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Bicycle facility planning using GIS and multi-criteria decision analysis

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ABSTRACT

Sustainable transport has become an important goal in transportation planning and research in recent decades. One emphasis of sustainable transport is to develop a multi-modal transportation system, in which bicycling facility planning is playing an important role. Recently, many bicycle facility planning methods have been proposed, and can be divided into two groups: supply- and demand-based models. While these two groups of models have been applied separately, few studies, however, have incorporated variables from these two groups of models together for bicycle facility planning. To address this issue, this paper proposes a multi-criteria evaluation (MCE) analysis to integrate both supply- and demand-based criteria for bicycle facility planning. Analysis was performed at two geographic levels: network level and neighborhood level, and a Geographic Information System (GIS) based exploratory spatial data analysis (ESDA) method was applied to explore the spatial patterns of bicycle facilities at the neighborhood level. This model was applied to Milwaukee City, WI, U.S.A., and results suggest that a combination of GIS and MCE analysis can serve as a better alternative to plan for optimal bicycle facilities, highlighting inadequacies of typical supply-side measures, and meet multiple planning objectives of government agencies, planners and bicyclists.

Introduction

Sustainable transport, defined as “satisfying current transport and mobility needs without compromising the ability of future generations to meet these needs” (Black, 1996) has become an important goal in transportation planning and research recently. One major reason is that the current auto-dependent urban transportation systems in U.S. cities are considered not sustainable (Newman & Kenworthy, 1999). In particular, the auto-dependent city has contributed to the degradation of natural environments (e.g. water, air, vegetation, and soils) and depletion of finite natural resources (e.g. petroleum) (Black, 1997; Greene & Wegener, 1997; Hanson, 2005). Moreover, congestion is becoming a critical problem which has cost 12 trillion dollars per year globally and has exacerbated air pollution due to “stop and go” traffic (Miller & Shaw, 2001). Newman and Kenworthy (1999) have stated that an ideal sustainable postmodern city should include a prominence of walking, cycling, transit, cars as supplementary, and air for global transit. Moreover, to achieve a sustainable transportation network, alternative modes of transportation must be accessible, perceived as safe, and desirable. In response to the negative externalities associated with the automobile culture, the U.S. Federal Government has recognized the need for developing a heterogeneous transportation system.

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Federal regulations have mandated local governments to comprehensively assess multi-modal transportation planning. The passage of the Clean Air Act Amendments in 1990 attempted to promote sustainability by curtailing auto emissions, especially in urban areas (Hanson & Giuliano, 2004). Moreover, the Intermodal Surface Transportation Efficiency Act (ISTEA) was passed by U.S. Congress in 1991, and is intended to allocate funds towards non-highway projects such as: walking, bicycling, and public transit (Garder, 1994). The act requires that metropolitan areas with a population greater than 200,000 have their transportation plans approved by the federal government every 3 years, with a clear motive to reduce congestion and improve air quality. More importantly, the ISTEA has served as the impetus to seriously plan for sustainable transportation by incorporating measures which promote alternative modes of transport, such as public transit, bicycling, and walking facilities. Another asset to bicyclists is that the ISTEA has allotted money to implement bicycling transportation facilities and each state is required to have a bicycle and pedestrian coordinator (Feske, 1994; Hanson & Giuliano, 2004). States such as Wisconsin have mandated that a bicycle role be in place during all transportation planning. Furthermore, according to Wisconsin State Statute 85.023, the Wisconsin Department of Transportation (WIDOT) is to provide assistance in the development of bicycle facilities (Huber, 2003).

Typical bicycle facility planning models can be divided into two groups: supply- and demand-based models. Supply-based bicycle facility planning relies on two overarching theories; (a) all major arterials and collectors should have bike facilities, or, (b) a quantitative model, such as a bicycle level of service (BLOS), hazard score analysis, or bicycle compatibility index (BCI) should be calculated and reviewed prior to bicycle route planning (Harkey, Reinfurt et al., 1998; Huber, Personal communication, 2005; Landis, 1996). In other words, bicycle facility planning is either ad-hoc, or utilizes a quantitative level of service type model to assess roadway conditions for the bicyclists. A quantitative level of service analysis measures the level of comfort of the roadway. This supply-side analysis quantifies engineering type roadway variables such as speed limit, heavy truck traffic, roadway width, etc. The popular supply-based analysis is the BLOS developed by Landis, Vattikuti, and Brannick (1997) and the BCI model developed by Harkey et al. (1998). While such a supply-based analysis indirectly addresses the "safety" factor, there is no guarantee that it will induce bicycle traffic or produce the most "desired" pathway. In fact, a study by Parkin, Wardman, & Page (2007) has called into question whether the improvement of bicycle facilities lessens the perceived risk, or increases the usages of bicycle facilities.

To address the issues associated with bicycle travel demand, or how many bicyclists will use a roadway, various demand-based methods have been developed to predict non-motorized travel and they include: aggregate behavior studies, sketch plan methods, discrete choice models, market analysis, and facility demand potential models (Schwartz, 1999; Turner, Hotternstein, & Shunk, 1997; Turner, Texas et al., 1997). In particular, Landis (1996) proposed the Latent Demand Score (LDS) model to estimate travel demand with bicycle trip generators and attractors, such as employments, shopping centers, parks, and schools. The LDS model provides an indication of the likelihood that a road segment will be utilized if a bicycle facility is present. This model, however, does not include detrimental attributes that prohibit bicycling and fails to link safety and environmental conditions at the facility level.

