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Bicycle Accessibility GIS Analysis for Bike Master Planning with a Consideration of Level of Traffic Stress (LTS) and Energy Consumption

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Abstract: Measuring the impact of bicycle infrastructure and other mobility improvements has been a challenge in the practice of transportation planning. Transportation planners are increasingly required to conduct complex analyses to provide supporting evidence for proposed plans and communicate well with both decision makers and the public. Cyclists experience two important factors on roads: (a) travel stress related to the built environment along with the traffic conditions and (b) changes in physical burden due to topography. This study develops a method that integrates an energy consumption calculation and "bicycling stress" score to take into account external conditions that influence cyclists substantially. In this method, the level of traffic stress (LTS) is used to select street segments appropriate for different comfort levels among cyclists and is combined with biking energy consumption, in addition to distance, which is used as travel impedance to consider the effects of slopes and street intersections. The integrated Geographic Information System (GIS) analysis methods are used to evaluate bicycle infrastructure improvements in the coming years in Montgomery County, MD, USA. The analysis results demonstrated that the infrastructure improvements in the county's bike master plan are well-targeted to improve bicycling accessibility. Furthermore, the use of energy as opposed to distance to generate bikeshed areas results in smaller bikesheds compared to distance-generated bikesheds. The method presented herein allows planners to characterize and quantify the impact of bicycle infrastructure and prioritize locations for improvements.

Keywords: GIS; transportation; bicycle; traffic; energy consumption; transportation planning; bicycle infrastructure planning

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1. Introduction

Bicycle planning has become an important part of local transportation planning in urbanized areas in the US. In that context, Geographic Information System (GIS) is used in a variety of tasks, ranging from simple mapping to advanced analysis. Examples include understanding factors influencing mode choice (Dill & Voros, 2006 [1]), mapping the location and quality of bicycle infrastructure to identify areas of high and low bikeability (Greenstein, 2015) [2], and using vector data to understand the connectivity of the bicycle network (Mekuria, et al., 2012) [3]. GIS analyses allows for better understanding of where bicycle infrastructure needs to exist and how it should be prioritized.

The Montgomery County Planning Office, Maryland, has developed GIS analyses for use in their Bicycle Master Plan and future bicycle infrastructure planning (Maryland-National Park and Planning Commission: Montgomery County, 2018a) [4]. Montgomery County's bicycle accessibility model allows analysts to impose constraints on the bicycle network by removing segments with a level of traffic stress (LTS) exceeding a certain tolerance from the traversable network. The planning office utilizes the LTS method in a variety of GIS analyses, including prioritization of proposed infrastructure, identification of gaps in the existing network, and minimization of travel along higher-stress streets. Transportation planners slightly modified the LTS proposed by Mekuria, et al. (2012) [3] which accounts for the level of safety perceived by existing and potential cyclists who have different levels of tolerance regarding risk and stress in biking. This method classifies streets by the number of vehicle traffic lanes, traffic speed, and attributes of bicycle infrastructure. The modified LTS method employed by the Planning Department is slightly more nuanced to accommodate local variations in the road network in Montgomery County (Maryland-National Park and Planning Commission: Montgomery County, 2018c) [5].

The study presented here integrates an energy consumption method proposed by Iseki and Tingstrom (2014) [6] with the Montgomery County LTS GIS analysis. The integrated method allows for the delineation of bicycle catchment areas (bikesheds) using biking energy consumption as a travel impedance and LTS values as a traversability restriction. Utilizing energy consumption enables analysts to consider elevation change by incorporating effort, or energy, required to complete the trip as a variable expressed in joules. Using this energy consumption impedance, a bike accessibility analysis was conducted with metro stations and high schools as trip origins. Although the importance of topography has been noted in other studies, few have incorporated elevation change into analyses and none have combined energy consumption with an evaluation of the quality of the bicycle network as provided by the LTS method.

The analyses findings indicate that County-planned bicycle improvements are well targeted to increase multi-modal transportation options and accessibility to significant community assets under both modes of analysis. The energy consumption model for bikesheds may, however, prove useful in refining the locations of proposed bicycle infrastructure improvements due to the smaller bikesheds created using the method, offering a conservative estimate of accessibility.

This study will highlight recent literature on GIS analyses in bicycle planning, energy consumption methods, and LTS methods. A summary of data sources and methods used in this study will then be discussed, followed by analysis results. The conclusion will include a brief summary of findings, limitations to be addressed, and planning implications.

The model presented herein is introduced as an alternative method to traditional distance methods, which fail to take topography into account when assessing accessibility. Combining these methods with an index of biking stress level allows for a more nuanced understanding of accessibility and of the characteristics relevant to creating successful transportation networks. The energy consumption model detailed in this paper is of particular interest to planning practitioners, as it contributes to current issues faced in the field.

