Investigating and Prioritizing Factors for Quantifying Bikeability

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Valerian Kwigizile, Jun-Seok Oh, and Sia M Lyimo
Western Michigan University

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Valerian Kwigizile, Jun-Seok Oh, and Sia M Lyimo

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16. Abstract

Bikeability is an important element that must be considered in planning bicycle facilities. The resource constraints make it imperative for the planners and engineers to be able to identify and shortlist important factors that promote cyclists’ friendly environment. The current study utilized the Analytical Hierarchy Process (AHP), a multiple criteria decision analysis technique, to rank the relative importance of bikeability factors for on-road bicycle facilities. AHP is the most applied multiple criteria decision analysis technique due to its ability to convert subjective judgment to a numerical value which can easily be incorporated in the decision-making process. A survey was administered to experienced cyclists and experts (i.e. planners and engineers), who were asked to rank the relative importance of one factor over the other when assessing the bikeability of on-road designated bike lanes, shared lanes, off-road bicycle facilities, intersections and bicycle infrastructure network. While this report documents summary results for other facilities studies, it gives detailed analysis results for on-road designated bike lanes since they had sufficient responses from the survey. Out of 21 factors that were investigated, the presence and enforcement of passing distance laws was ranked as the most important factor to consider when assessing the bikeability of on-road bicycle facilities. Other important factors, in descending order of importance, were bike lane marking, presence of on-street parking, bike lane type, presence of roadside hazards, motor vehicle speed, presence of paved shoulders and motor vehicle volume, among others. The results from this research form a basis for the factors deemed important by cyclists, planners and designers when assessing the bikeability of on-road bicycle lanes.

17. Key Words
Bikeability, Analytical Hierarchy Process (AHP)

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1 INTRODUCTION AND BACKGROUND

1.1 Research background and problem statement

The American Association of Retired Persons (AARP) Policy Book 2017-2018, Chapter 9, defines a livable community as one that is safe and secure, has affordable and appropriate housing and *transportation options*, and supportive community features and services. Very often, transportation options are limited to the availability of transportation modes and infrastructure needed for a specific mode of transportation. Active transportation options such as biking and walking facilitate livability not only by increasing mobility but also by improving the health status of community members. Among its health benefits, regular cycling increase cardiovascular fitness, muscle strength and flexibility, joint mobility, etc. These benefits of active transportation options have called for more efforts to implement or improve facilities in order to attract more users towards active transportation options. However, due to limited funds for transportation projects that currently face the transportation sector in the US, non-motorized projects (e.g. bicycle facilities improvements) have to compete with other transportation projects such as bridge and roads in terms of economic importance, budget and usability. Often, they are treated as optional projects.

A need to attract more people to using bikes as their mode of transportation makes it imperative to ensure their safety and comfort are observed. To a cyclist, safety and comfort are subjective to individual perceptions and expections. Research shows that different cyclists rank the level of safety or/and comfort of a route differently. Cyclists consider different factors to measure how bikeable different routes are with respect to how they perceive the level of comfort and safety offered by the particular routes. Bikeability is an important element that must be considered in the planning of bicycle facilities. Ensuring that a community is bikeable is crucial to improving both mobility and health status of its residents. A number of studies have established methods to measure and quantify bikeability of an area. Measuring bikeability refers to an assessment of an entire bikeway-network in terms of the ability and perceived comfort and convenience to access important destinations (Lower et al. 2013). However, the resource constraints make it imperative for the planners and engineers to be able to identify and shortlist important factors that promote cyclists' friendly environment. This research intended to demonstrate a methodological approach for identifying the important factors impacting the bikeability of a given facility.

1.2 Objective of the study

The main objective of this study was to investigate, identify, analyze and prioritize bikeability factors of selected bicycle facilities. Although the focus of the study was on bikeability of on-road designated bike facilities, other facilities such as off-road bicycle facilities, intersection related bicycle facilities, and overall bicycle network were also explored. This report presents details of the analysis of on-road designated bike facilities, with tentative findings on other facilities presented in the appendix.

1.3 Overview of research tasks

The research conducted a comprehensive literature review to identify different factors that have been used in different methodologies to quantify the bikeability of an area. A list of factors that were deemed important by different research in the quantification of bikeability of an area was developed and used for further analysis. After literature review, narrowing down of the resulted list of factors was conducted by combining factors that were related but only different on how they were named (eg. posted speed limit, 85th percentile vehicle speed, vehicle running speed were all termed as vehicle speed). A survey to transportation experts (engineers and planners) as well as cyclists was conducted. The responders comprised of regional and city engineers from transportation agencies in Michigan. Last, the Analytical Hierarchy Process (AHP) was employed to prioritize bikeability factors for different facilities. The results may help transportation practitioners (planners and engineers) in making more informed decisions, such as where to invest resources to improve bicycle facilities in order to increase the rate of bicycle usage.

1.4 Scope of research and report organization

This research focused on the analysis of the survey data in order to prioritize bikeability factors. Chapter 2 of this report presents a summary of the literature review focusing on factors associated with bikeability of different road sections. It also summarizes previous work on the measures of bikeability. Chapter 3 presents a description of the methodology used. Chapter 4 documents the results of the analysis conducted. Chapter 5 highlights general conclusions and recommendations from this research while Chapter 6 lists additional references relevant to this study. Lastly, a number of appendices present supllimental results from this study.

2 LITERATURE REVIEW

2.1 Introduction

Recently in the United States, there has been an increased interest in promoting cycling as an alternative mode of transportation. This is mainly due to its undeniable benefits not only to cyclicts, but also the transportation sector and communities at large. Environmental and health benefits are among the important advantages of cycling over motorized transportation options. Among its health benefits, regular cycling increases cardiovascular fitness, muscle strength, and flexibility, joint mobility, etc. Despite these benefits, cycling is yet to become a priority mode of transportation among the majority of people in the United States. Factors for the slow adoption can be explained from the safety perspective to the level of comfort provided by this type of transportation. When a cyclist is involved in a crash, it's basically the cyclist who gets hit by a vehicle and most likely to be injured. The design of a bicycle exposes the cyclists to a physical impact with a vehicle when a crash occurs.