Bicycle demand models typically utilize aggregate data to determine flows from one area to another. As a result, this approach does not indicate site specific facility improvements or represent actual increase in usage if a bicycle facility is implemented (Hyodo, Suzuki, Takahashi. 2000; Porter, Suhrbier, & Schwartz, 1999; Schwartz, 1999). According to the Wisconsin Bicycle Planning Guidance Handbook (WBPG) (Huber, 2003), planning of bicycle facilities should include factors from both supply and demand sides. This recommendation is designed to support the development of bicycle facilities that will be safe and desirable. Therefore, there is a need to develop a bicycle facility planning model that incorporates factors from both supply and demand sides.

Geographic Information System (GIS) has been at the forefront of quantifying multiple factors to meet these goals with varying levels of success. For example, GIS has been used to perform multiple criteria analysis for both utilitarian and off-street bicycle paths, estimate bicycle demand, conduct least cost path analysis, assess transportation risk, and construct Decision Support Systems (Atkinson, Deadman, Dudycha, & Traynor, 2005; Aultman-Hall, Hall & Baetz, 1997; Fuller, Williamson, Jeffe, & James, 2003; Huang & Ye, 1995; Landis, 1996; Luedtke & Plazak, 2003; Malczewski, 1999; Mescher, 1996; Nash, Cope, James, & Parker, 2005; Snyder, Whitmore Schneider, & Becker, 2008; Wigan, Richardson, & Brunton, 1998) With the assistance of GIS, bicycle facility planning models have potential to incorporate multiple criteria from both supply and demand sides. As such, a GIS-based multiple criteria decision analysis model, which can address the needs of all types of utilitarian riders and satisfy explicit bicycle route planning criteria, shows great promise in non-motorized transportation planning.

This paper proposes a comprehensive bicycle planning methodology, using GIS, multi-criteria decision analysis, and exploratory spatial data analysis (ESDA) to evaluate the quality of bicycle facilities utilizing supply and demand-based objectives. Analyses were conducted at two levels: network (bicycle facility) level and neighborhood level. Network level analysis can address site specific issues and provide detailed information for further improvements. By contrast, neighborhood level analysis provides a strategic view of bicycle facilities in an urban area, and facilitates policy development and implementations. It is at this scale that in-depth neighborhood analysis is warranted. The remainder of this paper is organized as follows: Section 2 describes the study area and data. Section 3 details the supply- and demand-based network level bicycle facility planning, including developing and analyzing the bicycle level of service (BLOS) and the demand potential index (Demand). In addition to the network level analysis, Section 4 reports a strategic analysis of bicycle facilities at the neighborhood level by applying the ESDA technique. Finally, Section 5 concludes this paper.

Study area and data

The City of Milwaukee, WI (Fig. 1) was utilized for a comprehensive bicycle facility analysis. The *Milwaukee Journal Sentinel*, reported that 17% of the adult households in the City of Milwaukee are in the market for a new bike and that over 50% of

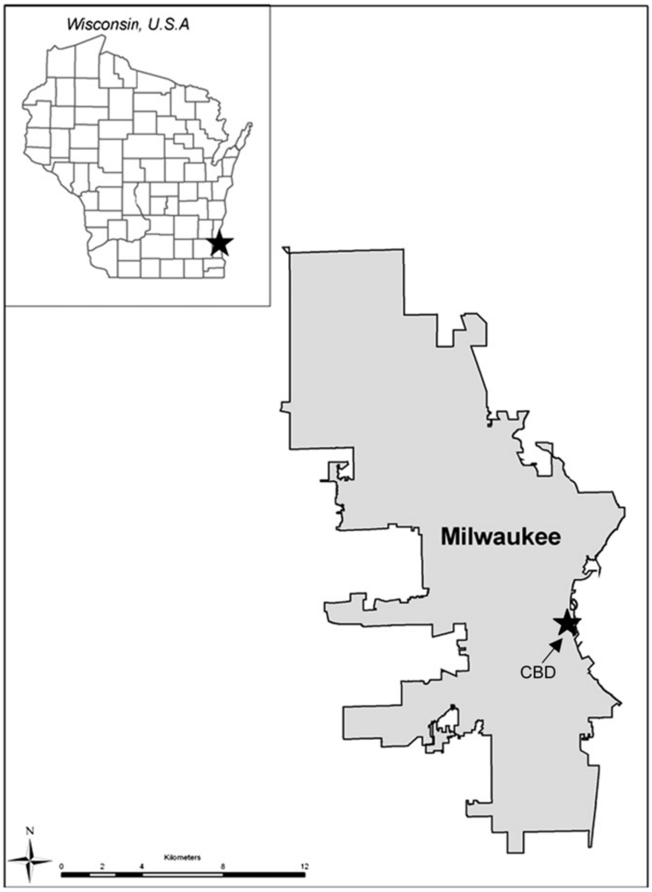

Fig. 1. City of Milwaukee.

households own bicycles already, but at the same time according to the United States 2000 Census, Milwaukee holds only a 0.34% bicycle mode share (Kegel, 2005). Milwaukee is listed as one of the top ten worst cities for walking and bicycling commuting, but in the top ten for recreational bicycling and walking (Allen, 2005). This gap in bicycling habits indicates that: current on-street bicycle facilities are insufficient, and/or utilitarian bicycling is not encouraged. Surveys also indicate that recreational riders would be willing to commute with bicycles if a suitable bicycling environment were provided. There are currently 96.5 miles of existing on-street bicycle facilities in the City of Milwaukee and well over 100 miles of off-street bicycle routes (Huber, Personal communication, 2005). Therefore, planning for bicycle facilities that speak to recreational riders and commuters show the greatest promise to increase rider-ship for all trip purposes (Huber, 2003).

