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A GIS BIKEABILITY/BIKESHED ANALYSIS INCORPORATING TOPOGRAPHY, STREET NETWORK AND STREET CONNECTIVITY

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ABSTRACT

In recent years, bike planning has garnered attention from planners and the public as a sustainable mode of transportation and as a means to exercise and reduce health risks. In addition, following the success of bike-sharing programs in Paris and Lyon, France, and Montreal, Canada, several US cities initiated similar programs. With this background, GISs have been applied to conduct a spatial analysis and produce heat maps of bike-travel demand and suitable areas for a bike-sharing program. These studies include a variety of factors, such as demographics of residents, land use, street types, and available bike facilities and transit services. However, there have been few studies that take topography and street connectivity into account.

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 GIS analysis. Using the case in Montgomery County, Maryland, USA, where elevation and street connectivity vary substantially among neighborhoods, this study shows how the size and shape of bikesheds originating from proposed light rail stations vary in the GIS analysis with or without taking into account these critical factors. The analysis results have significant implications for various bike planning programs using a GIS analysis.

Keywords: bike planning, topography, street connectivity, energy consumption to travel, spatial analysis, geographic information systems.

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 vehicle traveling and increasing trips and distances travelled by walking and cycling could lead to important health benefits through increasing physical activity and thereby reducing the associated burden of chronic non-infectious disease (Fraser and Lock 2010) and through reduction of urban air pollution. Following the success of bike-sharing program in Paris and Lyon, France, and Montreal, Canada, several US cities, such as Washington, D.C., Minneapolis, Minnesota, and Irvine, California, initiated similar programs. With this background, GISs have been applied to conduct a spatial analysis and produce heat maps of bike-travel demand and identify suitable areas for bike-sharing programs. Such studies include a variety of factors to examine, such as demographics of residents, land use, street types, and available bike facilities and transit services.

An analysis in transportation planning often assumes that people want to minimize the generalized costs of travel, which is often measured by travel time or travel distance—in particular in a GIS analysis. Under this assumption, a cyclist is expected to pick the shortest distance offered by a street network. Although a street network used in a GIS analysis typically does not contain information about elevation, street grids do not exist on a perfectly planar surface in reality, and many cities have streets with varying gradients requiring differing degrees of effort to traverse. For example, there may be a scenario where a cyclist chooses a slightly longer route to avoid a steeper uphill climb. 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. For example, 30 percent of respondents cited "too many hills" as a barrier compared to 23 percent that chose "distances to places are too great" on a random phone survey asking to identify environmental factors that prevented the respondents from riding more (Dill and Voros 2007). Despite the substantial impacts on people's decision to bike, there have been few studies that take into account topography, street network connectivity, and energy consumption to travel in an analysis.

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 GIS analysis of street network connectivity that determines bicycle sheds surrounding eleven stations of a proposed light rail line. 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 GIS analysis.

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 and Taylor 2009). Generalized costs of travel and travel impedance take into account a variety of burdens on travellers from monetary costs (e.g. fuel cost and transit fare) to travel time, from insecurity (e.g. against crimes) to discomfort (e.g. waiting in rain or a cold weather).

A range of factors in the built environment significantly affects impedance for those traveling by biking and walking. Density of establishments, diversity of establishments and land uses, and design of street network (3Ds) directly influence the physical distance cyclists and pedestrians are willing to travel from the trip origin to potential destinations (Cervero and Kockelman 1997). Unfavorable conditions in topography/terrain (e.g. steep slopes), road surface (e.g. uneven surface and potholes), 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 for the same distance, and therefore increase travel impedance (Wardman, Parkins, and Page 2008; Fraser and Lock 2010). 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 and Allen 1997).

Most cyclists in regular trips desire to lower travel impedance and human energy consumption (Yamashita et al. 1998). A study in the UK by Wardman, Parkins, and Page (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 a higher share of cycle commuting mode than any other physical environment variables. 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 et al. (2009) 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.

In recent years, 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. Although the idea of incorporating topographical data is not new within the literature of GIS application for bicycle planning, its use is still limited. De Baets at al. (2011) developed a methodology using GISs to evaluate a bicycle route network, identifying bottlenecks in terms of width and elevation of cycle paths, the width of safety buffer between a cycle path and vehicle road, and presence of road guardrails. 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 (DEM) in GIS to generate slope values as attributes for road segments across the city. The slope values were simplified and grouped into four categories: 1) 0.0 to 3.0%, 2) 3.1 to 6.0%, 3) 6.1 to 8.0%, and 4) greater than 8.0%. The resulting slope category information was then appended to each segment of the street network across the study zone using the Grid Analysis MGE (Modular GIS

Environment) Module. With a street network file that included slope information, Yamashita et al. estimated the length attribute of the road links based on planar distance and the slope, and used the MGE Network Analysis module to identify optimal bike routes between two points. Yamashita et al.'s approach has the advantage of creating a citywide street network dataset with slope data for each segment, and with a higher resolution than Winters et al. (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 in ArcGIS Spatial Analyst, 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 network dataset to generate the bicycle race route.

Winters et al. (2010) incorporated two topographical measures into their GIS analysis, "hilliness" and "steepness," using a DEM raster file (30 meter resolution). These two variables were evaluated for three spatial zones per trip: route; origin; and destination. "Hilliness" was evaluated based on the standard deviation of the elevation for certain points inside each of three buffered zones per bicycle trip: trip origin, route corridor, and destination. "Steepness" was evaluated only for the route zone, based on the percentage of segments steeper than 5% along the total route after splitting each street segment every 100 meters. "Steepness" values were assigned for each route, rather than for every segment in the road network.

In 2012, the website Walkscore.com released its "Bike Score" rankings of the ten most bikeable large cities in the US according to an index that weighs hilliness among three other equally weighted components (Walk Score, 2012). "Hilliness" is determined based on the steepest grade inside a 200-meter radius. The results create a citywide index showing the relative bikeability of neighborhoods within a city in the form of a heat map; however, based on the description of their methodology and testing the website's commuter function, it is not clear and seems unlikely that topography is being used as a criterion to define the commuter sheds that the web site generates.

A common limitation to all of the GIS approaches reviewed is the reliance on DEM files and the assumption that road elevation can accurately be inferred from the natural terrain topography.

