderately correlated (Pearson correlation 0.45–0.65), not enough to restrict offering all to the models but perhaps affecting the number of factors retained in each model. Overall, it is clear that some kind of bicycle amenity is important, but our models did not indicate that one type was better than another.

We found that areas with a lower density of arterial roads or highways had a higher likelihood of cycling. In Bogota, Columbia, the overall street density (high versus low) predicted cycling.³⁸ Yet all roads are not equally valued by cyclists, indicating that road measures should be stratified by road type.⁹ Other GIS-based research has found that cyclists choose local roads over major roads.^{18,49,50} In our study, the density of designated bicycle routes or off-road paths was not significant in multivariable models. However, measures of bicycle routes have been significant elsewhere. In an ecological study of 35 large US cities, bike lane density was important: Each additional mile of bike lane per square mile was associated with a 1% increase in the bicycle mode share. In individual-level studies, living closer to a regional trail system predicted overall cycling in Portland³⁷ and trail use in the Twin Cities.⁵¹ A Metro Vancouver survey of cyclist preferences found that roads and paths tailored to cycling were valued but also that these preferences did not correspond with current use of different road and path types.⁹ Instead, in areas where the ideal infrastructure (separated paths or bikeways) is not available, bicycle travel may take place along sub-optimal but best available road types (local roads). This may account for why bicycle routes and off-road paths were not significant in our models.

Trip distance is a fundamental consideration in mode choice. In our study, the median distance for bicycle trips was 2.5 km, less than half of the 6.0 km median distance for car trips. We found that distance was significant in all multivariable models and that for each additional 10 km of trip distance, people were only 40–60% as likely to make the trip by bicycle. This relationship was consistent whether we included all trips or only those less than 5 km. Distance was even more important to rare cyclists, who were only 32% as likely to use a bicycle for an additional 10 km of distance. The importance of trip distance for cycling has been found by other researchers, and several studies have restricted their study populations to people who live within a bikeable distance of their workplace.^{15,39,52}

It is important to consider whether the distances traveled by bicycle in this study would contribute sufficient physical activity for health. The recommended 30 min per day of physical activity⁶ translates to about 7.5 km total distance for average cycling speeds of 15 km/h. Since this amount can be obtained in several bouts of exercise, a trip by bicycle to and from a destination ~4 km away would satisfy daily physical activity requirements. In our data, one third of the bicycle trips were this distance or longer. Of the car trips, about one third were at least 4 km but less than 12 km, corresponding to 15–45 min bicycle travel times. Shifting these trips to cycling from driving can therefore be expected to improve individual health. While there are increased risks of personal injury and possibly air pollution exposure associated with this shift, evidence indicates that the multiple health benefits of cycling outweigh the risks.^{53–55} In addition, there is evidence that physical activity via active transportation is easier to maintain than other forms of exercise, such as going to a gym.⁵⁶

This study explicitly considered place, by measuring the built environment in different spatial zones: along the route and around the origin and destination. We found that place was important, since in each zone different built environment factors influenced cycling. For example, hilliness was significant only in the route zone, but not in the origin or destination zones. Land use mix was significant only within the origin zone, but not along routes or at destinations. Only intersection density was significant in all three zones, but it had a stronger effect within the route and destination zones than the origin zone. In our cross-zonal model, where factors from all zones were offered, the majority of significant factors were route measures, suggesting that route characteristics were a primary consideration in making the decision to cycle instead of drive. If only origin or origin and destination zones were considered, certain influential factors such as topography, road network composition, and bicycle facilities may have been missed for planning and policy decision making.