The current bicycle network (Fig. 2) for the City of Milwaukee was derived from the Wisconsin Bicycle Federation's database and represents current conditions up to 2007. The road network consists of the topologically accurate road GIS layer with the Dual Independent Map Encoding (DIME) format. This road network was developed by the City of Milwaukee's Engineering Department and is currently the most precise road network available. For the purposes of this research, only current on-street bicycle facilities were assessed due to their prominence in utilitarian travel (Aultman-Hall, Hall, & Baetz, 1997). Highway engineering road variables for all roads in southeastern Wisconsin were obtained from the Wisconsin Department of Transportation. The engineering road data, coupled with the DIME network, contains traffic counts, heavy truck volume, parking width, number of travel lanes, and travel lane width. Demographic variables were obtained from the United States Census Bureau. Population data at the block level was used in this analysis. In addition, crime data from the City of Milwaukee for the year 2003 was also incorporated in this study. Businesses, parks, schools, and recreational area data was utilized in this study in order to account for desirable origin-destinations and aesthetics. Business data was obtained from the City of Milwaukee and selected via the federal Standard Industrial Classification (SCI) code. Park, recreation, and school data was obtained from the Milwaukee County Parks Department.

Network analysis

In traditional transportation planning, large areal units, such as cities, census tracts, or traffic analysis zones (TAZs), have been typically employed as the basic unit of analysis (An & Chen, 2007). Such aggregated analysis, however, cannot satisfy the

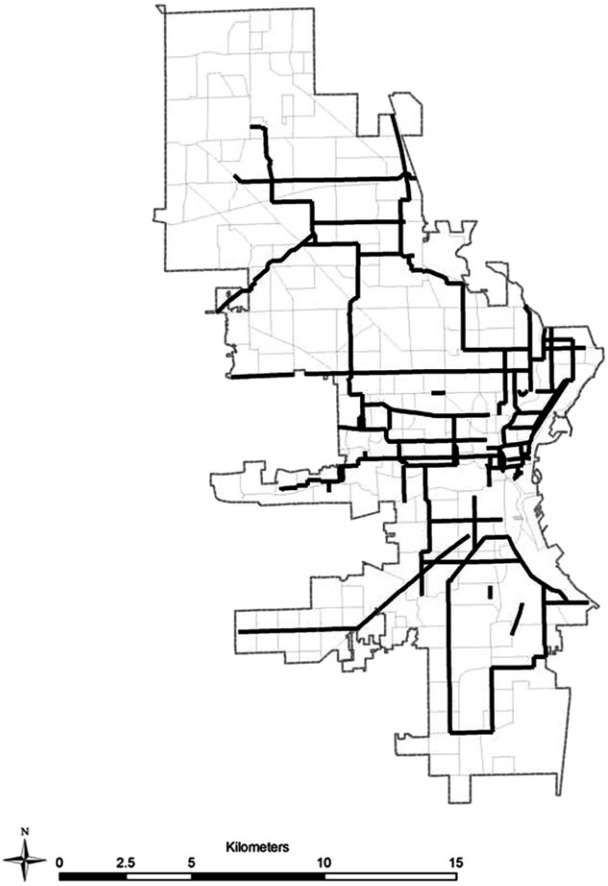

Fig. 2. City of Milwaukee Bicycle Facilities.

requirements of bicycle facility planning as many bike trips are within an aggregated unit and micro-environments are important to bicyclists. As a result, recent bicycle facility planning utilizes linear transportation segments or corridors as the unit of analysis. Examples of bicycle transportation studies that utilize a linear unit of analysis include crash and safety studies, travel demand models, and level of service analysis (Aultman-Hall, Hall, & Baetz, 1997; Huang & Ye, 1995; Wigan et al., 1998). Therefore, the first emphasis of this paper is to perform supply- and demand-based bicycle facility analysis at the road network level.

Supply-based bicycle facility planning: BLOS

In transportation mode choice analysis, risk is considered a major factor that prohibits people from cycling (Aultman-Hall, Hall, & Baetz, 1997; Dill & Carr, 2003; Landis, 1996; Landis et al., 1997). Because of this real or perceived risk, the literature has exposed a slew of bicycling risk factors. The majority of risks that bicyclists face are directly related to automobile traffic, personal security, driver behavior, topography, weather, and overall stress of the immediate environment, all of which are from the supply side of bicycle facilities (Parkin et al., 2007). As a result, safety is a major determinant in a cyclist's choice of routes, and is one of the commonly used measures to plan for bicycle facilities in most metropolitan planning organizations (MPOs) (Allen-Munley, Daniel, & Dhar, 2004). To quantify safety, various researchers have attempted to model "bicyclist comfort" either quantitatively or qualitatively. One popular technique to measure the comfort level of the road network is the bicycle level of service (BLOS) index (Landis et al., 1997). This measure assesses participant's perceptions of physical roadway conditions. Specifically, the BLOS index is a function of per-lane motor vehicle traffic volume, speed of motor vehicles, traffic mix, potential cross-street traffic generation, pavement surface condition, and pavement width for bicycling (Landis, 1996; Landis et al., 1997). Due to the engineering similarities of the BLOS, the method has made great strides in bicycle planning amongst transportation engineers and planners alike. For this research, the BLOS index (see equation (1)) is calculated based on the methodology provided by Landis et al. (1997).

$$BLOS = 0.507 ln(Vol_{15}/L_n) + 0.199 SP_t (1 + 10.38 HV)^2 + 7.066 (1/PR_5)^2 - 0.005 W_e^2 + 0.760 \tag{1}$$

Where Vol_{15} indicates the volume of directional traffic in 15 min; L_n indicates the number of directional through lanes, SP_t is the effective speed limit, the posted speed limit determined by the Wisconsin Department of Transportation; HV indicates the percentage of heavy vehicles; PR_5 indicates the FHWA's 5-point pavement surface condition rating (e.g. 5 represents the best); W_e is the average effective width of outside through lane.