3. METHODOLOGY FOR INCORPORATING TOPOGRAPHY AND ENERGY CONSUMPTION INTO GIS BIKESHED ANALYSIS

This section explains the GIS-based methodology developed for this study, and presents examples of the effects of topography on the boundaries of the bikeshed. The primary focus of this study is to develop a methodology to identify bikesheds. We apply ArcGIS Network Analyst Service Area function to draw bikeshed boundaries by finding routes minimizing

travel impedance.[1] In most cases, factors that are readily available, such as travel distance and travel time, are chosen as the travel impedance. Travel distance is the most basic factor, which can be directly measured from a GIS shapefile. However, a street shapefile usually does not factor in a change in altitude, and measures distance between two points on the completely flat surface, using the planar length (Longley et al 2005). Although travel time could be a better variable, by taking into account the effects of topography on biking, such travel time data are not readily available. Thus, it is important and necessary to identify a better travel impedance factor to more accurately estimate cyclists' generalized costs of travel that allow us to take into account the varying slope of the roads in the study area. In this study, we decided to use energy consumption to bike as the impedance factor.

The version of the "steady-speed power equation" published by Wilson (2004) is used to estimate the total energy expressed in joules a bicycle rider would need to traverse each street segment, taking into account street distance and slope, and characteristics of bicycle and a bike rider (Eq. (1)).

$$W_{rider} = [K_A * (V + V_W)^2 + m * g * (s + C_R)] * V \qquad (1)$$

Table 1 shows descriptions and values used for variables and coefficients in the bikesheds analysis. We estimate the energy consumption for an average US male rider with a combined rider and bicycle weight of 80 kg. The values for drag factor and tire rolling resistance coefficient were obtained also from Wilson (2004) and were chosen as representative of the rolling and aerodynamic characteristics of a hybrid bicycle, as could typically be used for commuting purposes. As energy output varies by velocity, we also assumed that the rider would attempt to maintain an average speed of 4 m/s, which seemed reasonable based on the GPS observations of Menghini et al. (2009). This velocity assumption is necessary to estimate first the energy output per second (watts), which is further multiplied by the time to travel each street segment (the distance of street segment divided by velocity) to obtain energy consumption per street segment (joules).

Table 1: Values Used for Variables and Coefficients in the Analysis of Bikesheds

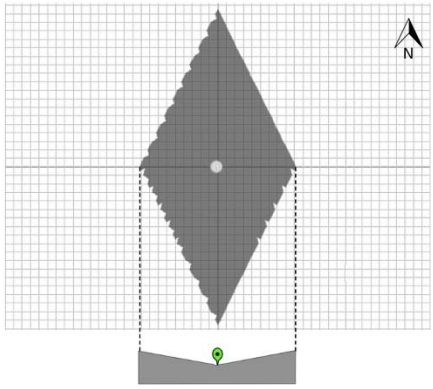
Variables and Coefficients	Description	Value
W_{rider}	Energy consumption of the rider in Watts	To be calculated
K_A	Drag factor	0.245
V	Velocity	4 m/s
V_W	Wind velocity	0
M	Mass of the rider	80 kg
G	Acceleration of gravity	9.807 m/s^2
S	Slope	Obtained from GIS
C_R	Tire rolling resistance coefficient	0.004

[1] ESRI ArcGIS 9.2 Desktop Help:
http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=Finding%20a%20service%20area

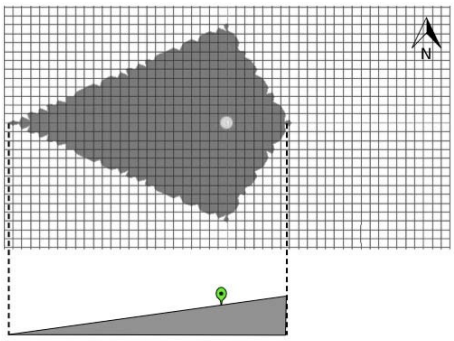
With Equation (1), values, and assumptions, the following examples show how the bikeshed boundary is impacted when street slope values representing the area topography are taken into account in modelling. Figure 1(a) shows the extent and cross-sectional view of a bikeshed in a "valley" with a slope of 2.8 percent applied to all streets running east-to-west and west-to-east from the central north-to-south axis.

Figure 1: Examples Showing the Effects on Topology on Bikeshed

(a) Extent and cross-sectional view of "valley" bikeshed with a slope of 2.8 percent



(b) Extent and cross-sectional view of "hillside" bikeshed with a 1.5 percent slope.



(c) Extent and cross-sectional view of near and distant hills with 4 percent slope.

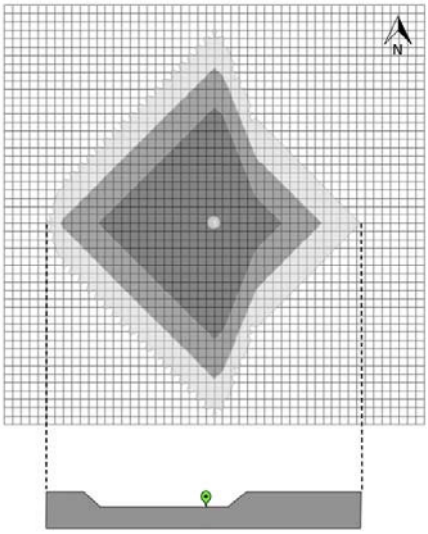


Figure 1 clearly shows how the bikeshed area with the central point as a trip origin expands further along the flat terrain running north or south than either east or west, which are uphill. In Figure 1(b), a slope of 1.5 percent is applied to all streets running east-to-west. No slope is applied to north-south streets. The bikeshed area expands heading downhill (toward the west) and is substantially reduced heading uphill (toward the east). Figure 1(c) shows the case with a slope of 4 percent running west-east and starting 1-grid east of the trip origin; and a slope of 4 percent running east-west and starting 18 grids west of trip origin. Figure 1(c) depicts how the bikeshed area and shape vary by the proximity of steep slopes to the trip origin. An uphill slope with close proximity to the trip origin (on the east side) shrinks the bikeshed more substantially than an equal-sized uphill slope at a greater distance from the trip origin (on the western edge). A bikeshed will be smaller when steep slopes characterize a station's immediate neighborhood than when steep slopes are found at a greater distance from a station, even though both cases may have similar values of slopes. These simple examples clearly show how topography and consideration of energy consumption of biking as travel impedance affect the size and shape of bikeshed.