2. Literature Review

In recent practice, transportation planners have increasingly incorporated a number of variables in GIS analysis to more accurately reflect current conditions in bike infrastructure, the built environment, and traffic conditions. Variables including the type of bicycle infrastructure, the posted traffic speed, conflicts or obstacles, and the quality of the infrastructure have been incorporated to more accurately describe and understand the motivations of cyclists, gaps in bike networks, and the location of priority service areas in order to implement multi-modal transportation systems (Necessary, 2016) [7]. Studies increasingly acknowledge the complex social, economic, and environmental impacts of mobility (Dill & Gliebe, 2008; Reilly & Landis, 2002; Scott & Ciuro, n.d) [1,8,9], but some argue that these tools and methods are limited in their ability to accurately describe the characteristics of bicycle infrastructure (Necessary, 2016) [7].

Studies on bicycle accessibility tend to identify similar factors that encourage or discourage biking. Conceptually, these factors are considered to lower generalized costs of biking, so that biking becomes a more viable alternative to other modes of travel. The range of factors consistently given the highest weight in recent literature are associated with existing bicycle infrastructure. This includes protected and unprotected bicycle lanes (Greenstein, 2015) [2], trails (Mekuria, et al., 2012) [3], quality of the infrastructure (Necessary, 2016) [7], and other features meant to reduce the stress of cyclists through perceived or actual safety (Greenstein, 2015) [2]. In an Austin bikeability study, bicycling stress was assigned the highest weight amongst other variables, in congruence with studies conducted in Portland, Seattle, and Vancouver (Greenstein, 2015) [2]. These studies agree that perceived safety is a primary factor in inducing more bicycle trips (Dill & Carr, n.d; Greenstein, 2015; Foster, 2014) [10,11].

Another factor consistently mentioned in studies on biking is the street network itself. As Greenstein (2015) [2] notes in her analysis, "As connectivity increases, travel distances decrease and route options increase". A street network with more connections allows cyclists to choose a route that avoids streets with heavy traffic, substandard bicycle infrastructure, or significant changes in elevation. In assessing network connectivity, studies frequently include measures of infrastructure and conclude they are one of the most important factors in increasing the appeal and ease of biking. (Parast 2010; Geller, et al. 2009; Cervero & Duncan, 2006; Reilly & Landis, 2002; Winters & Cooper, 2008 [8,12–15]).

Level of traffic stress (LTS) and level of service (LOS) methods have been proposed for evaluating the stress and perceived safety cyclists experience. Mekuria, et al. (2012) [3] assigns a numeric LTS value (1, 2, 3, or 4) to road segments based on traffic attributes such as speed, signalization, and daily traffic volume before factoring in the bicycle infrastructure (protected lanes, bikeable shoulders, and bicycle-only trails). The lower the number, the "safer" the road segment is for cyclists. Level of service (LOS) methods rely on street segment designations defined by user level of satisfaction. While both methods assign scores to road segments, LOS adds a level of detail beyond simply using bicycle facilities and traffic speed. In practice, this has been accomplished through video surveys and field rides (Foster, et al., 2015; Jensen, 2007) [16,17], as well as mathematical approaches which quantify perceptions of satisfaction (Foster, 2014; Okon, et al., 2017) [11,18]. The LTS method is generally preferred in practice because it is less data-intensive than the LOS method (Mekuria et al., 2012) [3].

The influence of slope and of elevation on bicycling are points of contention. While slope has not been statistically proven to influence cycling (Cervero & Duncan 2003; Dill & Voros, 2006) [19,20], Cervero and Duncan (2003) [19] utilized discrete-choice logit modeling to identify a correlation between walking and slope. They remark that there are likely similarities between the two travel modes. Other studies have included slope as a variable but provided it with a lower weight than other factors, such as bicycle infrastructure and network connectivity (Greenstein, 2015) [2]. However, differences in rider profiles (recreational and commuting, for example) may account for the differences in results (Greenstein, 2015) [2]. Macias (2016) [21] also found that incorporating infrastructure characteristics has a greater impact on the size of pedestrian catchment areas than changes in elevation.

One common method of capturing the "maximum travel cost" pedestrians or cyclists are willing to spend is by producing catchment areas. This is done by computing an impedance (like a travel time or a distance) for a segment of the network (such as a block). A simple catchment area can be computed using a time impedance (the length of a segment divided by an average speed) or a distance impedance (using the length of the segment). Iseki and Tingstrom's study (2014) [6] demonstrates a new method of calculating catchment areas by incorporating slope and using energy as an impedance value instead of distance. The method attributes values to road segments based on the energy required to traverse them, calculated from a function of the speed of the cyclist, the distance of the segment, wind resistance, tire resistance, and the slope of the road segment. The study demonstrates that this method can incorporate both slope and the road network to generate a detailed bicycle catchment area.

Following the trends to identify interconnecting factors impacting bike transit, Macias (2016) [21] found that conventional methods of determining catchment areas "can misjudge factors that are important in determining walkability and transit-oriented development." Distance-calculated catchment areas illustrate network connectivity without expressing other infrastructure characteristics (Necessary 2016) [7] and do not adequately describe accessibility. Researchers have begun recognizing the importance of topography and incorporating it into the creation of pedestrian catchment areas. Consistently, this new method has been found to produce smaller areas (Macias, 2016; Daniel & Burns, 2018) [21,22], regardless of differences in impedance calculation. While Macias (2016) [21] calculated average slope and pedestrian power values, Daniel and Burns (2018) [22] used time as impedance.