A need to attract more people into using bikes as their mode of transportation calls for necessary arrangements in making sure that their safety is observed. However, due to limited funds for transportation projects facing the transportation sector in the US, non-motorized projects (e.g. bicycle facilities improvements) have to compete with other transportation projects such as bridges and roads. Often, bicycle projects are treated as optional (Mclean, 2012). The US Department of Transportation (USDOT) signed a policy statement on March 11, 2010, on bicycle and pedestrian accommodation. It requires that all local agencies fully incorporate safe and convenient bicycling and walking facilities into federal funded transportation projects (FHWA, 2010). However, engineers and planners are faced with three limitations when conducting safety or planning analysis for bicyclists; insufficient data regarding bicycle crashes, lack of bicycle volume data on a network scale, and the lack of tools to analyze safety improvements and bicycle planning applications (Lowry et al., 2012). The thirdlimitation was the focus of this project. Engineers and planners need to have an efficient methodology for which they will be able to prioritize different elements of the bicycle facilities to be improved under the constrains of limited budget (Wang et al., 2016). The methodology needs to identify projects that offer the greatest gain in bicycle network connectivity, accessibility, and safety (Lowry et al., 2012). The three elements can be summarized in one word, bikeability.

2.2 What is Bikeability

Bikeability is defined as the comfortability in traversing a section or network using a bike (Mclean and Louis, 2012). Also, it is the ability of a person to bike or an area to be biked (Nielsen and Skov-Petersen, 2018). It can also be used to define how conducive/friendly an area is for bicycling (Krenn et al., 2015; Winters et al., 2013), and compatibility of roadways to bicycling (Harkey et al., 1998). Bikeability is also a measure of how an area, roadway section or network is accessible by bike.

2.3 Bikeability Measures

Ensuring bikeability of a community is crucial to improving mobility and health status of its citizens. Various studies have established methods to measure and quantify bikeability of an area. Measuring bikeability refers to an assessment of entire bikeway-network in terms of the ability and perceived comfort and convenience to access important destinations (Lowry et al., 2013). Previous research mainly focused on developing the subjective measure of bikeability based on a list of measurable parameters. Krenn et al., (Krenn et al., 2015) measured the bikeability index based on some roadway components, including, cycling infrastructure, presence of separated bicycle pathways, main roads without parallel bicycle lanes, green and aquatic areas, and topography. The combination of bicycle Level of Service (LOS) and Hansen-based accessibility measure was used to quantify the bikeability by Lowry et al. (Lowry et al., 2013). In addition, some researchers used the roadway components for measuring the additive index of bikeability. Winters et al. (Winters et al., 2013) developed an additive index consisting of five components; bike route density, bike route separation, connectivity, topography, and destination density. Similarly, Van Dyck et al. (2012) used proximity to destinations, walking and cycling facilities, difficulties in parking near local shopping areas, and aesthetics for measuring bikeability. In another study, Wahlgren and Schantz (Wahlgren and Schantz, 2012) used a regression equation for estimating the bikeability with the independent variables such as ugly or beautiful, greenery, course of the route, exhaust fumes, and congestion. Among the earlier studies, Emery et al (Emery et al., 2003) and Harkey et al. (Harkey et al., 1998) used different components of the categories “street condition”, “road” and “street facilities” to quantify the cycling friendliness of a street segment.

In a study to develop bicycle suitability score, factors such as shoulder or travel lane width, average daily traffic (ADT) volume per lane, vehicle speed and pavement surface quality were used (Turner et al., 1997). A bicycle compatibility index (BCI) that estimates how compatible a roadway is to biking was found to be impacted by factors such as bicycle lane width, vehicle speed, presence of on-street parking, development along the roadside, curb lane traffic volume and development along the roadside (Harkey et al., 1998). Meanwhile, the bicycle stress level measure developed by the Australian Geelong bike plan team in 1978 considered only three variables; curb lane width, motor vehicle speed and traffic volume (Harkey et al., 1998; Sorton and Walsh, 1994). In this study, other important variables expected to impact the suitability of a place for biking were not considered, thus the methodology was deemed not useful in the case that infrastructure improvements prioritization is of essence (Wang et al., 2016). Compatibility of the road for cyclists (CRC) index was developed by Noël et al. (Noël et al., 2003). This study used ranking from experts to rank important factors in cyclists’ perception of lack of safety and comfort. Riding space available to cyclists ranked the highest of all other factors (Noël et al., 2003). Appendix 7.1 shows a summary of different bikeability factors and their corresponding measure in which they were used. The names of factors used might not be as exactly as how they were used in the typical study.

The review of the literature shows that there is a number of factors associated with the bikeability of a bicycle route. However, the priority of these factors is not consistent among different methodologies. The importance of different bikeability factors is weighted differently in various studies. For example, the bike score provided by Bike Score uses equal weights for bike lanes, hills, destinations, and road connectivity, and bike commuting mode share (Walk Score, n.d.). In addition, bikeability factors such as width of outside lane, width of bike lane, width of shoulders, proportion of on-street parking occupancy, vehicle traffic volume, vehicle speeds, percentage of heavy vehicles, pavement condition, presence of curb and number of through lanes are weighted differently in some studies (Bai et al., 2017; Dixon, 1996; Kang and Lee, 2012; Landis, 1994; Petritsch et al., 2008). The study by Herbie and Liggett (Huff Herbie and Liggett, 2014) concluded that while speed was found to be the least important variable in the determination of link bicycle LOS (BLOS), traffic volume, width, and percent of heavy vehicles can significantly affect the final score if the values are large enough (Huff Herbie and Liggett, 2014). Lane width was found to have the highest contribution in the determination of the bicycle LOS for off-road bicycle facilities (Kang and Lee, 2012). Other important factors included were; a number of access and egress points, pedestrian volume and number of encounters. Due to the limitation of sample sizes, bicycle volume factor was excluded (Kang and Lee, 2012). Bai et al (Bai et al., 2017) estimated the level of service of mid-block bicycle lanes with mixed two-wheeled traffic (e-scooters, e-bikes, and conventional bikes). It was found that bicyclists perceived higher levels of comfort with an increase in the width of bicycle lanes at mid-block and a decrease in bicycle volumes. Other additional factors considered were the presence of physical separation between motorized traffic and bicycles, the proportion of e-bikes and e-scooters in the traffic mix and the presence of bicycle lanes.