The resultant BLOS score represents the degree of comfort (safety) for bicyclists, with the lowest score representing the best safety conditions for bicyclists. For easy interpretation, the BLOS is classified into six grades, including A ($\leq$ 1.50), B (1.51–2.50), C (2.51–3.50), D (3.51–4.50), E (4.51–5.50), and F ($>$ 5.50).

The BLOS grade for each road segment in City Milwaukee is illustrated in Fig. 3. We can infer that the BLOS grades generally comply with road types. That is, the majority of residential (local) roads receive satisfactory BLOS grades (e.g. A or B), while most collector and arterial roads receive lower BLOS grades (e.g. C or under). Moreover, several segments of arterial roads receive a grade of F. Spatially, the road segments with lower grades are evenly spaced in the study area, with a small cluster in the downtown Milwaukee. The cluster may be due to the high density of arterial roads and high traffic volumes in the downtown area.

Demand-based bicycle facility planning: demand potential index

Bicycle traffic demand related factor selection and ranking

The factors influencing bicycle traffic demand selected and ranked by the authors were based on the WBPG, relevant literature, and interviews with personnel from the Bicycle Federation of Wisconsin and the Wisconsin Department of Transportation. The influential factors utilized in this project consist of: bicycle traffic generators and attractors (e.g. population,

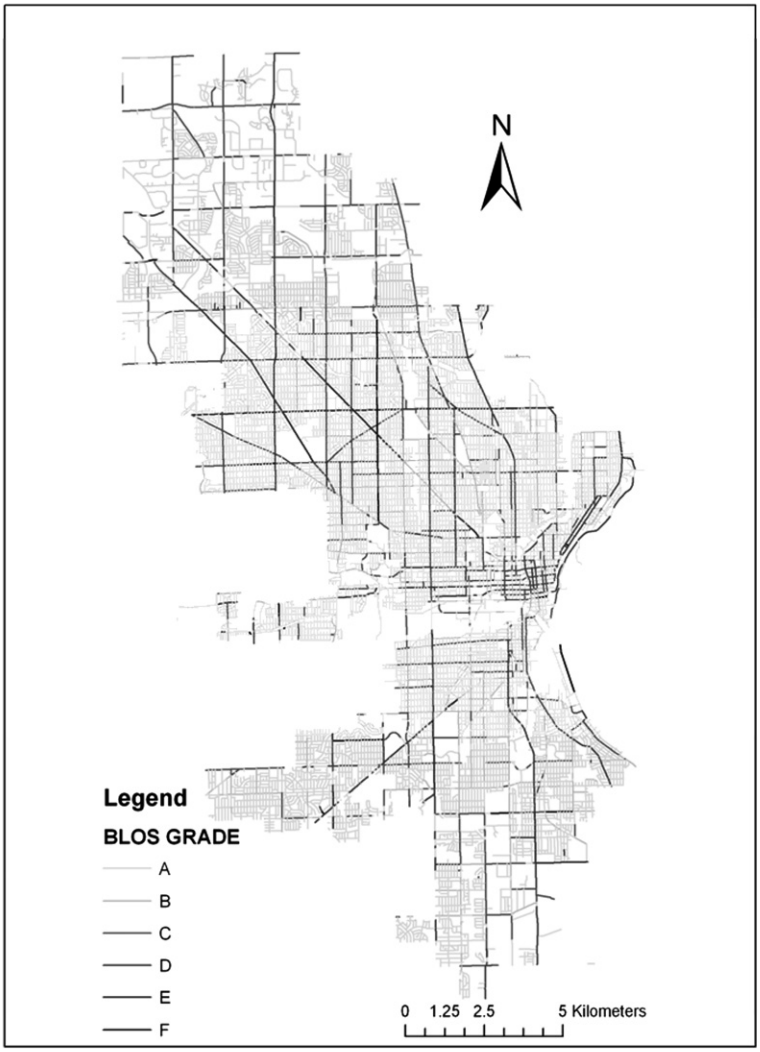

Fig. 3. City of Milwaukee BLOS Index.

desirable businesses, schools, and recreational areas, parks), and inhibitors (e.g. crimes). A major bicycle traffic detractor is the fear of crime near on-street or on side paths. For example, Sener, Eluru, and Bhat (2009) found that 21% of survey respondents viewed dangerous crime as a deterrent to bicycling and Ravenscroft, Uzzell, and Leach (2002) found that the fear of crime had a significant impact on the use of recreation bicycle routes. Therefore, for this study, crime is considered the major bicycle traffic inhibitor and weighted the highest in order to minimize their effect during bicycle route selection (see Table 1). The WBPG handbook states that commercial and retail centers should be incorporated in bicycle planning (Huber, 2003). Commercial business data was limited to four types of establishments: restaurants, taverns, bicycle stores, and coffee shops. Based on personal experience and interviews with bicyclists, these are the most frequented establishments that may enhance the bicyclist's experience. Schools are inherently important to a wide range of bicyclists and potential bicyclists. Education institutions are a vital component in bicycle facility planning because they generate a large amount of bicycle trips. It has been estimated that bicycling involves approximately 15–30% trips to schools and remains at 10% year round near college campuses (Huber, 2003). Recreation areas include playgrounds and places where the public has open access to open space and public events. Therefore, recreation areas and parks, although ranked separately, were considered generators and magnets and integral to bicycle facility planning as stated in WBPG. In addition, parks can be desirable destination, or in route amenity that enhances the aesthetics of the bicycle facility, and also provide weather relief. As a result, the percent of park space is positively associated to the amount of bicycling or walking (Allen, 2005). Parks, recreation areas, scenic trails etc., attract a higher amount of bicycle trips than the community average, and therefore, parks were incorporated into this analysis.