Although the importance of topography, as well as traffic stress, has been noted in the aforementioned studies, none have combined energy consumption with an LTS method to the best of our knowledge. A method of developing bicycle catchment areas is necessary to inform bicycle infrastructure and illustrate characteristics influencing biking access. The existing studies on micromobility (Greenstein, 2015; Parast, 2010) [2,14] assess access at a geographic area level rather than examining the impact of individual improvements. This paper demonstrates a methodological approach that can be used to evaluate the accessibility of micromobility improvements by combining the level of traffic street (LTS) method of facility classification with the energy consumption method by Iseki and Tingstrom (2014) [6] to develop nuanced service areas for micromobility infrastructure. This method enables planners and researchers to evaluate the impact of proposed infrastructure improvements and quantify the accessibility of destinations.

3. Description of Study: Study Area, Data, Data Sources, and Analytical Methods

This study enhances the existing model capability by incorporating consideration of topography and demonstrating how the results from the distance and energy consumption methods differ. In this study, we worked with the Montgomery County Planning Department, Maryland to complete an accessibility analysis for bike planning.

Montgomery County is located adjacent to Washington, D.C., and is among the most populous and affluent counties in the state of Maryland. It has several large population centers, with density primarily located along the Interstate 270 corridor leading to the nation's capital. In 2018, the county developed a Bicycle Master Plan with the goal of enabling bicycling to become a viable transportation option and creating a "world-class bicycling community" (Maryland-National Park and Planning Commission: Montgomery County, 2018a) [4] (The implementation of the recommendations made in the BMP is ongoing. Readers with an interest in the list of proposed improvements as well as their implementation status can check the "Montgomery County = Bicycle Master Plan" and "2019–2020 Bicycle Master Plan Biennial Monitoring Report" available at https://montgomeryplanning.org/planning/transportation/bicycle-planning/bicycle-master-plan/, accessed on 25 August 2022). The proposed extensive bicycle infrastructure planned for in the Bicycle Master Plan includes the addition of bikeable shoulders, neighborhood connectors, neighborhood greenways, off-street trails, priority-shared lane markings, separated bike lanes, side paths, and trails. A map of planned improvements is shown in Figure 1.

For the creation of its Bicycle Master Plan, the county relied on research from a consultant to classify high rates of bicycling, low rates of bicycle crashes, and high levels of satisfaction with bicycling conditions as the necessary components of a "world-class" bicycling network. In pursuance of these goals, the county established three elements for its plan: safety, comfort, and connectivity. To identify necessary changes to the existing infrastructure, the county conducted its own LTS analyses. Bikeways were prioritized through a demand model that relied on information from the LTS network and the percentage of dwelling units located on low-stress roads within 2 miles of key destinations. The county also created a matrix of trips likely to generate the most bicycling based on clusters of homes and jobs, proximity to key destinations, and connectivity between activity hubs.