Bicycle infrastructure improvements are essential in increasing the bikeability of a bicycle network, an intersection or a road segment. These improvements can either be intersection related or the entire bicycle infrastructure network or on roadway segments such as bike lanes, shared lanes, off-road pathways such as cycle tracks and trails. They aim at increasing cycling rates – inherently the bikeability of given bicycle facilities. Different research has explained the impacts of different factors on the bikeability of urban roadways (Bai et al., 2017; Chen et al., 2017; Kang and Lee, 2012; Koh and Wong, 2013), bicycle infrastructure networks (Krenn et al., 2015; McNeil, 2011; Mekuria et al., 2012; Nielsen and Skov-Petersen, 2018; Winters et al., 2013) and intersections (Chen et al., 2017). However, the literature lacks on the prioritization of bikeability factors for on-road bicycle facilities (specifically designated bike lanes). On-road bicycle facilities improvements such as bike lanes are believed to correlate with higher cycling rates (Dill, 2003; Krenn et al., 2015; McNeil et al., 2015; Pucher et al., 2011; Wang et al., 2016). Furthermore, on-street bike lanes and wide curb lanes are believed to provide a good condition for bicyclists. This study aimed at investigating and prioritizing different factors that impact the bikeability of on-road bicycle facilities based on experts perceptions.

3 METHODOLOGY

3.1 The Analytical Hierarchy Process (AHP)

A methodology for multi-criteria ranking, i.e. Analytical Hierarchy Process (AHP), proposed by Saaty in 1975 was used in this study. It is the most applied multiple criteria decision analysis technique in solving complex problems (Zyoud and Fuchs-Hanusch, 2017). Its foundation is based on the use of paired comparisons to derive ratio scales. The methodology is applicable whenever a conclusion is to be made from a list of multiple criteria (Saaty, 1987). It's a common practice among engineers and planners to be faced with multiple criteria decision-making situations. Most of the times, transportation projects involve the combination of many procedures and stages (phases), thus multiple criteria decision situations are inevitable. When the decision involves criteria that can be measured (e.g. cost of products), the ranking is easier. However, when the decision is subjective (based on personal preference and views), the AHP methodology is highly favored (Saaty, 1987). It enables decision-makers to reach to a systematic and optimal solution of complex and unstructured real word problems (Dolan, 1989). The methodology has been used by other researchers from other fields such as medical (Dolan, 1989; Hancerliogullari Koksalmis et al., 2019), environmental (Baffoe, 2019; Blagojevic et al., 2019; Gnanavelbabu and Arunagiri, 2018), and engineering (STEVIĆ et al., 2017; Zhang and Wang, 2011). It has also been applied by traffic engineers (Liwei. H, Yulong. P, Zhuo. Q, 2009). The AHP technique involves the following steps.

1.1.1 Definition of the main goal

As the name suggests, AHP involves hierarchy approach of decision making, thus it is vital for all the important factors influencing the decision to be identified. The hierarchy is preceded with the main goal followed by main criteria. Each of the criterion is followed by sub-criteria that contain different alternatives (Saaty, Thomas - Process, 1980). For this research, the main goal is to identify and prioritize important factors used in the assessment of the bikeability of on-road bicycle facilities. This goal was communicated very well to the experts selected for this research. Engineers and planners were informed of the main objective of the research and how their responses were going to be utilized.

A total of 75 township and city engineers and planners in Michigan were invited to participate.

1.1.2 Identification of Influence of Factors in Achieving the Main Goal

A detailed literature review on factors considered important in developing different bikeability measures was conducted. A comprehensive list of factors important in the determination of bikeability of roadway facilities was identified. For each of the bicycle facilities, the identified factors resulted in a list of comparison pairs to be ranked whose total number was given by **Equation 1.**

$$n_c = \frac{n*(n-1)}{2} \tag{1}$$

For which (n_c) is the total number of pairs of comparisons for a given number of factors (n) to be assessed.

1.1.3 Pairwise Comparison

The developed pairs of factors were sent to planners and engineers for ranking. The aim was to obtain at least 20 responses. Different research that used AHP had different sample sizes. Research by Blagojevic et al (Blagojevic et al., 2019) used 15 decision-makers to determine the relative importance of factors affecting the success of innovations in forest technology. In another study, Stević et al (STEVIĆ et al., 2017) used only 5 expert responses to define the most important criteria for suppliers’ evaluation in construction companies. Given a pair of factors in the present study, experts were asked to rank the relative importance of one factor over the other when assessing the bikeability of on-road designated bike lanes, off-road bicycle facilities, shared lanes, intersections, and bicycle infrastructure network. Saaty’s 9-point scale, shown in Table 1, was used. Only the odd numbers (1,3,5,7 and 9) were provided to experts to be used for ranking. The even numbers were not used because no compromise of results was required (Saaty, Thomas - Process, 1980; Saaty, 1987).