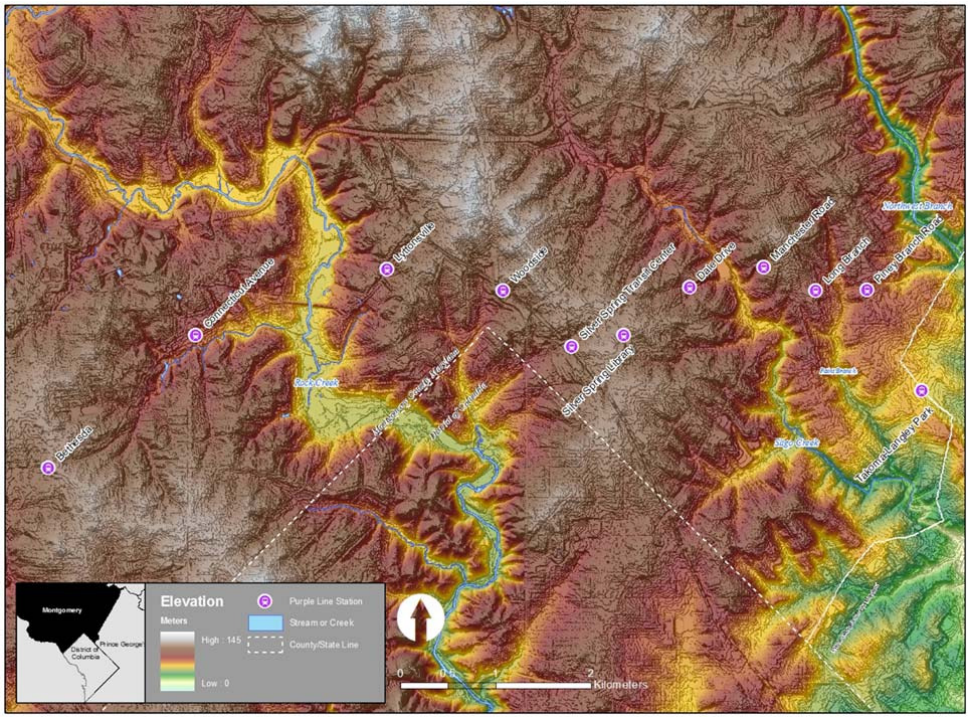
4. APPLICATION OF METHODOLOGICAL APPROACH AND DATA SOURCES

In this section, we apply the methodology demonstrated in the previous section to real conditions in Montgomery County, Maryland, USA, using data presented in Table 2. The Maryland Transit Administration has invested significant resources in planning the Purple Line, a light rail corridor to serve Montgomery and Prince George's County. Bicycle access to the planned stations can form a vital connection between the Purple Line and residents in the surrounding neighborhoods. In particular, this study focuses on the eleven stations in Montgomery County, where elevation varies substantially in some neighborhoods (Figure 2), as defined by MTA's Locally Preferred Alternative (LPA) (Maryland Transit Administration 2011). In Figure 2, areas of high contrast representing Rock Creek, Sligo Creek, and North West Branch correspond to steeper areas, requiring more energy to traverse. Flatter street segments such as those around Bethesda require less energy.

Table 2: Data and Data Sources

Data	Source
LPA Purple Line station locations	Maryland Transit Administration and Whitman, Requardt & Associates, LLP
National Elevation Dataset 1/9 Arc-Second	US Geological Survey
Street network	StreetMap USA, Esri Inc.
WMATA Metrorail system	GIS Program, Office of the Chief Technology Officer, District of Columbia

Figure 2: Topography of the Study Area and the Eleven Proposed Light Rail Station Locations



In most GIS analyses, identifying “service areas” uses two basic methods. The most basic method uses the straight line (as the crow flies) distance to create a circle buffer with a constant radius. The next is a widely available method in the ArcGIS Network Analyst called the “Service Area” function that identifies an area using the street distance in the street network without considering slopes. For a comparison purpose, we call these two conventional techniques Method 1 and Method 2.

In this study, we developed two alternative methods (Method 3 and 4) for incorporating the steady-speed power equation (Eq.(1)) into a GIS-based analysis of bikesheds in order to take into account the effects of slope on biking travel distance. In general, both alternatives improve upon previous methods. In our approach, like Yamashita et al. (1998), we first create a network dataset with slope information for all street segments within the study area, which in this case fell within an 8-kilometer buffer around the proposed Purple Line station locations. When creating the network dataset, we did not further divide each street segment as Winters et al. (2010) did because the median street segment length was 102.8 meters and short enough. The technique by Winters et al. would be useful for a street grid that has longer distances between intersections that may result in substantial errors in the slope estimation. Unlike Yamashita et al. (1998), we maintain a spectrum of slope values for road segments, rather than grouping the slopes into only a small number of categories (e.g. greater than 5% or not), so that we do not lose details of slope information. Compared to the studies reviewed, we also improved accuracy by obtaining elevation data from a 1/9 Arc-Second DEM, where prior examples used 1/3 Arc-Second elevation datasets. Lastly, our method departs from previous ones by using a single impedance value that represents the combined effect of both distance and slope, which we obtain from the steady-speed power equation.

The initial step for both methods is to use the ArcGIS 3D Analyst extension's *Add Surface Information* function to append elevation data from the DEM to the street layer, converting the layer into a three dimensional feature. We then used the Calculate Geometry function to calculate the X and Y coordinates for endpoints (Start_X, Start_Y, End_X, and End_Y), and the Z-value or elevation (Start_Z and End_Z) for all street segment endpoints. The average slope of each road segment is established using the following equation (2) based on the Pythagorean theorem provided by Price (2009) to calculate the relative slope from start to endpoints in a new field Slope_StoE:

$$\text{Slope\_StoE} = \frac{[\text{End\_Z}] - [\text{Start\_Z}]}{(([\text{Start\_X}] - [\text{End\_X}])^2 + ([\text{Start\_Y}] - [\text{End\_Y}])^2)^{0.5}} \times 100 \qquad (2)$$