The last factor utilized in this paper is population. Population provides a general index of access and demand. If a bicycle facility is present, it is useless if people cannot access it, or the immediate population does not support it. Access and demand are critical in measuring present and future performance of transportation networks (Mescher, 1996; Miller & Shaw, 2001). Population in terms of a bicycle network will provide an estimate of potential demand for and access to bicycle facilities. According to the WBPG and the Bicycle Federation of Wisconsin (BFW), bicyclists will not deviate further than two blocks (e.g. 660 feet in Midwestern cities) away from a direct route. In this study, all off-network routes within 2 blocks of each road segment were summarized using an ESRI ArcGIS 3.3 Avenue script. Parks, schools, census block population, and recreation areas were summarized within a 660 ft of every road link and then joined to each road link. In addition, population data from census blocks within the 660 ft threshold was also summarized and attached to each road link.

Demand potential index generation

With all these selected and ranked factors that influence bicycle travel demand, it is necessary to generate a single measurement representing the potential demand (*DEMAND*) of bicycle facilities. In order to derive the demand potential index of bicycle facilities, a modified simple additive weighting (SAW) method was employed to integrate all demand related factors. SAW can be divided into three steps, including 1) factor normalization through linear value functions, 2) weight calculation based on factor rankings, and 3) summation of the weighted normalized factors.

The first step of SAW is to calculate the normalized value for each factor through linear value functions. There are two reasons for normalizing these factors. Firstly, the values of factors are significantly different. For instance, the number of people having access to a bicycle facility is much higher than the number of parks near to that facility. Secondly, bicycle traffic generators and attractors (positive factors) and inhibitors (negative factors) need to be treated differently. For bicycle generators and attractors, the higher the value, the higher the demand potential. But for bicycle inhibitors, the higher the value, the lower the demand potential. Therefore, for this research, linear value functions (see equation (2)) are utilized to normalize each demand related factor.

$$\begin{aligned} x_i' &= \frac{(x_i - x_{min})}{x_{max} - x_{min}} \quad \textit{For bicycle demand generators and attractors} \\ x_i' &= \frac{(x_{max} - x_i)}{x_{max} - x_{min}} \quad \textit{For bicycle demand inhibitors} \end{aligned} \tag{2}$$

Where x_i is the original value for a particular factor, x_{min} and x_{max} are the minimum and maximum value for that factor. The resultant value for each factor ranges from 0 to 1, and takes both positive factors (demand generators and attractors) and negative factors (demand inhibitors) into account.

With each normalized factor, the second step of SAW is to calculate the weight for each factor based on its ranked position through a normalizing weighting function (equation (3)). The weighting approach simply converts the ranking order of the factor to normalized weight values w_i (see Table 1) such that a higher weight is given to a higher ranked factor, and the summation of all the weights equals to 1.

Table 1
Factor selection, ranking, normalized weighting.

Criterion	Rank	Normalized weight
Crime	1	6/21
Businesses	2	5/21
Schools	3	4/21
Recreation areas	4	3/21
Parks	5	2/21
Population	6	1/21

$$w_i = \frac{n - r_i + 1}{n(n+1)/2} \tag{3}$$

where *wi* is the normalized weight for the *i*th factor; *n* is the number of factors under consideration; *ri* is the rank position of the factor.

With the normalized factor values and normalized weights, a demand potential index (see equation (4)) for each segment of bicycle facilities can be calculated as a weighted summation of normalized factor values.

$$\begin{aligned} & DEMAND = \textstyle\sum_{i=1}^{n} w_i x_i' \\ & (i = 1 \ldots\ldots n) \end{aligned} \tag{4}$$

Where *DEMAND* is the demand potential index for a road segment, x_i' is the normalized value for factor *i* for that road segment, and w_i is the normalized weight for factor *i*.

The demand potential index for each road segment in Milwaukee City is reported in Fig. 4. Based on the author's familiarity of the road and bicycle network in the study area, Fig. 4 indicates that major arterial roads have elevated demand index values, while most local and collector roads have lower values. This pattern is consistent with the distributions of commercial, educational, and recreational activities, as businesses, schools, recreational areas, and parks are major attractors for utilitarian bicycling. Moreover, low demand potential can be found in the inner city neighborhoods (northwest of the City), as crime rates in these neighborhoods are relatively high. Comparing with the supply-based bicycle facility analysis (Fig. 3), we found