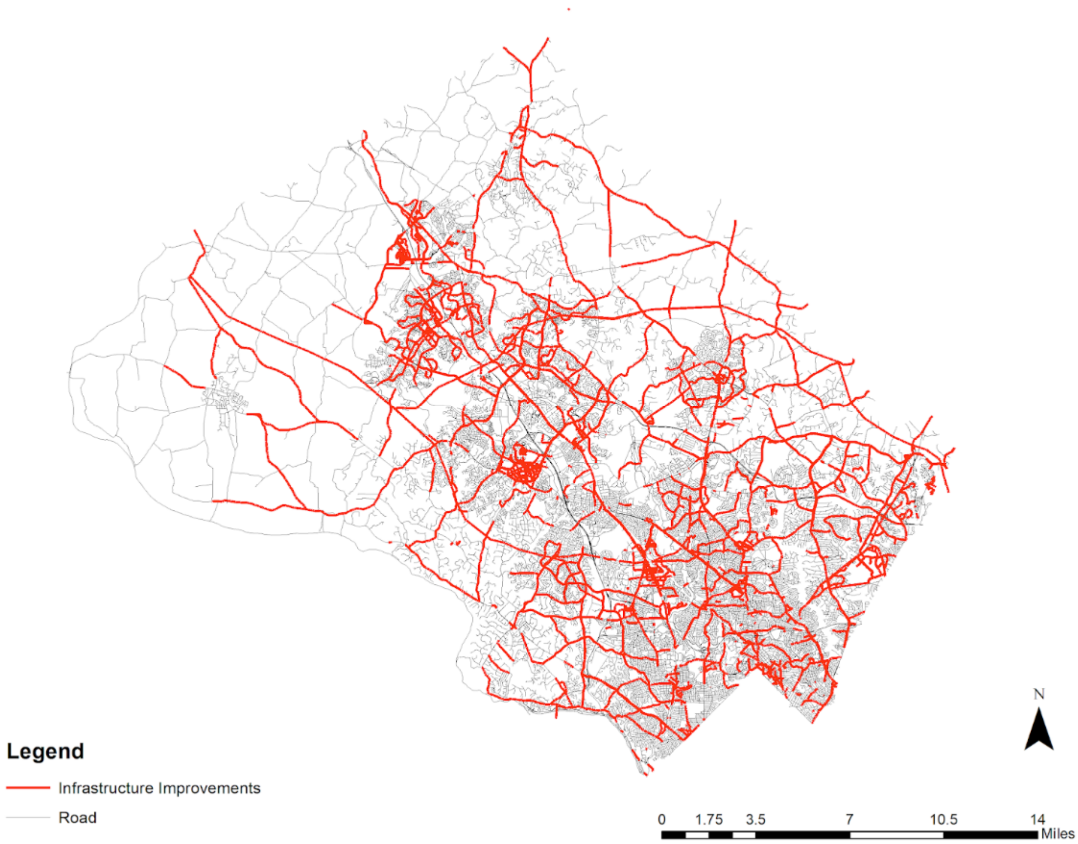

Figure 1. Planned Bicycle Infrastructure Improvements. Note: This map was created by the authors based on the data obtained from the Montgomery County Planning Department. The Bicycle Master Plan identified and selected more than half of these proposed improvements as new infrastructure.

3.1. Data and Data Sources

Shapefiles for Montgomery County Metro Stations, Purple Line Stations, Public High Schools, and Capital Bikeshare Stations were obtained from the Montgomery County GIS Open Data site [23–27]. Elevation data was obtained from the 3D Elevation Program (3DEP) of the United States Geological Survey (USGS) [28]. Bicycle network GIS files were originally provided by the Montgomery County Planning Department for this study via direct contact. The network included centerline data and characteristics of each road segment with the current infrastructure's LTS and planned LTS, based on the County's evaluation of the infrastructure in place (Maryland-National Park and Planning Commission: Montgomery County, 2018b) [29], after the construction of new infrastructure under their BMP (hereafter referred to as existing and planned infrastructure). The BMP proposes extensive improvement projects including the addition of bikeable shoulders, neighborhood connectors, neighborhood greenways, off-street trails, priority shared lane markings, separated bicycle lanes, and side paths. It identifies more than half of these proposed improvements as new infrastructure (Maryland-National Park and Planning Commission: Montgomery County, 2018a) [4].

3.2. Analytical Methods

Variables for bicycle infrastructure and perceived safety used in this study were the LTS values assigned to each road by the Montgomery County Planning Department (Maryland-National Park and Planning Commission: Montgomery County, 2018c) [5]. As a part of Montgomery County's BMP, street segments were surveyed and assigned a level of stress value related to traffic conditions and bicycle infrastructure. The survey is based on the method proposed by Mekuria, et al. (2012) [3] Montgomery County relied on the following variables to determine LTS values: the number of traffic lanes, speed limit or prevailing speed, frequency of on-street parking turnover, presence of a bikeway facility, presence of right turn lane(s), length of the right turn lane, turn lane configuration, the width of the cross street, the speed limit of the cross street, and the presence or absence of median refuge. These variables were identified as factors impacting cyclist stress, as well as being commonly available and easily measured (The method considered no daily or seasonal variations in traffic speed and volume, which could be affected by the factors, such as rush hour, snow impedance, lighting, and the occurrence of holidays. Traffic speeds used are posted speed limits, and traffic volume is the average daily traffic. Local governments do not collect data on local traffic volume so often to find out seasonal variations party because they are usually concerned with the maximum traffic volume). All criteria were scored individually and then aggregated based on the "weakest link" logic. In other words, the aggregation is not a summation of multiple scores but is based on the highest stress score among all criteria for each street segment. Even if a street segment had mostly low-stress characteristics, the occurrence of a single higher-stress attribute dictated the stress level for the segment.

In addition to the four levels of LTS (1, 2, 3, or 4) in the study by Mekuria, et al. (2012) [3], the Montgomery County Planning Department included three additional stress values—0, 2.5, and 5 in order to provide more nuance. LTS 0 identifies completely separated bicycling infrastructure such as separated paths and trails; LTS 2.5 sought to create a middle option between LTS 2 and LTS 3 to indicate a street that has some additional stress factors but may still be traversable to relatively unskilled cyclists; LTS 5 identifies roads with very high-speed limits and little to no bicycle infrastructure. In summary, the department used these rules to develop and implement a complex scoring system for each segment of the bicycle network. As such, each segment of the network has an LTS score based on its vehicle traffic load and speed and the type of bicycle infrastructure provided (Maryland-National Park and Planning Commission: Montgomery County, 2018c) [5].

As the first step in calculating the level of energy consumption, the street network was divided into smaller segments using a 100 m by 100 m fishnet. Elevation was extracted to the start and end points of the line segments from USGS DEM elevation layers. These points were then used to calculate the actual length of the road segment, accounting for elevation change, and to calculate the slope for each line segment.

Using the method proposed by Iseki and Tingstrom (2014) [6], an energy consumption value (in watts) was calculated for each line segment using the following equation and values, allowing for drag factor (D), velocity (V), rider mass (M), gravity (g), slope (S), tire resistance (R), and adjusted length (L):

$$\text{Energy} = ([D \times (V)^2 \times M \times g \times (S + R)] \times V) \times [L/V] \tag{1}$$

where D = 0.245; V = 4.0; M = 80; g = 9.807; R = 0.004.

This formula quantifies the energy required to traverse the road segment at a constant speed. After creating a network dataset, energy penalties for turns based on the street type (local, secondary, or primary) were created, also taken from the study by Iseki and Tingstrom (2014) [6].