Method 3: Absolute Slope Method

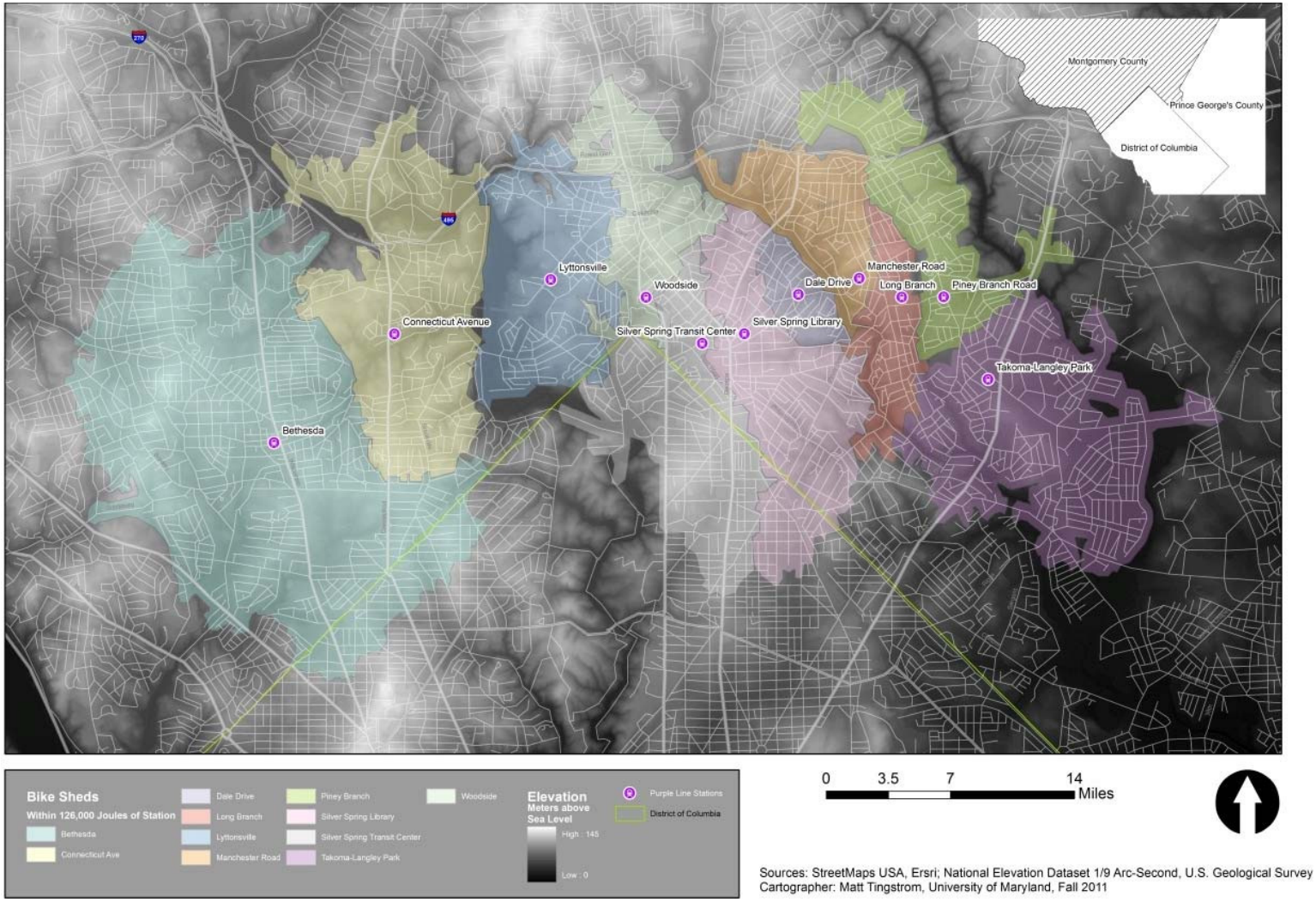
Under Method 3, all street segment slopes obtained from Eq. (2) are treated as absolute values when using the steady-speed power equation (Bicycle Power Equation: Eq. (1)) to calculate per-second energy consumption for each road segment (expressed in watts) that measures travel impedance with the effect of uphill slope regardless of travel direction. The length of each street segment is also divided by the assumed 4 m/s target speed to calculate the amount of time spent to traverse each segment. Finally, the amount of time, expressed in seconds, is then multiplied by the *Watts* value to obtain the total energy consumption in the unit of joules for each street segment. We use the joule values as travel impedance when creating the network dataset to be used by the Network Analyst Service Area function in obtaining bikesheds.

Figure 3 depicts bikesheds identified in Method 3 with elevation in background. Figure 3 shows no overlap between sheds in order to identify the nearest station based on energy consumption and for visual clarity. Hillier areas result in smaller sheds (e.g. Lyttonsville Station), while those with flatter terrain yield bikesheds larger and more spread out (e.g. Bethesda and Takoma-Langley Park stations).

Method 4: Relative Slope Method

The use of absolute slope values in Method 3 essentially means only the "uphill" energy consumption is calculated. An assumption for this method is that a cyclist making a round-trip has to go uphill on one of the one-way trips, and that this affects the distance s/he is willing to bike. In Method 4, we relax this assumption by taking into account the direction of travel, which can either be towards or away from the light rail station. Specifically, following the calculation of the slope Eq. (2), the relative slope for travelling the opposite direction, from end to start points, Slope_EtoS, is obtained by multiplying Slope_StoE by (-1). From these slope values, we again used Eq. (1) to obtain two travel impedance values in joules for each street segment in two travel directions. When steeper segments in the downhill direction result in impedance values that are negative, indicating that the cyclist would not need to pedal to maintain the assumed velocity, these segments are reassigned the value of zero.

Figure 3: Map of Bikesheds Obtained by the Absolute Slope Method

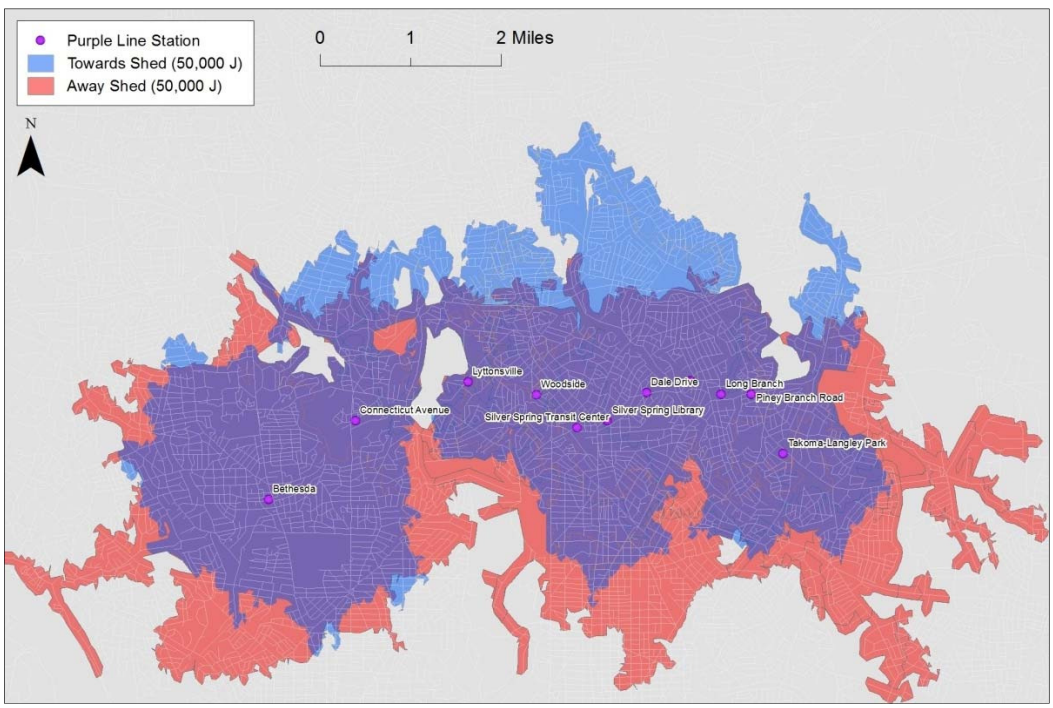


Sources: StreetMaps USA, Esri; National Elevation Dataset 1/9 Arc-Second, U.S. Geological Survey
Cartographer: Matt Tingstrom, University of Maryland, Fall 2011