Table 1 Saaty's Fundamental Point Scale

Intensity of importance	Description
1	Equal importance
3	Moderate importance
5	Essential or strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values between two adjacent judgments (can be used when a compromise in judgment is needed)

Source: (Saaty, 1987)

1.1.4 Development of Pairwise Comparison Matrices

A pairwise comparison matrix is an *n x n* reciprocal matrix that summarizes results of each comparison pair. It is a signature matrix whose diagonal elements equal to 1. The actual weights (a_{ij}) provided by experts for each comparison pair are entered at the upper side of the diagonal. Let $a_{ij} = w$ denote the relative importance (weight) of factor i over j for i,j = 1,2,……,n then the relative importance of j over i is $\frac{1}{a_{ij}}$. The reciprocal of each weight is entered bellow the diagonal as shown in **Equation 2** with matrix A being the comparison matrix and W = a_{ij} for i,j = 1,2,….n being the relative weight assigned.

$$A = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \dots & a_{2n} \\ \frac{1}{a_{31}} & \frac{1}{a_{32}} & \dots & a_{3n} \\ \frac{1}{a_{31}} & \dots & \dots & \dots\ a_{41} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{1}{a_{n1}} & \frac{1}{a_{n2}} & \dots & 1 \end{bmatrix} \tag{2}$$

Determination of Consistency Index (CI) and the Consistency Ratio (CR)

It is vital to check for the consistency of the resulted matrices. Essentially, what the CI does is to make sure that a person is consistent in ranking the given pair. For example, if one says β is moderate important than μ and μ is very strong important than θ it's our expectation that the importance of β to be higher than that of θ and not otherwise.

The consistency ratio (CR) is the ratio between the CI and the Random Index (RI) as shown in **Equation 3**. RI is the average random consistency index generated from a sample of 500 randomly generated reciprocal matrix (Saaty, 1987).

$$CR = \frac{CI}{RI} = \frac{\frac{\lambda_{max}-n}{n-1}}{RI} \qquad (3)$$

Where;

CR = Consistency Ratio,

CI = Consistency Index,

RI = Random Consistency Index,

λ_{max} = Principle eigenvalue of the matrix A.

The equation by Saaty (Saaty, 1987) is useable for problems with n ≤ 11 factors and it requires that the comparison matrix will only be considered for further analysis if it passes a consistency test (CR <= 0.1). This limits its usefulness when there are more than 11 factors to be assessed. For that reason, a methodology proposed by Antonio Alonso & Teresa Lamata (Antonio Alonso and Teresa Lamata, 2006) was adopted. This methodology allows for adaptability regardless of the number of factors available. The matrix is considered sufficiently consistent as a Boolean function with two parameters as shown in **Equation 4** (Antonio Alonso and Teresa Lamata, 2006).

$$F(\lambda_{max}, \alpha) \qquad (4)$$

Where; α is the term that relates calculated consistency error from matrix A and the average error of the matrices with the same dimensions as matrix A. Table 2 is the sample for values of λ_{max} and random index for dimensions greater than 15 by Antonio Alonso & Teresa Lamata (Antonio Alonso and Teresa Lamata, 2006). Thus, a matrix is considered consistent if it satisfies the following condition stipulated in **Equation 5**;

$$\frac{Error\ (A)}{Avg\ Erro\ (n)} \leq \alpha\ ; \frac{\lambda_{max}\ (A)-n}{\lambda_{max}\ (n)-n} \leq \alpha \tag{5}$$

This paper used a consistency ratio of 0.3 as the threshold for a matrix to be involved in further analysis. A CR ≤ 0.3 was chosen due to a higher number of factors that experts were asked to rank (n=21).

Table 2 Maximum Eigen Value (λmax) and Random Index (RI)

n	16	17	18	19	20	21	22	23	24
$\boldsymbol{\lambda_{max}}$	39.9676	42.7375	45.5074	48.2774	51.0473	53.8172	56.5872	59.3571	62.1270
RI	1.5978	1.6086	1.6181	1.6265	1.6341	1.6409	1.6470	1.6526	1.6577

Source: (Antonio Alonso and Teresa Lamata, 2006)

3.2 Individual and Group Decision Making

A total of 23 experts responded to the survey. Thirteen (13) out of the 23 respondents had a consistency ratio above the threshold, i.e. 0.3. In order to come up with a group decision, the aggregation of individual priorities approach was used (Ramanathan et al, 1994). The individual priorities from each expert were multiplied by the weight assigned to each of the experts. Assigning weights to experts intends to account for the effects of outliers, which were those experts whose ranking diverge from the majority (Blagojevic et al., 2019). Three possible scenarios exist that explain the occurrence of outliers; (i) knowing less than other group members, (ii) knowing more than other group members and (iii) an intentional misrepresentation of their views (Blagojevic et al., 2016; Regan et al., 2006). Three methods are suggested in dealing with the problem: (a) Assigning equal weights to the experts (b) considering the difference between the individual ranking and the group ranking (Blagojevic et al., 2016; Dong et al., 2010; Regan et al., 2006) and (c) separately assigning equal weights to groups of similar preferences. Since it's impossible to ascertain which of the three contributed for the outlier occurrence, thus all three methods are to be considered. However previous analysis shows that they all yielded similar results (Blagojevic et al., 2019). For that matter, this research considered the difference between the individual ranking and the group ranking as shown in **Equation 6.**

$$ED = \left[\sum_{i=1}^{n}\left(w_{ij} - w_i^{avg}\right)^2\right]^{\frac{1}{2}} \text{ for j = 1,2, 3, …………………m} \quad (6)$$

Where;

ED = is the distance of the j^th expert
m = is the number of experts
n = number of factors
w_{ij} = is the weight assigned to factor i by expert j
w_i^{avg} = is the group weight (geometric mean)

The influence (weight) of an expert in the group ranking (χ) is determined by **Equation 7**. The lower the ED value the closer is the expert's views to the group and greater is the influence of that expert to the group (decision) ranking. In addition, the geometric mean of the individual priorities was used to obtain group priorities (Saaty, 1987).

$$\chi_i = \frac{1/_{ED_i}}{\sum_{i=1}^{m} 1/_{ED_i}} \quad (7)$$

The obtained ED values and the expert's weighted factors were multiplied to obtain the group weighted value for the corresponding factor. Appendix 7.2is a typical example from the on-road designated bike lanes final factor weights, ED values, and influence of each expert. Expert E3, E4, and E7 had the closest ranking to the group ranking (ED = 0.12), thus having a higher influence in the final group decision (χ = 0.10). Expert E11 has the furthest of all (ED = 0.20), hence the least contribution to the final group decision (χ = 0.06).