Based on the assumption that people will not bike on street segments with an LTS higher than their tolerance level, the maximum LTS is selected for each run of analysis as a restriction in a path-finding analysis. Because Montgomery County's LTS index is comprised of seven values, the accessibility models in this analysis can display fourteen different scenarios based on the stress tolerance values selected and the method used.

The resulting bikesheds were limited at either 4.4 miles or 50,000 joules; the distance limit was proposed by Iseki and Tingstrom (2014) [6] while the latter is its energy equivalent over flat terrain. Energy consumption was calculated to and from each location (as a trip destination and origin) to account for a direction-dependent change in energy and the intersection of the resulting bikesheds was used for comparison with distance method bikesheds. The proposed model assumes an adult rider at 80 kg which should be adjusted, together with distance/energy cutoffs, for younger riders.

The method proposed by Iseki and Tingstrom (2014) [6] was the first to incorporate energy consumption into bicycle planning in 2014. Other studies that have used topography as a factor have used a raster analysis which weighted the average slope of an area, along with a variety of factors (Greenstein, 2015) [2]. This study considers LTS and topography for individual roads to generate a catchment area, rather than conducting a raster analysis of weighted scores. The results demonstrate a more granular view of bicycle accessibility.

4. Analysis of the Results

The developed method was applied to two types of bicycle accessibility analyses. The results showed that the energy consumption method generates significantly smaller bikesheds than those generated by the distance method. Furthermore, these results show that the planned improvements under the BMP of Montgomery County metro stations and public high schools, beginning at the least restrictive levels of stress. Metro stations' low LTS bikeshed areas will grow between 864% and 2003% as a result of the planned improvements and those of public high schools will increase between 817% and 1590% at the none LTS.

4.1. Metro Station Bikeshed Scenario Analysis

Sixteen scenarios were created with Montgomery County metro stations as destinations. Each scenario was generated using either the distance or energy method (with cutoffs of 4.4 miles and 50,000 joules) and incorporates stress level index scores. Four different stress level scores, ranging from low (value of 2) to high (value of 5), were included. These values were chosen to demonstrate the differences in bikesheds based on rider profiles. Low (value of 2) represents the highest stress value accepted by novice cyclists while high (value of 5) represents the highest accepted stress value for most advanced cyclists. These designations represent the County's profiles when assigning values to road segments which itself is based on the classification scheme proposed by Mekuria et al. (2012) [3]. Under this approach, LTS 2 is identified as the standard for bicycle facilities most adults will feel comfortable with and increasing LTS values are classified as only being acceptable to veteran cyclists. These four stress level index values were tested using both distance and energy methods. Finally, the current infrastructure was compared with the planned infrastructure.

Table 1 and Figure 1 show how the energy-LTS method delivers smaller estimations compared to a distance-LTS methodology. While both methods show an increase in the accessible area, the gain calculated using the energy-LTS method is less than half (48%) of the distance-LTS method for the lowest stress level (2). The shape of the bikesheds is also of interest. Because the energy-LTS method requires an overlap of the destination and origin trips; the resulting bikesheds can be lopsided in specific directions. In particular, areas with continuous slopes (rather than changes in slope) face greater penalties, limiting the size of the bikeshed.

Table 1. Change in bikeshed area from existing to planned infrastructure by percentage and square mileage using the energy consumption and distance methods with the LTS method.

	Percent Gain (%)		Area Gain (mi^2)		Existing Total Area (mi^2)		BMP Total Area (mi^2)	
	Energy	Distance	Energy	Distance	Energy	Distance	Energy	Distance
Level of Stress: 2	+2003	+864	+53.98	+110.64	2.70	12.80	56.68	123.44
Level of Stress: 3	+123	+67	+31.22	+49.53	25.46	73.91	56.68	123.44
Level of Stress: 4	+38	+13	+15.73	+13.89	40.95	109.54	56.68	123.44
Level of Stress: 5	+26	+8	+11.80	+9.20	44.87	114.24	56.68	123.44

In both methods, scenarios using the planned infrastructure improvement stress level values produce the same area. This indicates major upgrades along the most stressful roads. There appear to be significant proposed changes to existing infrastructure, such as the implementation of a new bicycle trail along an electric corridor and bicycle improvements along major, inter-county thoroughfares. These types of improvements allow for biking along primary connectors which previously had prohibitive LTS values. Gains decreased as the level of stress tolerance increased because most infrastructure improvements were directed at network segments with a high level of stress. The gains at the high level of stress are a result of new infrastructure, such as bike trails.

Table 1 shows the sizes of bikesheds obtained in 16 scenarios, depending on the allowable LTS and impedance method used, as well as the changes in bikeshed area and percentage from the current conditions to the planned state under the BMP. The change in the stress level scores for a large number of major roads results in large changes in the area of the bikesheds for both methods. The energy method has large changes in the size of the bikeshed. However, the size of energy bikesheds is still significantly smaller than bikesheds generated using the distance method. Changes in bikeshed areas are shown in Figure 2.