With two joules values established for every street segment, Method 4 allows us to draw two sets of bikesheds using the ArcGIS Network Analyst Service Area function: (1) a service area with the travel direction set to "away" from the stations and a threshold value of energy consumption, and (2) a second service area with the travel direction set to "toward" the stations and with a threshold value.

Figure 4 demonstrates the basic idea of Method 4, indicating how far one can bike "away" from (blue plus purple) and "toward" (pink plus purple) each station given the same level of energy (50,000 joule*s*). In areas with hilly terrain, these two service areas can cover widely different geographic areas. Purple area presents the overlapping area of the "towards" bikeshed (light blue) and the "away" bikeshed (red). As elevation is generally higher on the north side of the entire area, the "towards" bikeshed extends to the north side and the "away" bikeshed extends to the south side.

Figure 4: Map of "toward" and "away" Bikesheds and Their Intersection Area with the Threshold of Energy Consumption, 50,000 joules



Method 5 Incorporating Intersection Impedance

In the final development of our GIS bikeshed analysis method, we included bicyclist energy consumption at street intersections, in addition to the impedance from each street segment. We estimated the amount of energy consumed to accelerate from 0 to 4 m/s at a rate of 0.4 m/s^2 based on the same cyclist and bicycle characteristics as before[2] to obtain an amount of 1007 *Joules*. Based on the assumption that the bicyclist incurs different levels of impedance depending on type of intersection and the travel direction, energy consumption totals in

[2] Details are available upon request from the authors.

Joules for a single stop at intersections with more than two ways were obtained as shown in Table 3.[3] The last column in Table 3 shows equivalent distance that a cyclist could travel on a flat roadway using the amount of energy expended for each corresponding movement through an intersection.

These intersection impedance values were entered into the ArcGIS Global Turns evaluator, so that they are included in the analysis using ArcGIS Network Analyst Service Area function. Keeping both intersection and street segment impedance in the unit of joules, not only simplifies the use of Network Analyst's service area function, but also shows the relative cost of the two and how they affect a cyclist's energy consumption.

Table 3: Estimated Energy Consumption by Intersection and Travel Direction

Direction	From / Cross / To	# of stops	Joules	Flat Equivalent Distance (m)
Left Turn	Local-Arterial-Arterial	2	2014	285
	Arterial-Arterial-Arterial	2	2014	285
	Arterial-Local-Local	1	1007	143
	Local-Local-Local	1	1007	143
Right Turn	Local-Local-Local	0.5	503	71
	Local-Arterial-Arterial	1	1007	143
	Arterial-Arterial-Arterial	1	1007	143
	Arterial-Local-Local	0	0	-
Straight	Local-Local-Local	0.5	503	71
	Local-Arterial-Local	1	1007	143
	Arterial-Arterial-Arterial	1	1007	143
	Arterial-Local-Arterial	0	0	-