4 RESULTS AND DISCUSSION

4.1 Bikeability Factors for On-road Designated Bike Lanes

For on-road designated bike lanes, a total of 21 factors were identified from literature review. Consequently, this number of factors resulted in a total of 210 pairs of comparisons. Table 3 is a list of factors examined in this study.

Table 3 Important Factors Affecting Bikeability of On-Road Bicycle Facilities

Bikeability Factor	Description
Passing distance laws	Presence and enforcement of passing distance laws
Pavement marking	Presence of bike lane marking
On-street parking	Presence of on-street parking
Bike lane type	Conventional or buffered bike lanes
Road-side hazards	Presence of ditches, storm grates, etc.
Speed	Motor vehicle speed on the adjacent lane
Shoulders	Presence of paved shoulder
Vehicle volume	Motor vehicle volume
Bike lane width	Width of a designated bike lane
Heavy vehicles	Presence of heavy vehicles
Sight distance restrictions	Sight distance restrictions
Street lighting	Presence of street lighting
Pavement condition	Pavement condition
Number of lanes	Number of motor vehicle travel lanes
Scenery	Presence of trees (green areas)
Number of driveways	Number of driveways/cross-traffic generators
Road grade/slope	Severity of road slope/grade
Motor vehicle travel lane width	Width of the motor vehicle travel lane
Number of transit stops	Number of transit stops
On-street parking angle	On-street parking angle
Bicycle volume	Bicycle volume

The identified factors were presented to experts (engineers and planers). A total of 23 experts responded to the survey. Results from 13 out of the 23 respondents were used since they had a consistency ratio (CR) above the threshold, i.e. 0.3. Table 4 shows the final group decision (factor weights) derived from the individual factor weights (priorities). Results show that the presence and enforcement of passing distance laws is ranked as the highest important factor (0.107) to consider when assessing the bikeability of on-road bicycle facilities. This result is in line with previous studies on the importance of sufficient passing distance by motorists to cyclists. Cyclists' willingness to bike in a mixed traffic road is affected by their perception of how drivers notice and treat them (Iwińska et al., 2018; Kaplan et al., 2019). Thus, cyclists consider areas where drivers observe enough passing distance more bikeable. Studies suggest that efforts to increase the perceived legitimacy of cyclists as road users are vital in increasing cycling rates and safety (Bonham and Johnson, 2018; Delbosc et al., 2019; Oldmeadow et al., 2019). In 2018, Michigan passed a law that requires motorists overtaking bicyclists traveling in the same direction to pass with at least three feet of distance to the left of a bicycle. Thus ranking enforcement of passing distance as the most important factor may be reflecting the ongoing efforts by the Michigan planners and engineers to foster the safety of cyclists. Furthermore, results show that other among the ten most important factors include; presence of bike lane marking (0.101), presence of on-street parking (0.072), bike lane type (0.067), presence of road-side hazards (e.g ditches, storm grates) (0.066), motor vehicle speed (0.061), presence of paved shoulders (0.056), motor vehicle volume (0.054), bike lane width (0.047) and presence of heavy vehicles (0.043).

Presence of on-street parking is mainly associated with hazards posed by open vehicle door to cyclists. A cyclist in motion encountering a parked vehicle with the door open is faced with a potential cause for injury. Cyclists-open vehicle door crashes are a safety issue of concern amongst cyclists (Johnson et al., 2013; Sener et al., 2009). Physical separation of cyclists from on-street parkings (for example using buffered bike lanes) is among the potential mitigations of such crashes.

Bike lane type, which in this study referred to the manner at which cyclists are separated from motorists, has a great impact on the perception of bikeability. The higher degree of separation from motorists the safer it is perceived by cyclists (Iwińska et al., 2018). Cyclists feel safer when they are separated from motorists (Winters et al., 2013). For on-road bicycle facilities, the separation can be achieved by pavement markings (buffered lanes). Research shows bike lanes are associated with lower potential cyclists' risks on roads (Kondo et al., 2018; Parker et al., 2013; Pulugurtha and Thakur, 2015) and also increase cycling activities (Dill, 2003; McNeil et al., 2015).

Table 4 Final Factor Weights for Bikeability of On-Road Designated Bike Lanes

Bikeability factor	Weight
Presence and enforcement of passing distance law	0.107
Presence of bike lane marking	0.101
Presence of on-street parking	0.072
Bike lane type (e.g. conventional, buffered, etc.)	0.067
Road-side hazards (e.g. ditches, storm grates, etc.)	0.066
Motor vehicle speed on the adjacent lane	0.061
Presence of paved shoulder	0.056
Motor vehicle volume	0.054
Bike lane width	0.047
Presence of heavy vehicles	0.043
Sight distance restrictions	0.042
Street lighting	0.039
Pavement condition	0.035
Number of motor vehicle travel lanes	0.035
Presence of trees (green areas)	0.031
Number of driveways	0.029
Road grade/slope (length and severity)	0.032
Motor vehicle travel lane width	0.028
Number of transit stops	0.023
On-street parking angle	0.021
Bicycle volume	0.019

Bike lane width, which represents the effective space available to a cyclist, increases safety perceptions of a cyclist and reduces crashes (Pulugurtha and Thakur, 2015). Wider bike lanes increase the level of comfort perceived by cyclists (Bai et al., 2017). Another factor that was given a higher priority by experts in the assessment of on-road bicycle facilities' bikeability is the presence of roadside hazards. These include things such as ditches, storm grates, pointed trees toward the roadway e.t.c. Their presence on the roadway reduces the cycling rate by negatively impacting the perception of bikeability of a particular roadway. This is due to a potential injury hazard posed to cyclists by such hazards.