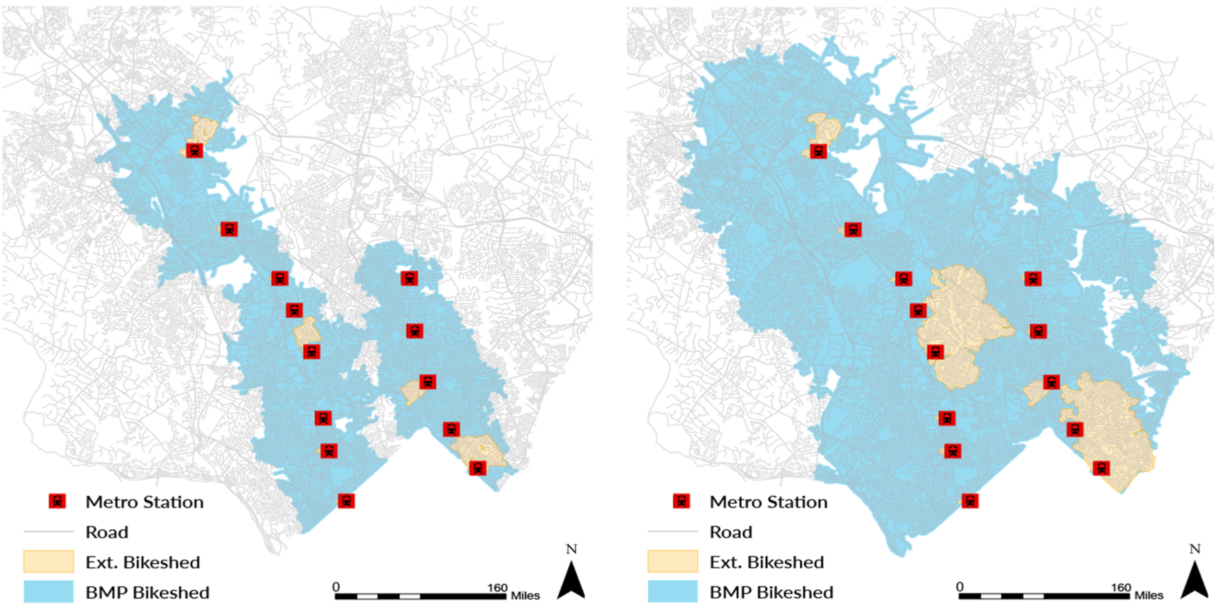

Figure 2. Existing vs. planned infrastructure at a low-stress level using the energy consumption and distance methods with the LTS method. Note: The left map shows existing and planned bikesheds at the low stress level using the energy consumption method. The right map shows existing and planned bikesheds at the low stress level using the distance method with the cutoff values of 50,000 joules and 4.4 miles.

4.2. High School Accessibility: Bikeshed Scenario Analysis

Bikesheds were created at every level of stress for 25 of 26 Montgomery County public high schools as trip origins (excluding one vocational/technical high school without feeder schools). These were created for existing and planned bicycle infrastructure, using distance (with a limit of 4.4 miles) and energy consumption methods (with a limit of 50,000 joules). As was found in the analysis of metro stations, the bikesheds with a 4.4-mile limit exceeded those with a 50,000 joule limit in the area at every LTS.

Like the comparison of metro station bikesheds, biking accessibility to high schools with current infrastructure is limited and does not exceed 30 square miles county-wide until reaching a “moderate high” level of stress (LTS 3). As shown in Figure 3, the resulting improvements from the Bicycle Master Plan to lower the LTS so that it is not a factor in the creation of bikesheds for most LTS values. The change in area is much more dramatic for distance-based bikesheds than for energy consumption-based bikesheds. This is related to significant elevation changes in the study area.

