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A new approach for bikeshed analysis with consideration of topography, street connectivity, and energy consumption

Hiroyuki Iseki [a,*], Matthew Tingstrom [b]

[a] National Center for Smart Growth Research and Education, University of Maryland, College Park, United States
[b] Urban Studies and Planning Program, The School of Architecture, Planning, and Preservation, University of Maryland, College Park, United States

A R T I C L E I N F O

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A B S T R A C T

In recent years, bike planning has gained the attention of planners and the public as a sustainable and active mode of transportation that can reduce traffic congestion, vehicle emissions, and health risks. Following the success of public bikesharing programs in cities in France and Canada, multiple US cities have initiated similar programs. With this background, spatial analysis has been applied to produce heat maps of bike-travel demand, and identify suitable areas for bikeshare infrastructure. Existing research considers a variety of factors, such as resident demographics, land use, street types, and availability of bike facilities and transit services. However, few studies fully account for topography and street connectivity.

The study proposes a method to combine topography and presence of intersections with estimates of energy used to bike, and incorporate the resulting travel-impedance factor, as well as street connectivity, into a spatial analysis. Using the case in Montgomery County, Maryland, USA, where elevation and street connectivity differ substantially among neighborhoods, this study shows how the size and shape of bikesheds (or bike demand catchment area) originating from the proposed light rail stations vary in the analysis with or without taking into account these critical factors. The analysis results have significant implications for various bike planning efforts using spatial analysis.

1. Introduction

In recent years, bike planning has garnered attention from the public as a sustainable mode of transportation and as a means to exercise and reduce health risks. Cycling has been increasingly recognized as an important component of both public health recommendations and active transport policy. Reducing private automobile travel and increasing trips by walking and cycling could lead to important health benefits through increased physical activity, thereby reducing the associated burden of chronic non-infectious disease (Fraser & Lock, 2010) and through reduction of urban air pollution. Following the success of public bikesharing programs in Paris and Lyon, France, and Montreal, Canada, several US cities, such as Washington, D.C., New York City, Chicago, and Minneapolis, initiated similar programs. With this background, GISs have been frequently used in bike planning to analyze, identify, and estimate: (1) bike route/path, (2) bike demand (heat map), and (3) bikesheds. We use the term "bikeshed" to mean a catchment area of bicycle trips or demand in relation to a single point analogous to the term, "watershed".[1] Such studies include a variety of factors to examine, such as resident demographics, land use, street types, and availability of bike facilities and transit services.

Transportation planning analyses often assumes that individuals want to minimize the generalized costs of travel, often measured by travel time or travel distance. Using this assumption in spatial analysis, a cyclist is expected to pick the shortest distance offered by a street network. Although a street network used in spatial analysis typically does not contain information about elevation, many cities have streets with varying gradients requiring differing

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* Corresponding author. Address: National Center for Smart Growth Research and Education, University of Maryland, College Park, 1112 K Preinkert Field House (Building 054), College Park, MD 20742, United States. Tel.: +1 301 405 4403, NCSG General Number: +1 301 405 6788; fax: +1 301 314 5639.

E-mail addresses: hiseki@umd.edu (H. Iseki), matt.tingstrom@gmail.com (M. Tingstrom).

[1] The concept of bikeshed has a formal relationship with the concept of market or service area that is defined as a "set of actual or potential customers of a given good or service supplier" (Thill, 2001). Similarly, bikesheds in this study show the area where people potentially bike to and from the proposed light rail stations, and their shapes and sizes are influenced by geometric and topologic properties and a transportation cost function (Hanjoul, Beguin, & Thill, 1989; O'Kelly & Miller, 1989; Thill, 2001; Thill, 2009). An analysis of service area and accessibility for intermodal facilities is another application of the same concept (Kim & Van Wee, 2011; Lim & Thill, 2008; Macharis & Pekin, 2009; Tittmann, Parker, Hart, & Jenkins, 2010).

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degrees of effort to traverse. Given that most bicycles are powered exclusively by the rider, the physical environment plays a major role in influencing cyclists' efforts and energy required to travel and, therefore, the decision to bike or not as well as the route to take.

In this paper, we develop a method to combine topography/terrain and presence of intersections with estimates of energy consumed to bike, and incorporate the resulting travel-impedance factor into a spatial analysis of street network connectivity that determines bicycle sheds surrounding eleven stations of a proposed light rail line.[2] This paper is organized as follows. Following this introduction, Section 2 briefly reviews the literature of factors that affect cycling and applications of spatial analysis for bicycle planning with special attention to the treatment of topography, terrains, and slopes. Section 3 describes the methodology developed, and presents examples of the effects of topography on estimations of bikesheds. Section 4 describes data, data sources, and the procedure to apply the proposed methodology in an application. Section 5 presents results of bikesheds estimated by the five different methods. Total area, total route length, street density, and magnitudes of slopes are analyzed within the bicycle sheds obtained by each method with or without taking into account the critical factors. The analysis results clearly show significant differences resulting from the five different methods of bikeshed analysis, and indicate the importance for bike planning spatial analysis. The paper concludes with a summary of findings and a brief discussion of the implications of our findings, challenges that we faced in the study, and suggestions for future work.