Motor vehicle speed is another important factor reported. This factor has a great role to play in the determination of whether the road is bikeable or not. A higher speed is associated with non-compliance to the passing distance law hence imposing danger to cyclists (Debnath et al., 2018). Motor vehicle speed has been used in multiple studies to study cyclists perception of roadway bikeability (Kim et al., 2007; Krenn et al., 2015; Llorca et al., 2017; Petritsch et al., 2008; Sener et al., 2009).

Presence of paved shoulders boosts cyclists perception of safety as it provides a safe space for riding, especially on high speed, high volume roadways. However, narrow paved shoulders make it difficult for cars to pass and therefore pose safety risks to cyclists (Mclean and Louis, 2012). This factor was ranked below other factors such as bike lane type, bike lane width, vehicle volume, etc. This might be because with the presence of on-road bicycle facilities such as designated bike lanes, paved shoulders might not be of importance to cyclists. However, its inclusion might suggest that experts think in some cases it might be important if the traffic volume is higher, heavy vehicles are present, motor vehicle travel speed are higher.

4.2 Other Bicycle Facilities

In addition to the main focus of this research, i.e on-road designated bike lanes, other bicycle facilities were also examined, including shared lanes, off-road bicycle facilities, intersection facilities and bicycle infrastructure network. However, due to limited responses for these facilities, a concrete conclusion was not possible to reach. Although it was impossible to make conclusive conclusions from the responses, the results provide an insight into the important factor for bikeability for these facilities. Summary results for the analysis of these other facilities are provided below.

Shared lanes

To reflect the shared lane scenarios, two factors were omitted from the list of factors used for the analysis of on-road designated bike lanes; bike lane type and bike lane width. These were replaced by “sharrow”; a sign that identify a shared lane. Thus a total of 20 factors were used that consequently resulted in a total of 190 pairs of comparisons. Only two experts had a consistency ratio above the threshold. Appendix 7.3 shows the final group decision (factor weights) derived from the individual factor weights (priorities). Contrary to the ranking of on-road designated bike lanes in which the presence of passing sight distance was ranked the highest, experts ranked vehicle speed on a shared lane as the most important factor. This is expected due to the reason that by sharing the lane, cyclists will be more concerned with the speed of the vehicle they are sharing the lane with. To our surprise, the presence of bicycle signage (sharrow) was ranked the least important factor by these two experts. In addition, the presence of paved shoulder was among the lower-ranked factors despite the expectation that in the absence of bike lane, one would desire presence of a shoulder. Was this a sample size issue or paved shoulders without a bike lane is not deemed important? These are some questions that need to be answered with a sample size big enough to draw conclusive conclusions. Other 10 most important factors for shared lanes were: the presence of on-street parking, motor vehicle volume, presence of heavy vehicles, sight distance restrictions, pavement conditions, on-street parking angle, presence and enforcement of passing distance law, number of transits and presence of paved shoulder.

Off-road bicycle facilities

Only five experts provided their rakings, out of which three were above the threshold for the consistency ratio. The results show that with regards to off-road bicycle facilities, facility width ranks the most important factor and presence of trees (green areas) was the least important of all. Other results in the order of their importance are presented in Appendix 7.4. Sight distance was ranked second important factor for bikeability of off-road bicycle facilities. This is higher than the priority assigned to it with respect to on-road designated facilities. This might be due to the fact that sight distance is a design factor in the design of roadways. Due to severe effects brought up by the absence of adequate sight distance, it is well maintained and provided along roadways. On the other hand, off-road bicycle facilities are physically separated from motor vehicles, hence even when the sight distance isn't adequate impacts aren't as severe as those on roadways (Smith, 1976).

As it was for the sight distance, pavement condition was also ranked among the top important factors. Good pavement condition of bicycle facilities is documented to increase ridership (Shirgoakar, 2016). However, some literature show that proper pavement marking outweighs the positive effects that pavement condition has on perceived route safety and preference (Vilarroel, 2016). The facility type (i.e., cycle track, a trail, a side path, etc) was ranked higher than the bicycle speed, as expected. Such types of facilities are said to offer a sense of safety and comfort to riders due to absence of high-speed motor vehicles. They are documented to increase the level of biking if are connected to important destinations (McNeil et al., 2015; Shirgaokar and Gillespie, 2016).

Intersections

Three types of intersections were referenced for analysis: signal-controlled intersections, stop-controlled intersections, and roundabouts. Each of the intersection type had specific factors related to it. Appendixes 7.5 through 7.7 are the weights assigned by two experts to each factor used in the assessment of bikeability of signal-controlled intersections, stop-controlled intersections and roundabouts, respectively. With regards to signal-controlled intersections, results show that intersection lighting is the highest-ranked factor. On the other hand, number of lanes crossed by a cyclist is the least. This might be due to the fact that the presence of signal control makes the crossing width less important because the cyclists are assured to safely cross the intersection by signal operation. Presence of combined bike lane/motor vehicle right turn lane was the second factor in the list. This might pose a safety concern among cyclists due to the difference between their turning speed and the speed of motorists. Other factors related to turning movements that were given higher weight included the volume of right-turning vehicles and the number of right-turn lanes.

Presence of a transit stop was another factor ranked higher. This is due to the conflict that might arise between the alighting passengers and cyclists as well as the bus movements/position with regard to cycling facility. Buses may create un-necessary stops to cyclists even at times that they might have crossed through hence can be a highly determining factor when deciding which roadway to bike on. In the order of their importance, other factors among the best ten were: pavement conditions, presence of exclusive through bike lanes (bike pockets), signal control design, the volume of left-turning vehicles and presence of intersection crossing marks.

Similar to the signal-controlled intersections, intersection lighting was also ranked the highest on stop-controlled intersections (Appendix 7.6). Other factors were as presented in the aforementioned appendix. The number of circulating lanes was assigned the highest priority of all in the analysis of the bikeability of roundabouts. Meanwhile, the presence of directional signs/markings was assigned the least important weight. Other factors are as in Appendix 7.7.