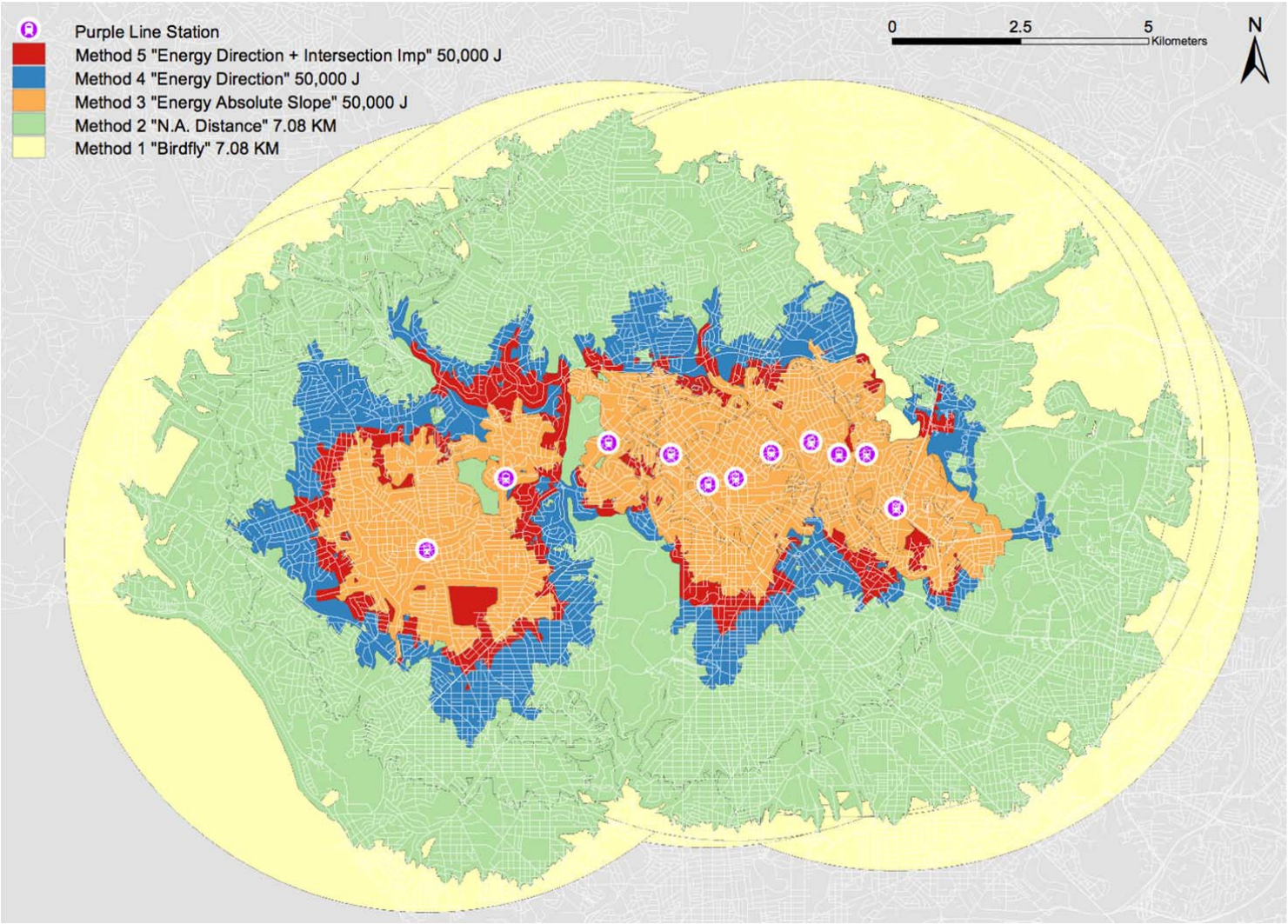
5. COMPARISON OF METHODS IN THE BIKESHED ANALYSIS

This section compares results of the bikeshed analysis using five different methods discussed in the previous section, using the two conventional methods (Methods 1 and 2) and the three methods developed in this study (Methods 3, 4, and 5) with the following conditions. In Method 3, 4, and 5, we used 50,000 joule*s* as a threshold of energy consumption corresponding to a cyclist's decision about whether or not to bike to and from a station. This 50,000 joules translates into 7.08 kilometers (km) of travel distance on a flat terrain without taking into account the effects of slopes.[4] In turn, 7.08 km is used in the two conventional methods. In Methods 2 through 5, the ArcGIS Network Analyst Service Area function allows us to take into account street network connectivity. Figure 5 presents the overall bikesheds obtained by each of five methods.

[3] The values in Table 3 generally assume that a cyclist expends the most energy for a left turn onto an arterial road by crossing via the parallel and perpendicular cross walks as recommended by the California Department of Motor Vehicles (2011), and the least amount of impedance from traveling straight across local roads while on an arterial road.

[4] We obtained 28.23 watts, energy consumption per second to bike on a flat street, by plugging in zero into *s* in Eq. (1). As calculation using a tool on http://bikecalculator.com/ gives us 32 watts, we think 28.23 watts is reasonable. Then dividing 50,000 joules by this 28.23 watts gave us 7.08km of travel distance on a flat land. Since this distance is very close to the average distance of 4.3 miles for trips made entirely by bicycle found in the study in Portland by Dill and Gliebe (2008), we consider it is a reasonable distance for the analysis.

Figure 5: Map of Bikesheds Obtained by Method 1 through 5



After creating 11 bicycle sheds in five different methods—total of 55 bikesheds—total area, total street (center line) length, and average street density were calculated to describe the geographic extent and characteristics of the bikesheds, and compared between the different methods (Figure 6 in a log scale). Figure 5 and Figure 6(a) clearly show the variance in the size of bikeshed by method and by station. The bikeshed areas obtained in the two conventional methods—Method 1 (light yellow circles) and Method 2 (light green)—are substantially larger than the areas obtained in our three new methods: Method 3 (orange), Method 4 (blue), and Method 5 (red), indicating that an analysis that does not take into account the effect of slope on energy consumption leads to an overestimation of the area that cyclists may actually consider biking.

Method 3 results in the smallest bikeshed because the absolute slope analysis assumes, in a sense, the worst case scenario in which cyclists are always pedaling uphill, ignoring the fact that they may go either up- or downhill on the same street depending on travel direction and consume very different levels of energy. Method 4 area (blue) is the *intersection* area of the "away" and "toward" bikesheds within the energy consumption of 50,000 joules in both travel directions. This intersection area, which contains a set of routes that can be reached by bike in both directions, is larger than Method 3 area (orange) because Method 4 allows cyclists to travel on downslopes without consuming energy. While Method 3 is simpler than Method 4 in regard to calculating the bikesheds, the inaccurate estimation of the amount of energy consumed for one-way trips due to a lack of consideration of travel direction and biking on downslopes in Method 3 is a significant limitation. Method 5 results in bikeshed sizes that are between those of Methods 3 and 4. A consideration of impedance, in addition to travel direction and the effects of downslope biking in Method 4, has made the bikeshed smaller, but not as small as the area obtained in Method 3.

Method 1 has the same bikeshed area of 157 sq-km for all station areas as the same straight-line distance was used. The bikeshed area obtained in Method 2 through 5 varies by station:

- Method 2: from 88.3 sq-km in Manchester Road to 108.5 sq-km in Silver Spring Transit Center with the average area of 97.2 sq-km;
- Method 3: from 2.7 sq-km in Connecticut Ave. to 11.2 sq-km in Bethesda with the average area of 6.0 sq-km; the Bethesda station's bikeshed ranked as the flattest and largest based on area and total street length within a bikeshed (Figure 6(b)).
- Method 4: from 10.8 sq-km in Lyttonsville to 26.9 sq-km in Bethesda with the average area of 15.7 sq-km.
- Method 5: from 6.2 sq-km in Lyttonsville to 15.4 sq-km in Bethesda with the average area of 9.0 sq-km.

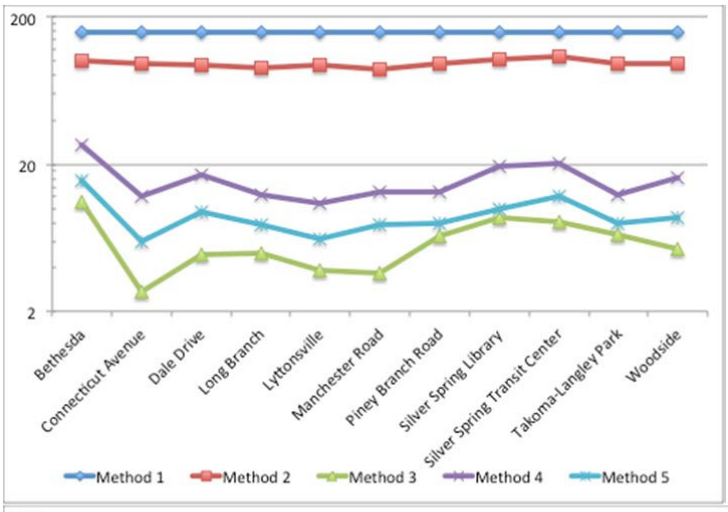
The greatest difference in bikeshed area between Method 4 and Method 5 is found in Bethesda, while the smallest difference is found in Lyttonsville. By normalizing based on the bikeshed area obtained in Method 1, the ratios in bikeshed by method are (Figure 7):

- [Method 1 : 2 : 3 : 4 : 5 = 100 : 64 : 7 : 17 : 10] for (a) Bethesda, and
- [Method 1 : 2 : 3 : 4 : 5 = 100 : 60 : 2 : 7 : 4] for (b) Lyttonsville.