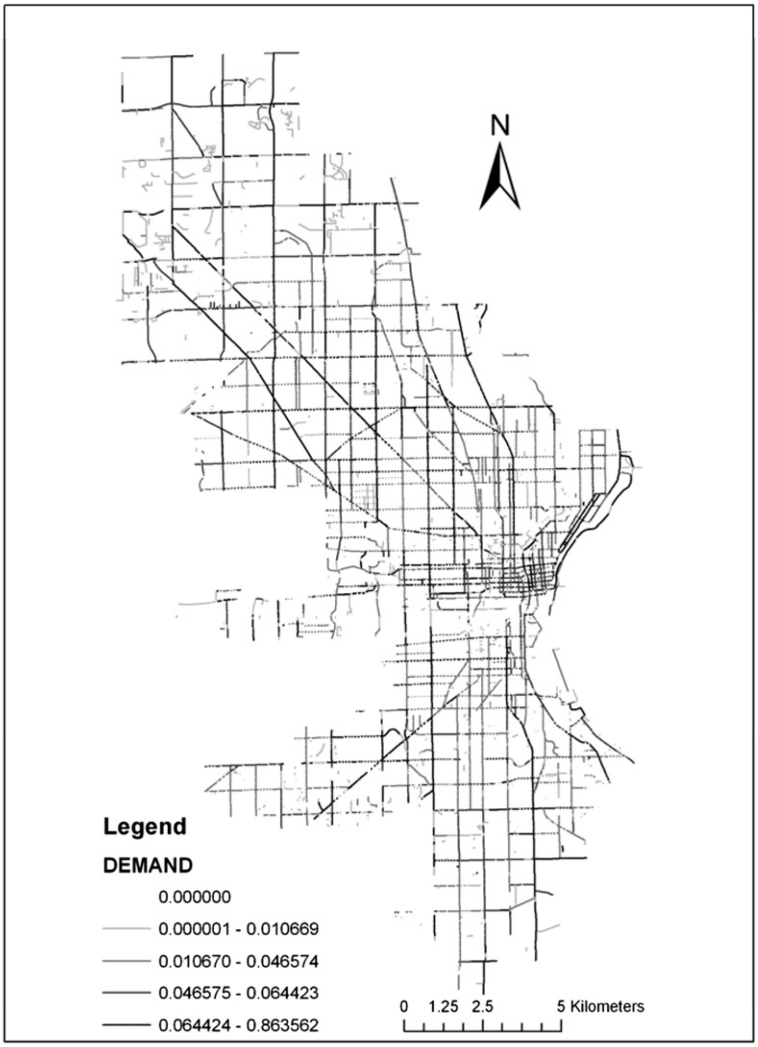

Fig. 4. City of Milwaukee Demand Index.

that, when applied to City Milwaukee, the supply-based and demand-based bicycle facility planning has contradictory objectives. That is, the demand potentials are higher along major arterial roads, while these areas at the same time have a lower BLOS. This result indicates the necessity of improving the BLOS for the major arterial roads.

Neighborhood analysis

While network analysis is important for identifying particular sections of bicycle facilities or corridors, neighborhood level analysis provides more information for strategic planning. A neighborhood is considered as the basic unit with urban planning implications. Specifically, the concept of neighborhood, or the local environment is sprinkled throughout the sustainability, planning, health, and transportation literatures- to name a few, as plausible units of investigation (Black, Paez, & Suthanaya, 2002; Cervero, 1996; Cervero & Duncan, 2003; Cervero & Kockelman, 1997; Ghose & Huxhold, 2005; Kwan & Weber, 2008; Rodríguez & Joo, 2004; Schwanen & Mokhtarian, 2005), The popularity of the neighborhood unit of analysis is in part due to the ideology that the neighborhood unit is justly appropriate, easily quantified, and integral to broad ranging tangible topics, such as mode choice and local character. For example, Cervero (1996) has delved into how neighborhood urban form affects mode choice and Schwanen and Mokhtarian (2005) corroborated these studies by assessing how neighborhood "type" is self selected by persons based on a preferred mode choice. Therefore, in addition to a linear segment by segment analysis, neighborhood based analysis is also necessary for planning for non-motorized transport modes.

In order to evaluate the overall and local spatial patterns of bicycle facilities at the neighborhood level and assess potential factors that affect bicycling, an ESDA was conducted. ESDA is typically employed to examine the spatial patterns of areal data, such as neighborhood data, and has been applied in many fields, including crime analysis, urban systems, public health studies, media research, and transportation planning (Miller & Shaw, 2001; Murray, McGuffog , Western, & Mullins, 2001; Murray & Tong, 2009; Myint, 2008; O'Sullivan & Unwin, 2003). ESDA can be employed for analyzing the global spatial trend of the data, e.g. the overall spatial pattern of BLOS or Demand Potential, and examining local hotspots, e.g. clusters of neighborhoods with better BLOS grades. ESDA can also provide a series of graphic tools, such as scatterplots and thematic maps, for better understanding the spatial patterns of variables. ESDA can be classified as two groups: global statistics and local statistics. Global statistics attempt to examine the global patterns of the spatial data, while local statistics highlights local variations. For this study, a common ESDA technique, spatial autocorrelation analysis, was applied. Spatial autocorrelation examines the degree of dependency/correlation among observations in a geographical region. For this study, the global and local patterns of bicycle facilities at the neighborhood level were uncovered using two common ESDA measures: Global and Local Moran's I indices (Anselin, 1993). Specifically, global Moran's I index measures the overall spatial association among geographical areas, while local Moran's I index examines the local similarities and variations. Both global and local Moran's I indices typically range from -1 to 1 with positive scores indicating similar values are spatially correlated and negative values indicating that unlike values are clustered.

For this study, ArcGIS and GeoDa programs were utilized to derive the global and local Moran's I indices at the neighborhood level. In particular, the mean BLOS and DEMAND indices for each neighborhood were deduced from the previous link based analysis. The DEMAND index value for each road segment was summarized and then divided by the neighborhood area to derive the mean. The mean BLOS value was obtained for each neighborhood polygon by summing the total BLOS values and then dividing by the number of road segments. With the average BLOS and DEMAND Index for each neighborhood, global and local Moran's I indices were derived. Fig. 5 represents the bivariate Moran scatterplot for the BLOS and Demand potential at the neighborhood level. For each scatterplot, the X axis represents the standardized value for a variable (e.g. BLOS or Demand), and the Y axis represents the mean standardized neighbor value for the same variable. There are four quadrants in each scatter plot, with the upper right (high-high clusters) and lower left (low-low clusters) quadrants indicating positive