Bicycle Infrastructure Network

A manner at which several bike facilities are connected to one another defines how efficient and effective the network is. When a cyclist is able to connect to different routes, it is likely that cyclict will use a bike for his different important destinations. With regards to the bicycle infrastructure network, a total of 16 factors were analyzed. Connectivity of bicycle facilities and route directness were ranked as very important factors for bikeability of a network. Also, the percentage of route miles with off-road bike facilities (e.g cycle tracks, trails, side paths, e.t.c) as well as the percentage of on-road route miles with designated bike facilities (e.g., bike lanes), were among the top fours factors for bikeability. The list of top five factors was capped with bike route wayfinding signage/markings. Other factors in the order of their importance are as presented in Appendix 7.8.

5 Conclusions and Recommendations

This research aimed at prioritizing bikeability factors for on-road bicycle facilities. Bike lanes provide designated space for cyclists to ride on. They improve the safety of cyclists and reduce crashes (Pulugurtha and Thakur, 2015). A total of 21 factors were extracted from different bikeability measures and 210 comparison pairs were presented to experts for ranking. Results show that the presence and enforcement of passing distance laws rank the highest of all the 21 factors. This indicates that experts think controlling drivers' behaviors around cyclists has a great impact in the bikeability of on-road bicycle facilities, a factor that to the best knowledge of a researcher hasn't been quantified in any of the current bikeability measures.

Despite the widespread use of the AHP technique in many other research areas, very little research exists in transportation studies. It is an easy and time-saving technique in dealing with multi-criterial decision making. Most importantly is its ability to convert subjective judgment to a numerical value that contains easy to understand the meaning. The technique can be used to prioritize the improvement of different bicycle facilities given the limited budget that planners and engineers might be faced with. Furthermore, the adaptability of the methodology to any number of decision-makers available is another strength. Integration of group decision technique into the AHP guarantees the consideration of experts' difference in opinions due to their experience.

Different from other similar researches that used cyclists' perceptions as a means of obtaining bikeability related information, this research used planners' and engineers' perception. With already existing studies on user perception, opinions from planners and engineers will strengthen their decision making especially when assurance is given that the two opinions (users and experts) are similar or with little deviation thus appropriate actions to be taken.

Results from this research form a basis to what factors are deemed important by experts when assessing the bikeability of on-road designated bike lanes. A follow-up survey that contains a lesser number of factors, for instance, the top-ranking factors can be used in future studies to refine the analysis. Further, these factors can be refined by incorporating focus group discussions and obtain expert views instead of using only the literature to gather important factors. Experience among experts wasn't a concern in this research. However, future research may want to examine priorities as a function of experts’ experience and impact of project size and type that experts have been involved in. It is also important that the opinions of cyclists be examined in contrast with experts opinions. Furthermore, differences and similarities in bikeability factors among other facilities such as shared lanes, exclusive off-road bicycle facilities, intersections and bike network should also be considered. Larger sample size is to be considered.

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7 APPENDIX

7.1 List of factors used with the corresponding bikeability measure

Bikeability factor	**BLOS**	**BCI**	**BSIR**	**BSL**	**RCI**	**IHS**	**BSR**	**BSS**	**BSA**	**CRC**	**BEQI**	**BQI**
Bike lane width	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
Presence of heavy vehicles	✓	✓		✓		✓				✓	✓	
Motor vehicle travel lane width	✓	✓	✓		✓		✓	✓	✓			
Number of driveways	✓	✓	✓	✓		✓			✓	✓	✓	
Number of motor vehicle travel lanes	✓		✓		✓		✓		✓		✓	
Presence of on-street parking	✓	✓	✓	✓	✓	✓	✓				✓	
Pavement condition	✓		✓		✓	✓	✓	✓	✓	✓	✓	
Presence of bike lane marking			✓	✓		✓			✓		✓	
Road grade/slope (length and severity)	✓		✓	✓	✓	✓	✓		✓		✓	
Road-side hazards (e.g. ditches, storm grates, e.t.c)			✓		✓	✓	✓		✓	✓		
Presence of trees (green areas)	✓	✓	✓		✓	✓	✓		✓		✓	
Presence of paved shoulder	✓	✓					✓		✓			
Sight distance restrictions	✓		✓		✓	✓	✓		✓		✓	
Motor vehicle volume	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Motor vehicle volume	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Street lighting						✓						
Number of transit stops							✓					
On-street parking angle												
Bicycle volume												
Presence and enforcement of passing distance law												
Bike lane type (e.g conventional, buffered, e.t.c)												

7.2 Individual Factor Weights (Priorities) by Each Expert (E)

Bikeability factor	**E_1**	**E_2**	**E_3**	**E_4**	**E_5**	**E_6**	**E_7**	**E_8**	**E_9**	**E_{10}**	**E_{11}**	**E_{12}**	**E_{13}**
Presence and enforcement of passing distance laws	6	1	14	5	1	1	11	1	2	8	18	4	18
Presence of bike lane marking	1	2	3	1	3	6	3	3	9	13	5	1	2
Presence of on-street parking	5	3	13	13	8	13	2	2	1	17	21	3	4
Bike lane type (e.g conventional, buffered, e.t.c)	2	5	12	16	17	5	4	11	5	3	2	5	21
Road-side hazards (e.g. ditches, storm grates, e.t.c)	3	20	6	2	2	3	10	5	19	9	4	20	14
Motor vehicle speed on the adjacent lane	4	8	4	3	4	4	9	13	12	1	12	8	17
Presence of paved shoulder	14	4	8	9	10	8	1	18	16	15	10	2	12
Motor vehicle volume	7	13	2	10	5	19	8	19	11	2	3	16	8
Bike lane width	8	7	15	12	6	9	6	8	3	10	9	7	20
Presence of heavy vehicles	10	21	1	6	7	12	15	17	18	5	6	21	16
Sight distance restrictions	13	19	9	4	20	2	5	9	15	18	16	10	3
Street lighting	17	6	11	11	15	15	13	4	14	12	15	6	15
Pavement condition	12	18	20	15	11	16	19	6	4	16	1	14	6
Number of motor vehicle travel lanes	20	16	5	21	9	7	12	20	8	6	14	15	7
Presence of trees (green areas)	19	10	16	14	14	17	16	12	13	19	17	11	1
Number of driveways	15	11	19	7	19	10	20	7	20	4	8	18	10
Road grade/slope (length and severity)	11	14	7	8	21	14	14	15	10	20	20	13	5
Motor vehicle travel lane width	9	9	10	20	12	11	7	16	21	11	13	19	19
Number of transit stops	16	12	18	17	16	20	21	14	7	7	11	17	9
On-street parking angle	18	15	17	19	18	18	18	10	17	21	7	9	13
Bicycle volume	21	17	21	18	13	21	17	21	6	14	19	12	11
Euclidean Distance (ED)	**0.16**	**0.19**	**0.12**	**0.12**	**0.18**	**0.18**	**0.12**	**0.17**	**0.18**	**0.20**	**0.20**	**0.17**	**0.17**