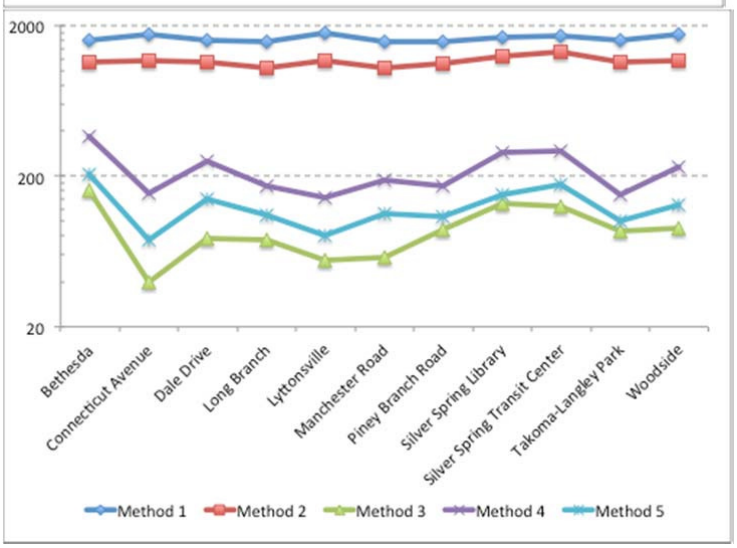
The difference in these two proposed station areas is partly due to the difference in the magnitude of intersection impedance that depends on the density of intersections; the number of intersections found within a 1 km radius circle from Bethesda and Lyttonsville stations are 156 and 73 respectively.

Figure 6: Comparison of Bikesheds

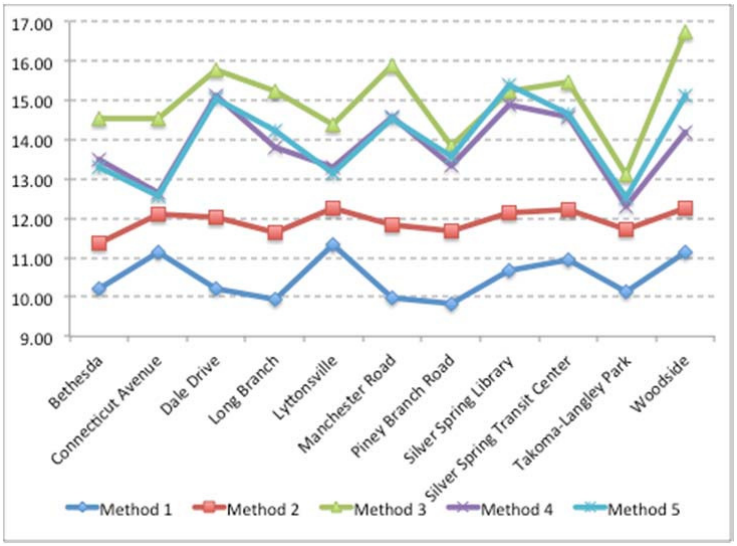
(a) Bikeshed Area (Square Kilometers-km^2; Log-scale)



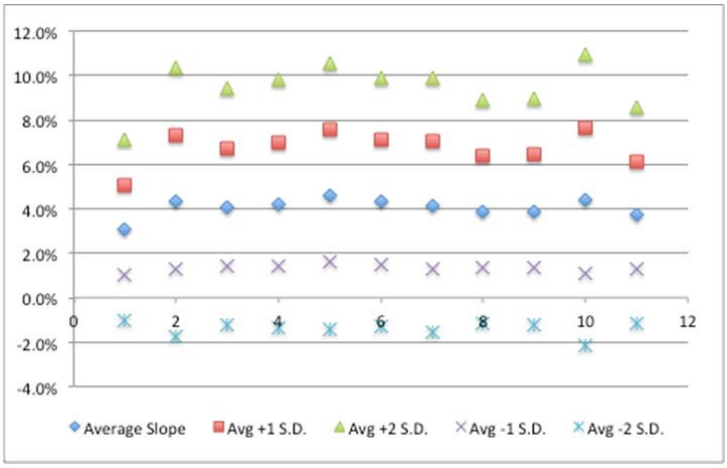
(b) Total Street Length in Bikesheds (Kilometers-km; Log-scale)



(c) Street Density in Bikesheds (1/km)