These findings underscore the necessity of including all three spatial zones. No prior bicycle research has analyzed this comprehensive set of zones when considering the influence of place. Studies often rely on physical activity survey data and thus have only participants' postal code as a spatial identifier,^{13,37,38} limiting the analysis to features around trip origins. A few studies have drawn on travel diary data, which details origins and destinations^{15,51}; only one of these explicitly considered destination characteristics in the analysis.¹⁵ We found a single study that considered route factors, which measured the built environment along the shortest routes between home and workplace for trips made by walking or cycling.³⁹ A multizonal concept has been previously proposed in a review of neighborhood audit tools that presented three key zones of a trip: the origin and destination, the

route taken, and the area in which the trip takes place,⁵⁷ but their conceptual model has yet to be applied empirically.

Strengths and Limitations

This study of the link between the built environment and physical activity is one of the few focused on cycling and the first to include those who cycle infrequently. The travel patterns of the infrequent but willing cyclist population, or the “near market”, are important to consider in order to have the maximum impact on behavioral change.⁵⁸ In our data, 290 (28.3%) of the bicycle trips were made by people who cycle less than once a month. Other research defines cyclists with thresholds such as those who cycle at least once per week, thus capturing only regular cyclists, and may oversample to get an adequate population size. Examples include a King County study with a high proportion of weekly cyclists (21% of 608 participants)¹⁴ and a Portland study where 83% of the 162 participants considered themselves regular cyclists.⁵⁹ Market research indicates that certain route preferences as well as cycling motivators and deterrents can differ between regular and infrequent cyclists.^{9,19} Therefore, research needs to capture the travel patterns of infrequent cyclists to identify environments that can attract new cyclists or increase cycling rates in those who cycle rarely.

The Cycling in Cities survey collected trip origin and destination locations, but for logistical reasons, the exact route traveled was not collected. This was not seen as a limitation as it is recognized that routes may vary by day or between people. A validation study conducted by the authors compared the shortest route (as used here) with the actual route for a subset of these trips.⁵⁰ It found that three quarters of trips were less than 10% longer than the shortest distance path. The actual and modeled trips did not differ significantly in terms of general built environment measures (air pollution, greenness, connectivity, land use) but did in terms of cycling infrastructure and road network. Specifically, people making bicycle trips were more likely to route away from highways and arterials and toward designated bicycle facilities, off-street paths, and local roads; conversely, those making car trips detoured to highways and arterials. This validation study suggests that using shortest routes, as done here, would in fact underestimate the influence of bicycle facilities on making bicycle trips.

Data limitations meant certain factors that could influence cycling were not included. One key factor is safety⁶⁰, however, geocoded locations of crash sites are not currently available for the region. End-of-trip facilities (bicycle racks, showers) are important to cyclists,¹⁹ but they are not yet identified in regional spatial datasets.

Our results provide additional evidence about built environment factors affecting cycling, where research remains rare. They describe travel behavior decisions in one geographic region, and similar analyses are needed elsewhere. Influences will vary: topography may play an influential role in hilly cities such as Vancouver or San Francisco, whereas green cover may be a serious consideration in regions with hot climates.

Finally, as with much of the research on the built environment, this is a cross-sectional study, and the findings provide evidence of associations, not causality. Since experimental studies are impossible in this field, a combination of quasi-experimental, before-and-after, and cross-sectional studies will be needed to build the body of evidence for causality.⁶¹

CONCLUSIONS

Using novel methodology tailored to cycling, we found that the built environment influenced decisions to bicycle instead of drive after accounting for trip distance and personal demographics. This study characterized the built environment around the trip origin and destination and along the route between the two, and found increased bicycling with less hilliness; less arterial roads and highways; higher intersection density; presence of bicycle-specific infrastructure including traffic calming, signage, road markings, and cyclist-activated traffic lights; more neighborhood commercial, educational and industrial land uses; less large commercial and single family housing land uses; greater land use mix; and higher population density. Different factors were important within each of the spatial zones, and when all spatial zones were considered together, more factors related to the route zone were significant influences on cycling. Future studies should explicitly consider these three spatial zones in order to fully explore the connection between urban form and travel behavior. These findings identified features that support cycling and can be used to develop land use and transportation planning policies that encourage active transportation for improved individual and community health.

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