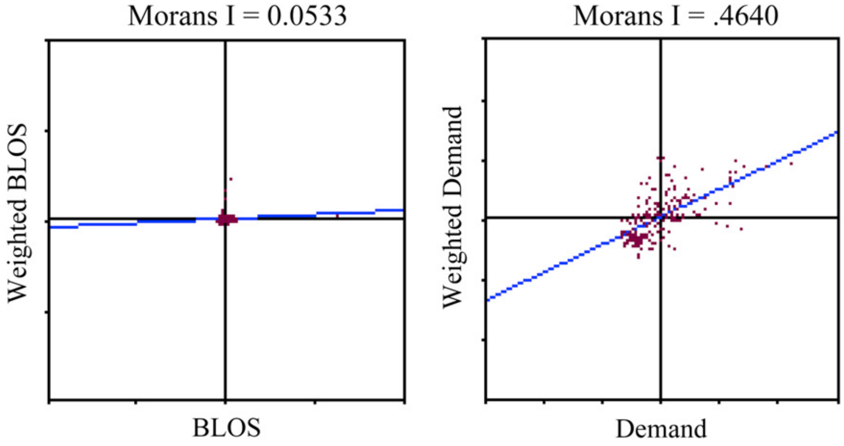

Fig. 5. Moran's I scatterplots for bicycle level of service (BLOS) and Demand Potential (Demand).

autocorrelation, and upper left (low-high clusters) and lower right (high-low clusters) quadrants indicating negative autocorrelation. The scatterplots displayed in Fig. 5a shows that there is almost zero autocorrelation for BLOS, with the global Moran's I equal to 0.05, and positive autocorrelation can be identified for Demand potential, with many points representing high-high clusters and low-low clusters, and the Global Moran's I index is 0.46, indicating statistically significant positive autocorrelation. We can infer from this that adjacent neighborhoods have similar potential travel demands, while there is no particular spatial patterns for BLOS. These scatterplots confirm the necessity of conducting a comprehensive supply- and demand-side analysis, as one approach cannot satisfy all bicycle planning goals.

In addition to the Moran scatterplots, BLOS and Demand potential cluster maps were also generated (see Figs. 6 and 7). Fig. 6 indicates that the spatial associations for BLOS are insignificant for most neighborhoods, although several small clusters exist. Among these, high-high clusters are located in the downtown of Milwaukee City, representing concentrations of unsafe roads for bicycling. From a planning standpoint, these neighborhoods should be examined more closely. At the same time, there are an even greater number of neighborhoods having low-low BLOS values, i.e., bike friendly neighborhoods. These neighborhoods are located at the west, south, and southwest of the Commercial Business District (CBD) of Milwaukee. These bike friendly neighborhoods possess relatively safe bicycling conditions.

Unlike the spatial patterns of BLOS, Fig. 7 indicates the existence of strong spatial associations of travel demand potential, with several major high-high and low-low neighborhood clusters. A major high-high cluster is located in the CBD of Milwaukee. This collection of neighborhoods is close to a major college campus (Marquette University), with a high population density and commercial/residential uses. We can infer that these neighborhoods hold high proportions of positive

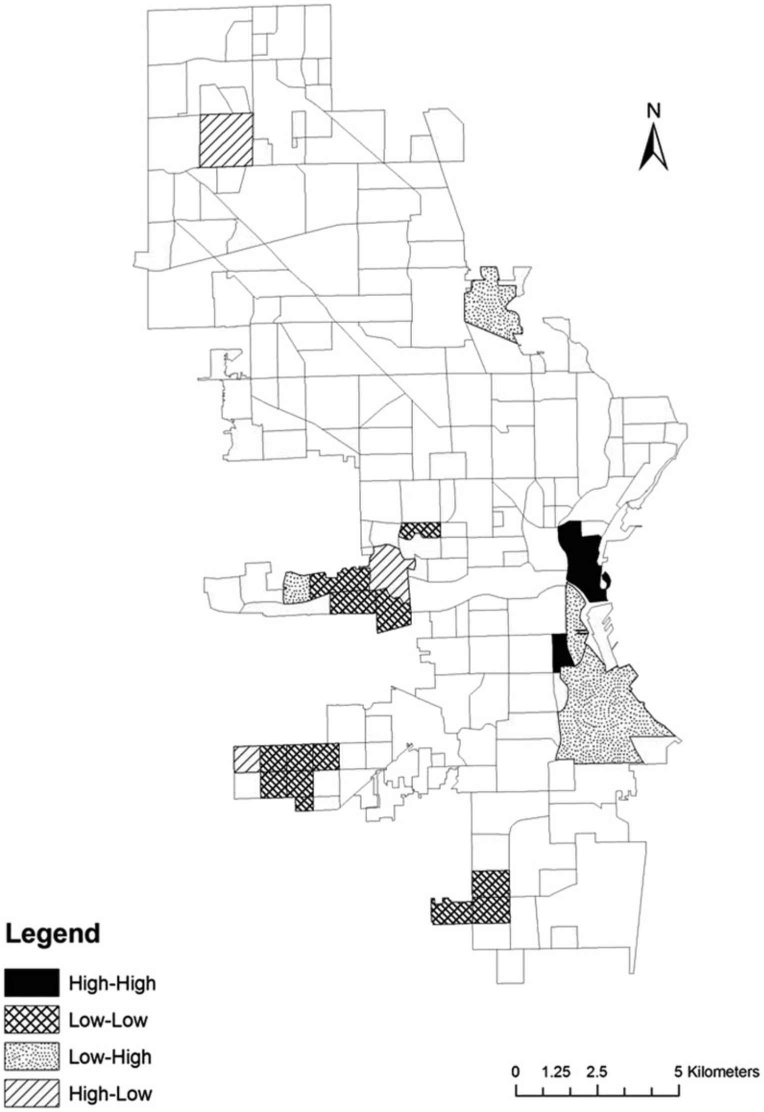

Fig. 6. BLOS cluster map.