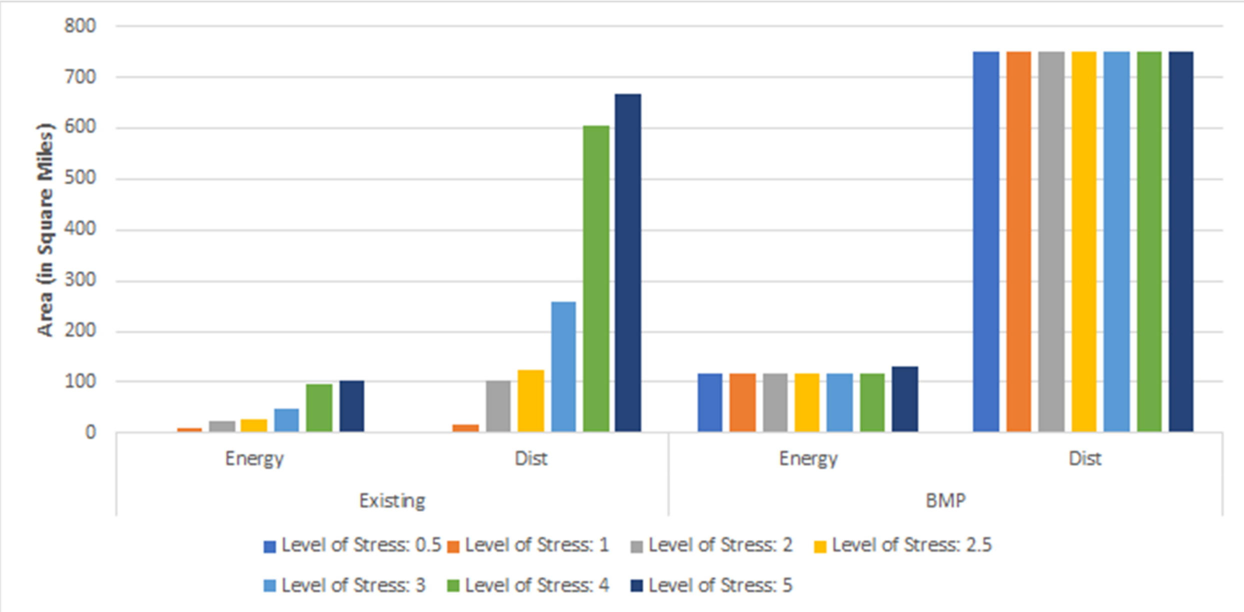

Figure 3. Area of bikeshed in square miles for all LTS values using the energy consumption and distance methods with the LTS method.

Currently, only one high school, Thomas S Wootton, is accessible at no level of stress (LTS 0.5) using the energy consumption method. All high schools are accessible using the distance method, but their total area constitutes less than one square mile. In fact, it is only at the low level of stress (LTS 2 or less) that every school becomes traversable with both methods (Figure 4). Even then, 24% of the 25 high schools have extremely small bikesheds; for example, Paint Branch High School's distance method—the larger of its two bikesheds—has an area of 0.01 square miles. Each of the six schools (Damascus, Seneca Valley, Quince Orchard, Gaithersburg, Walter Johnson, and Paint Branch) with extremely low accessibility is located on street segments with moderate high or higher LTS values (equal to 4 or higher) and with limited or no biking infrastructure. Those same six schools do not see any significant improvement in accessibility until the LTS is raised to the moderate high level, at which some schools still have limited accessibility in a bikeshed obtained in the energy consumption method. This isolation of energy consumption bikesheds contrasts with the connectivity of the distance consumption bikesheds.

Table 2 compares the sizes of bikeshed obtained in 28 scenarios, depending on the assumed LTS (7) and distance/energy method used (2), and shows bikeshed area and percentage changes from current conditions to the planned state (2). The planned infrastructure would increase the energy consumption model accessible square miles by 1590% and the distance model accessible square miles by 817% at no level of stress (LTS 0.5). Rates of improvement are highest at the lower LTSs, reinforcing the findings from the metro station bikeshed analysis. The significant increase in accessible square miles supports the metro analysis conclusion that improvements were well planned and indicates that one of the most significant barriers to current accessibility is the lack of appropriate infrastructure. The smaller gains at higher levels of stress coincide with the county's stated intent to minimize travel along higher-stress streets. The large gains at lower levels of stress illustrate the county's ability to successfully identify network gaps and increase connectivity between activity hubs.