(d) Slopes (percent) in Bikesheds Obtained in Method 5

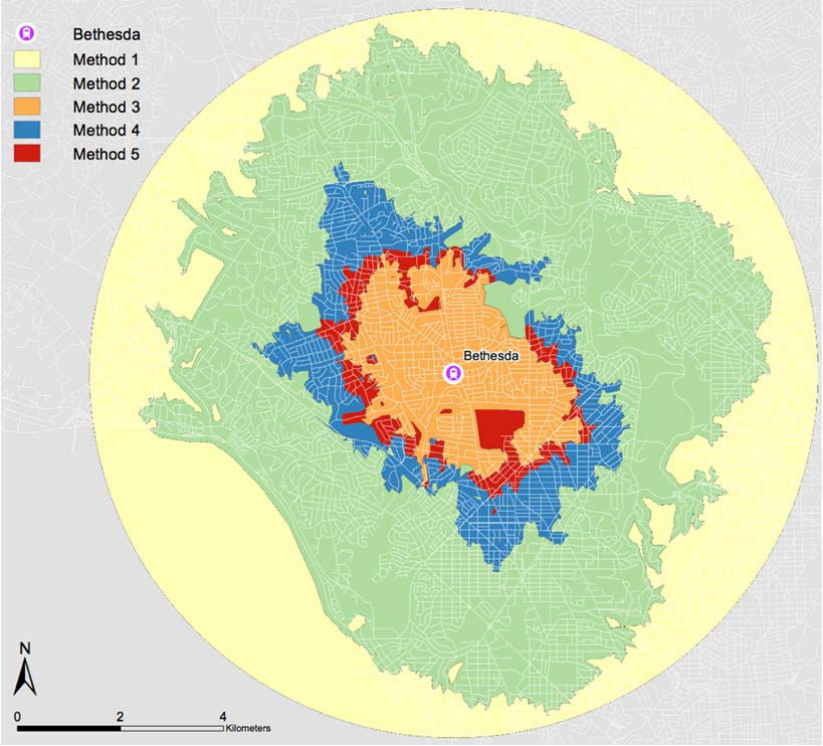


The total street lengths within the bikesheds in Figure 6(b) show the same pattern as the bikeshed areas in Figure 6(a). Total street length is subject to street density as well as the bikeshed size. Figure 6(c) shows street density in each of the 55 bikesheds obtained in the analysis. The first thing to note is that street density of the bikesheds obtained by Methods 1 and 2 are substantially lower than those in the other methods, indicating that, in general, street density decreases as one travels farther from a proposed station. This makes sense, as it is likely that light rail stations are built in higher density neighborhoods to attract more passengers. Among Methods 3, 4, and 5, five stations—Long Branch, Piney Branch Road, Silver Spring Transit Center, Takoma-Langley Park, and Woodside—show a monotonous decrease in street density as bikeshed area increases from Method 3 to Method 5 and then to Method 4. In contrast, in five station areas—Bethesda, Connecticut Avenue, Dale Drive, Lyttonsville, and Manchester Road—street density is highest in the stations' immediate neighborhoods (Method 3), but does not monotonously increase as the distance from each station increases. In the case of Silver Spring Library, Method 5, instead of Method 3, shows the highest street density. In addition, Piney Branch Road and Silver Spring Library differ less in street density among our different Methods, compared to the other station areas.

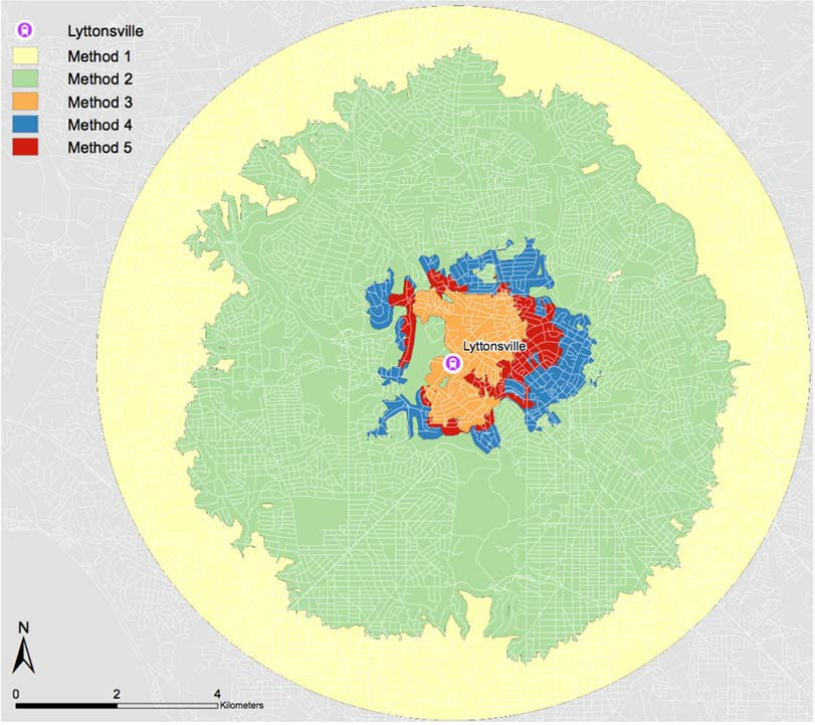
Figure 6(d) compares the slope values of the average, one-standard deviation, and two standard deviations among street segments within the bikesheds obtained in Method 5. Comparing the two station areas in the previous two cases—Bethesda and Lyttonsville—the average value of slope is 3.1% and 4.6%; the values of two standard deviations are 7.1% and 10.5% respectively. As expected, the higher values of slope have a larger variance. Although these values give a sense of the topography in the areas, they do not provide any information of spatial distribution of steep slopes. As demonstrated in Figure 1(c), a bikeshed becomes smaller when steep slopes characterize station's immediate neighborhoods than when slopes are found in a distance from a station, even though both cases may have similar average values of slopes. Note an area on the west side of the proposed Lyttonsville station that is not included in bikesheds in Method 3, 4, and 5 in Figure 7(b). This area is a valley with a creek with very limited street access. This difficult-to-access area near the station has substantial impacts that reduce the overall bikeshed size.

Figure 7: Identified Bikesheds in Method 1 through 5 in Bethesda Area and in Lyttonsville Area

(a) Bethesda



(b) Lyttonsville



6. CONCLUSION

In this study, we developed the GIS bikeshed analysis methods to combine street slope, distance, street connectivity, and energy consumption of biking into a single travel impedance factor measured in joules, and use this factor, instead of travel distance or time, in the ArcGIS Network Analysts to identify bikesheds. Based on our review of the literature, we found no prior examples of GIS-based bike planning analysis that considers energy consumption of traveling. Consideration of street slopes, energy consumption of biking, and street network connectivity significantly reduced the size of bikesheds and total street length within bikesheds. This indicates that an analysis without considering these factors will result in a substantial overestimation of bikeshed and biking demand level where steep slopes and circuitous roadway network can be seen in a study area. In addition, since topography and street network connectivity vary in different directions, the shape of bikeshed is far from being a circle, which is used in a simple buffer analysis. This difference implies the uneven catchment area of bikesheds, depending on the direction from an origin of bikeshed analysis—light rail stations in the case of our study. While part of findings in this paper could be obvious to those who know local topographic conditions, the geographic distribution of slopes makes it difficult to predict the effects of topography on the size and shape of bikesheds based on any simple summary indicator of street slopes.

The inclusion of intersection impedance also has substantial effects on the size and shape of bikesheds. This also has an importance implication as cyclists usually want to preserve kinetic energy, and therefore tend to avoid stops or even slowing down at intersections, as the *Idaho* (or *rolling*) *stop law* allows cyclists to treat stop signs as yield signs at intersections when it is safe to do so. The adoption of this law and bike planning to eliminate stops and keep continuity of bike paths—such as done in the City of Portland—can be clearly captured in the last method proposed in this paper.

One methodological limitation in the study presented is that slopes were estimated based on the difference between the segment's start and endpoints and the planar distance between them. While this method helps establish the average slope between the two points, it does not take into account any changes that may occur between them. For example, a street segment over a hill may have its maximum elevation somewhere between its endpoints, which this method currently would not capture. This risk of underestimating of slope could be reduced by dividing road segments into shorter segments and thus increasing the frequency with which the elevation in the street network is surveyed.

The methodology described in this paper can be improved in order to increase accuracy in a bike demand analysis in relation to fixed-route transit stations, stops, and terminals. First, the network dataset used could include bike trails or paths that are not contained in a street shapefile readily available to the public. Although such trails and paths seem to be limited in the study area, its addition will likely affect connectivity in a bikeshed analysis. In addition, demographic information of residents and workers in an analysis area could be taken into account to conduct a bike demand analysis.

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