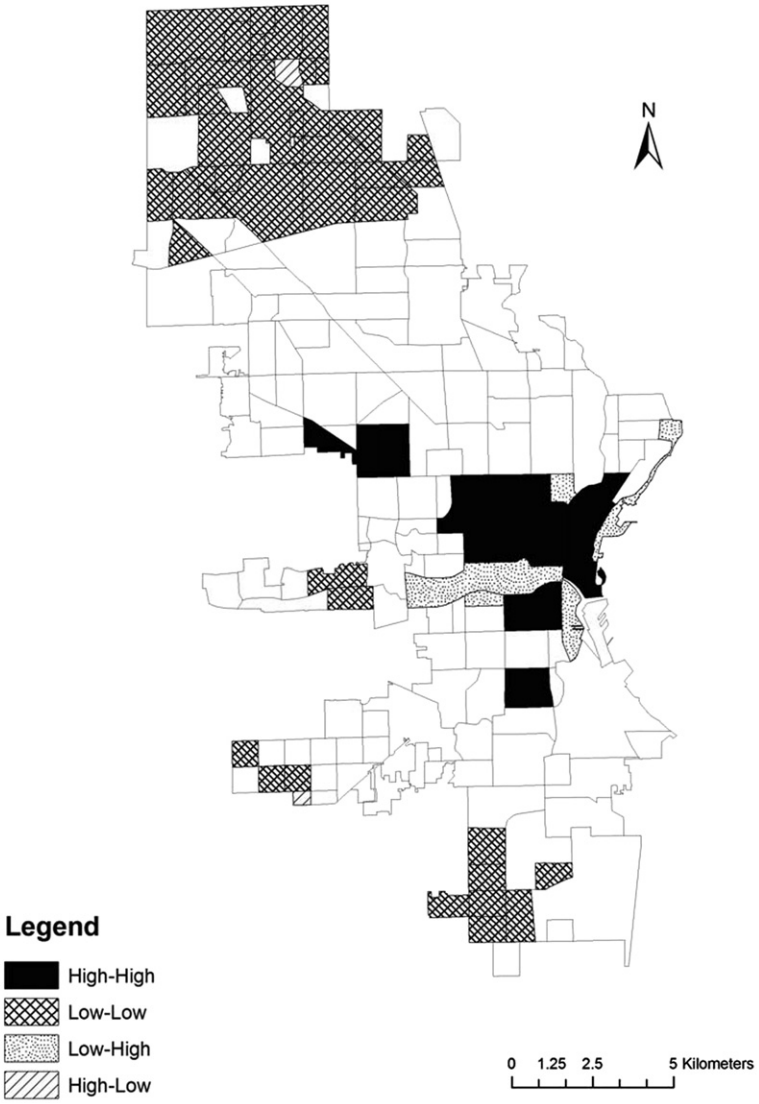

Fig. 7. DEMAND cluster map.

criteria, indicative of bicyclist's attractions. On the other hand, neighborhoods with low attraction to bicyclists are located in the northwest areas of the City. These neighborhoods are known for low density and relatively new incorporations.

When comparing Fig. 7 with Fig. 6 we observe interesting patterns. Neighborhoods that appear to be in sync in terms of high travel demand and high BLOS grades are non-existent. This disparate result indicates that a comprehensive accountability of supply and demand side factors be placed within a neighborhood bicycle planning framework. For example, there are several neighborhoods that contain qualities that make bicycling facilities attractive, conversely, there are two neighborhoods in that group that have a high mean BLOS value, which indicates a generally unsafe bicycling environment. This contradiction should have far reaching implications for planners looking to increase bicycle travel demand. At the same time there are several neighborhoods with low BLOS values, indicating safe bicycling neighborhoods. These exact same neighborhoods contain low mean travel demand values. This could provide opportunities for stakeholders to examine such neighborhoods through a qualitative lens in order to increase the "attraction" of an already existing safe bicycling neighborhood. At the same time, neighborhoods with high demand potential could lend itself to infrastructure improvements to increase the safety of roads for bicyclists.

Conclusions

Bicycle transportation is playing an important role in developing a multi-modal transportation system, an emphasis of sustainable transport. Current bicycle facility analysis methods, however, focus on either the supply side or the demand side, and cannot satisfy the requirements of comprehensive planning. Recognizing this limitation, this paper integrates both supply- and demand-based criteria and develops a comprehensive bicycle planning method using GIS, MCE, and ESDA. Analyses were conducted at two geographical levels: bicycle facility network and neighborhood levels. Analysis of results indicates that, at both geographical scales, neither supply- or demand-based bicycle facility planning is sufficient, and a comprehensive analysis which incorporating both supply- and demand-based planning criteria is important.

At the level of bicycle facility network, we found an opposite spatial pattern for BLOS and Demand Potential indices. In particular, BLOS grades are generally better in local and collector roads, and worse in major arterials. This result is reasonable as BLOS measures the safety of bicyclists using engineering criteria (e.g. traffic, number of lanes, etc.). Interestingly, local and collector roads have lower demand potentials, while major arterials have elevated demand potentials. These results present a dilemma for bicycle facility planning. That is, the roads with better BLOS grades are also associated with lower demands, and the ones with worse BLOS grades are connected to higher demands.

In addition to the network analyses, results from the neighborhood analyses also indicate the spatial mismatch from supply- and demand-based analyses. That is, there is a clear divergence between the spatial location and mean BLOS/Demand results. This contrast in neighborhood bicycling environments is evidenced throughout the study area. The CBD of Milwaukee City, for example, is the center of a high-high cluster for bicycle travel demand; this area, however, is also identified as a low-low cluster for BLOS grades.

In summary, this study highlights the importance of a comprehensive planning approach that integrates both supply- and demand-based objectives. Results from this study can provide planners and stakeholders policy implications related to bicycle facility planning. In particular, the analysis at the network level can help planners identify particular segments for further improvement, and the neighborhood level analysis can facilitate a city-wide strategic planning.

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