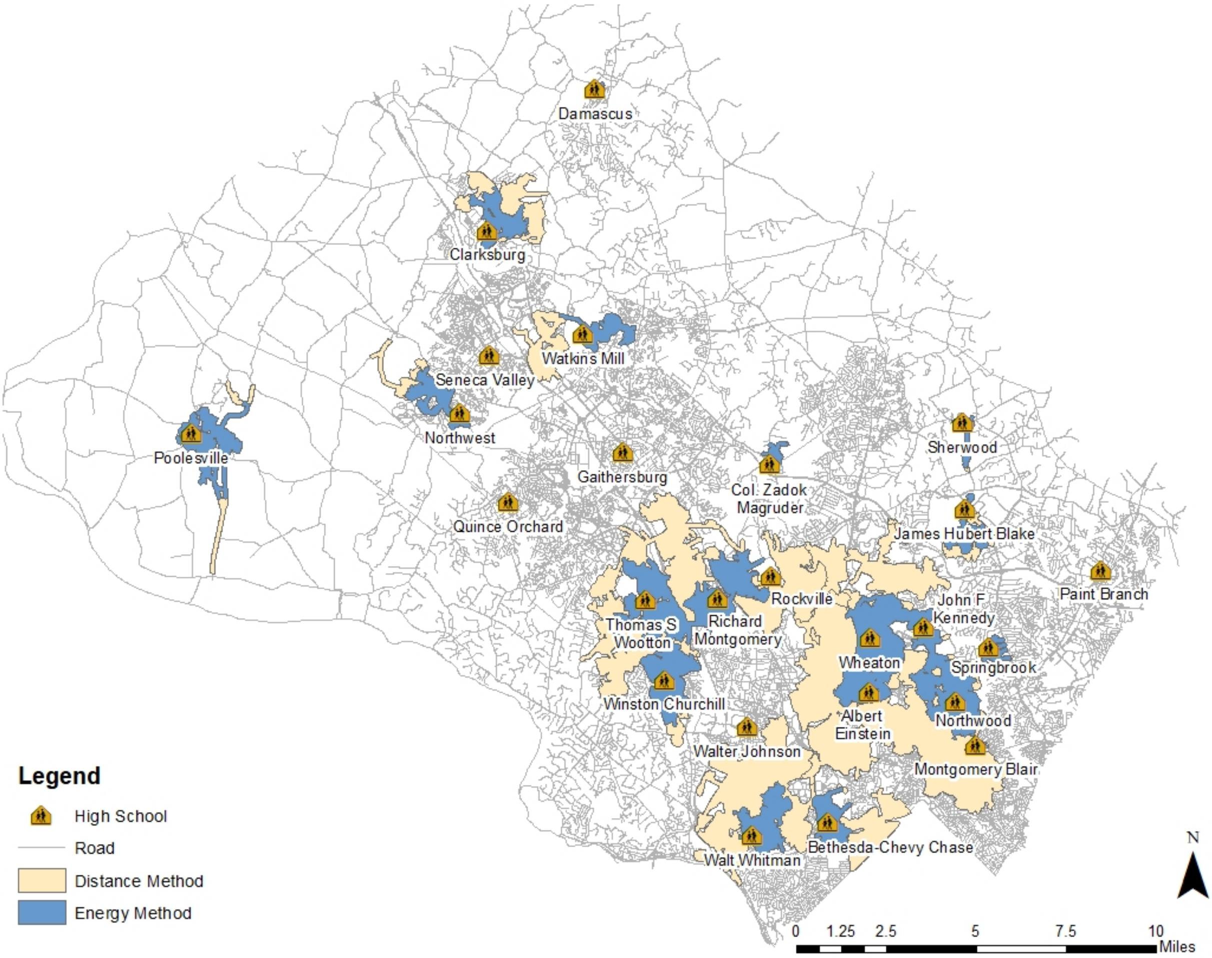

Figure 4. Difference in bikeshed area at the low level of stress using existing infrastructure using the energy consumption and distance methods with the LTS method.

Table 2. Change in bikeshed area from existing to planned infrastructure by percentage and square mileage using the energy consumption and distance methods.

	Percent Gain (%)		Area Gain (mi^2)		Existing Total Area (mi^2)		BMP Total Area (mi^2)	
	Energy	Distance	Energy	Distance	Energy	Distance	Energy	Distance
Level of Stress: 0.5	+1590	+817	+116.16	+750.00	0.07	0.91	116.23	750.91
Level of Stress: 1	+9	+41	+105.12	+732.97	11.11	17.95	116.23	750.91
Level of Stress: 2	+4	+6	+91.08	+647.15	25.15	103.77	116.23	750.91
Level of Stress: 2.5	+3	+5	+88.48	+625.44	27.75	125.48	116.23	750.91
Level of Stress: 3	+1	+2	+67.69	+492.61	48.54	258.30	116.23	750.91
Level of Stress: 4	+0.2	+0.2	+18.32	+147.00	97.91	603.91	116.23	750.91
Level of Stress: 5	+0.3	+0.1	+28.56	+85.09	103.87	665.83	132.43	750.91

5. Concluding Remarks

A bicycle accessibility analysis based on the combination of the LTS and energy consumption methods takes into account important external conditions that influence people's bike trips and provides a more realistic conceptualization of bike accessibility to transportation planners than without such considerations.

The findings demonstrate that the distance-based method overstates the accessibility of metro stations and public high schools. Although the inclusion of the LTS method reflects bicyclists' perceptions of safety, the inclusion of the energy consumption method allows for consideration of perceptions of difficulty as well. The latter illustrates that, when also accounting for the current infrastructure's LTS, there are many metro stations and high schools that are either inaccessible at certain levels of stress or have limited accessibility.

The analysis results demonstrate how a combined energy–LTS methodology can be used to develop realistic catchment areas to evaluate proposed infrastructure improvements, such as the Bicycle Master Plan. Our findings indicate that the energy method is instructive when examining specific sites. For example, planned infrastructure improves some schools' distance method connectivity dramatically but not energy consumption connectivity. Planned infrastructure for destinations with higher variability in elevation benefits from consideration of the energy consumption method. There is more isolation between bikesheds created with the energy consumption method than with the distance method, even when accounting for planned infrastructure. Examining areas using the energy method will better enable planners to determine where future bicycle infrastructure will have the greatest impact by allowing them to isolate the impact of individual improvements. While the adoption of e-bikes is occurring, which may lead to slope being less impactful, current adoption in the United States is slow compared to the rest of the world (Chen, 2022) [30]; and planners should continue to plan for conventional cycle trips.

Assumptions made in this study's proposed model are based on the average adult and likely overestimate the bikeshed for younger bicyclists. Reducing the 80 kg weight assumed for an adult rider to 40 or 50 kg for a child and adjusting the 4.4 mile and 50,000 Joule limits for younger riders should be tested, particularly for destinations frequented by younger populations. Changing the catchment area limit must also be reduced as the mass of the rider is changed, since a smaller mass corresponds to less energy consumption. Our model could also be extended to include travel demand within catchment areas based on different rider profiles with varied energy limits.

Incorporating energy consumption adds another layer of complexity to existing LTS calculation methods. The resulting method offers a more nuanced view of bikeability by demonstrating the impact of elevation on accessibility, which allows planners to better quantify the impact of bicycle infrastructure. Using stress level restrictions as scenarios, planners can evaluate the impact of bicycle improvements with greater precision.

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