Expert weighted factor (χ)	**0.08**	**0.07**	**0.10**	**0.10**	**0.07**	**0.07**	**0.10**	**0.07**	**0.07**	**0.06**	**0.06**	**0.07**	**0.07**

7.3 Overall Factor Weights for Shared Lane

Bikeability factor	**Weight**
Motor vehicle speed on a shared lane	0.129
Presence of on-street parking	0.075
Motor vehicle volume	0.070
Presence of heavy vehicles	0.068
Sight distance restrictions	0.063
Pavement condition	0.060
On-street parking angle	0.060
Presence and enforcement of passing distance law	0.053
Number of transit stops	0.053
Presence of paved shoulder	0.053
Number of driveways	0.044
Road-side hazards (e.g. ditches, storm grates, e.t.c)	0.038
Presence of shared lane marking (sharrows)	0.035
Number of motor vehicle travel lanes in cyclist's direction	0.035
Road grade/slope (length and severity)	0.033
Motor vehicle travel lane width	0.033
Street lighting	0.029
Bicycle volume	0.027
Presence of trees (green areas)	0.024
Presence of bicycle signage (e.g "share the road")	0.019

7.4 Final Factor Weights for Off-Road Bicycle Facilities

Bikeability factor	Weight
Facility width	0.215
Sight distance restrictions	0.140
Pavement condition	0.102
Frequency of encounters with other users	0.080
Facility type (e.g, cycle tracks, trails, side paths, e.t.c)	0.072
Bicycle speed	0.066
Facility grade/slope (length and severity)	0.062
Pedestrian volume	0.060
Bicycle volume	0.052
Pavement marking	0.047
The proportion of e-bikes and e-scooters	0.044
Street lighting	0.034
Presence of trees (green areas)	0.031

7.5 Final Factor Weight for the Bikeability of Signal-Controlled Intersection

Bikeability factor	Weight
Intersection lighting	0.191
Presence of combined bike lane/motor vehicle right turn lane	0.106
Volume of right-turning vehicles	0.102
Number of right-turn lanes	0.084
Presence of a transit stop	0.073
Pavement condition	0.065
Presence of exclusive through bike lanes (bicycle pockets)	0.064
Signal control design (e.g., exclusive bike signals, optimized signals, etc.)	0.053
Volume of left turning vehicles	0.051
Presence of “intersection crossing marks”	0.047
Presence of bicycle warning signs in advance of the merge/transition area	0.043
Presence of lane line extension markings	0.037
Presence of bike boxes or two-stage turn queue boxes	0.035
Presence of a skewed railroad crossing	0.027
Number of intersecting roads	0.024
Volume of vehicles on a crossed road	0.023
Number of lanes crossed	0.014

7.6 Final Factor Weight for the Bikeability of Stop-Controlled Intersection

Bikeability factor	Weight
Intersection lighting	0.234
Pavement condition	0.115
Volume of right-turning vehicles	0.110
Presence of speed-reducing measures (e.g speed humps)	0.098
Presence of a transit stop	0.096
Presence of All-Way Stop control	0.080
Presence of active warning beacons	0.064
Presence of bike lane markings	0.055
Presence of exclusive left-turn lane	0.047
Number of intersecting roads	0.040
Volume of left-turning vehicles	0.035
Volume of vehicles on a crossed road	0.033

7.7 Final Factor Weights for Bikeability of Roundabouts

Bikeability factor	Weight
Number of circulating lanes	0.281
Volume of circulating vehicles	0.236
Presence of slip lanes (i.e channelized right turn lane)	0.120
Presence of bike lane markings	0.118
Intersection lighting	0.089
Pavement condition	0.060
Intersection lighting	0.089
Presence of a transit stop	0.053
Presence of directional signs/markings	0.044

7.8 Final Factor Weights for Bikeability of Bicycle Infrastructure Network

Bikeability factor	Weight
Connectivity of bike facilities	0.177
Route directness	0.134
Percentage of route miles with off-road bike facilities (e.g cycle tracks, trails, side paths, e.t.c)	0.111
Percentage of on-road route miles with designated bike facilities (e.g., bike lanes)	0.089
Bike route way-finding signage/markings	0.070
Stop-controlled intersections density (per route miles)	0.062
Roundabouts density (per route miles)	0.060
Presence of bike parking places	0.059
Signal-controlled intersections density (per route miles)	0.058
Neighborhood bike-way density (bicycle boulevards)	0.041
Route accessibility to/from other transportation modes (eg transit services, park & ride, carpool, e.tc)	0.031
Presence of parks, green areas e.t.c. along the route	0.028
Presence of bike networks map	0.027
Presence of bike-sharing stations	0.022
Presence of dock-less bike service	0.018
Percentage of on-road route miles with shared lanes	0.013