2. Literature review

The literature on travel behavior and transportation economics tells us that travellers make a decision about where, when, and how to travel by applying the concept of generalized costs of travel and travel impedance (Hanson, 2004; Iseki & Taylor, 2009). Generalized costs of travel and travel impedance take into account a variety of burdens on travelers, such as monetary costs (e.g., fuel cost and transit fare), travel time, insecurity (e.g., against crimes), and discomfort (e.g., rain or a cold weather). Many factors affect generalized costs of travel and travel impedance for bicycling, and therefore also influence the level of demand and the extent of the service area for bicycling (Heinen, Maat, & van Wee, 2011; Hochmair, 2013). Such determinants include climate (Dill & Carr, 2003), topography or "hilliness" (Cervero & Duncan, 2003; Dill & Voros, 2007), attitudes about cycling (Dill & Voros, 2007; Ortuzar, Iacobelli, & Valeze, 2000), and socioeconomic factors, especially gender (Buehler, 2011; Hochmair, 2013).

In particular, various environmental factors affect travel impedance for those traveling by bicycle or foot significantly more than for those taking motorized travel modes (Heinen et al., 2011). Density of establishments, diversity of establishments and land uses, and design of the street network (3Ds) directly influence the physical distance cyclists and pedestrians are willing to travel from a trip origin to a potential destination (Cervero & Kockelman, 1997). Unfavorable conditions in topography/terrain (e.g., steep slopes), road surface (e.g., uneven or unpaved surfaces), street density and connectivity (e.g., sparse street network, circuitous roads, and cul-de-sacs), weather (e.g., rain, snow, and low temperature), and traffic conditions (e.g., high traffic and presence of heavy vehicles) can require much more effort from cyclists and pedestrians to travel the same distance, and therefore increase travel impedance (Fraser & Lock, 2010; Wardman, Parkin, & Page, 2008). Dill and Voros (2007) found 30% of respondents cited "too many hills" as a barrier compared to 23% that chose "distances to places are too great" on a random phone survey asking to identify environmental factors that prevented the respondents from cycling more. Availability of good facilities, such as sidewalks, bike lane/paths and off-road bike trails facilitate more comfortable, safe travel for cyclists and pedestrians (Nelson & Allen, 1997).

Most cyclists in utilitarian trips desire to lower travel impedance and human energy consumption (Yamashita, Dantas, Taco, & Yamamoto, 1998). A study in the UK by Wardman et al. (2008) found a hilliness/slope variable—the proportion of 1 km squares in a district with a mean slope of 3% or greater—more significantly correlated with bicycle commuting mode share than any other physical environment variables; they found the elasticity for hilliness of −0.894, indicating an 8.94% reduction in the bike mode share for commuting trips in relation to a 10% increase in the hilliness. The Delphi analysis in Iowa found "mountainous topography" was the most important to be considered in selecting most suitable routes for bicycle paths, while "hilly or rolling topography" was found less important (Souleyrette et al., 1996). Menghini, Carrasco, Schüssler, and Axhausen (2010) found topography—street gradient—to be a significant variable in regards to routing decisions of cyclists, comparing the bicyclists' actual routes observed through GPS data with a set of alternative shortest paths identified by GIS. Cervero and Duncan (2003) also found slope has a larger influence on the decision to bike than any of the built environment variables—including design, density, and diversity (3Ds)—in their analysis of travel behavior in San Francisco, using the 2000 Bay Area Travel Survey data. Given the significance of factors, such as hilliness, slope, and topography in influencing cyclists' travel behavior, the omission of these factors could be a substantial shortcoming in current bike planning analyses, especially in areas with a substantial variation in these factors.

Although the idea of incorporating topographical data is not new within the literature on the application of spatial analysis for bicycle planning, its application is still limited. De Baets, De Mol, and De Maeyer (2011) developed a methodology using a GIS to evaluate a bicycle route network, identifying bottlenecks in terms of width and elevation of cycle paths, the width of separation between a cycle path and roadway, and presence of road guards. However, De Baets et al. only used elevation data as an indicator of the degree of separation between the bike path and roadway and were not interested in the steepness of the path itself. Yamashita et al. (1998) used a Digital Terrain Model (DTM) in a GIS to generate slope values as attributes for road segments across the city and group them into four categories, which were appended to each segment of the street network in the study area. In the street network file with the slope information, the length attribute of each road link was estimated based on planar distance and the slope and used to identify optimal bike routes between two points. Yamashita et al.'s approach has the advantage of creating a city-wide street network system file with slope data for each segment that also has a higher resolution than Winters, Brauer, Setton, and Teschke (2010). As Yamashita et al.'s network analysis focused on route rather than service area identification, their approach is specifically for identifying likely bicycle corridors, but not catchment areas. Drucker (2003) combined the slope layer, which she generated from a DEM file, with a separate accident data layer to identify steep street segments that could pose high risk of accident for competitive bicyclists. However, Drucker did not incorporate the resulting slope data into the street network system file to generate the bicycle routes or catchment areas. Winters et al. (2010) evaluated two topographical measures "hilliness" and "steepness" in their spatial analysis. "Hilliness" was evaluated based on the standard deviation of the elevation for certain points inside

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[2] The earlier versions of this paper were presented in the 53rd Annual Conference of the Association of Collegiate Schools of Planning in 2012, the Transportation Research Board 92nd annual meeting in 2013, and the 12th World Conference on Transportation Research in 2013.