Effective Design Factors for Bicycle-Friendly Streets

Z. Asadi-Shekari, M. Moeinaddini, M. Zaly Shah, A. Hamzah

Abstract**—**Bicycle Level of Service (BLOS) is a measure for evaluating street conditions for cyclists. Currently, various methods are proposed for BLOS. These analytical methods however have some drawbacks: they usually assume cyclists as users that can share street facilities with motorized vehicles, it is not easy to link them to design process and they are not easy to follow. In addition, they only support a narrow range of cycling facilities and may not be applicable for all situations. Along this, the current paper introduces various effective design factors for bicycle-friendly streets. This study considers cyclists as users of streets who have special needs and facilities. Therefore, the key factors that influence BLOS based on different cycling facilities that are proposed by developed guidelines and literature are identified. The combination of these factors presents a complete set of effective design factors for bicycle-friendly streets. In addition, the weight of each factor in existing BLOS models is estimated and these effective factors are ranked based on these weights. These factors and their weights can be used in further studies to propose special bicycle-friendly street design model.

Keywords**—**Bicycle level of service, bicycle-friendly streets, cycling facilities, rating system, urban streets.

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I. Introduction

THE growing concern over environmental, economic and social problems that motorized vehicles produce, have made transportation planners and engineers to investigate solutions to promote green travel modes. Cycling is one of the most sustainable travel options that can reduce congestion and pollutions that are produced by automobiles [1] but it should have its own infrastructure such as bike lane, shelter facilities and separate path. Although there are different research and guidelines that try to consider non-motorized users, the results in communities are not sufficient to satisfy all people. NHTSA and BTS [2] found that adequate facilities such as bike lanes can be used by approximately just 5% of bike trips. Accordingly, necessary adjustments need to be made and demanding requirements should be provided to make streets convenient and safe for non-motorized users [3]-[13].

Designing is a complex process which needs tools and methods to assist, evaluate and improve the design. The application of analytical methods in street design and evaluation has always been a challenging task. Thus, it is important to represent a reliable method to assess streets for non-motorized users [3]. To improve street conditions for pedestrians and cyclists, it is necessary to evaluate existing walking and cycling facilities and find problems and failures. Streets evaluation has been done by level of service (LOS) in many studies. An overall measure for describing existing conditions, facilities, infrastructure and furniture in street and also assessing quality of service can be defined as LOS [4]. Bicycle level of service (BLOS) is useful in many phases such as proposing strategies, designing, planning, prioritizing and monitoring. Most of planners such as [14]-[16] utilized BLOS for estimating the level of safety and comfort of streets for cyclists. Davis [17] introduced bicycle safety index rating (BSIR) which is one of the primary mathematical models that evaluates important factors for cyclists in streets. Davis [18] also eliminated intersection evaluation from the BSIR model and validated roadway segment index (RSI) as the only method of bicycle suitability rating. Some variables and facilities that have influence on safety and comfort for bicyclists such as bike box, slope and marking were not considered in these models [4]. Sorton and Walsh [19] focused on the cyclists' facility design. The model has been criticized for leaving out important factors such as pavement and bike line conditions [20].

Bicycle compatibility index (BCI) is proposed by [21], [22] and developed by [23]. This model does not cover some effective variables such as lighting. Landis et al. [24] also introduced a measure for evaluating bicycle environment and facilities by considering several indicators that influence BLOS. Although Landis's model is an important model that is used by majority of guidelines, it does not consider some bicycle facilities and furniture such as signal and slope [4].

Most researchers have used direct observation and video techniques or questionnaire as data collection methods for their LOS models [4]. Usual analysis methods in street evaluations and LOS models are regression analysis (e.g., [21], [22], [24]), simulation (e.g., [25]) and point system (e.g., [15], [26]). The point system is not complex for designers to assess streets and it is easy to follow. This system can be extended and promoted by adding more indicators. It has also capability to be modified for different models.

What is most surprising about the current literature on evaluation bicycle condition is the lack of studies that consider cyclists as the significant street users with special needs and facilities [4]. The majority of previous studies assumed cyclists as users that can share street facilities with motorized vehicles. For instance, motorized and heavy motorized vehicles speed and volumes were important for ample studies (e.g., [19]-[22], [17], [24], [14]). However, there are some studies like [27] that conclude motor vehicle volume is not effective factor for BLOS. In addition, number of travel lanes

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in previous studies such as [18] and [24] also show that motorized vehicles facilities were used as basic infrastructures for cyclists.

There are some studies like [18], [15], [24] and [28] that considered special facilities such as pavement condition for cycling. Dixon [15] also paid much attention to some effective conflict factors such as driveways, side streets and barrier free that can reduce the effects of motorized vehicles. These studies did not consider enough infrastructure and facilities to have safe, secure, comfort and convenience cycling trip in one model. Especially, share lane, unpaved trails and multiuse trails that are used by pedestrian and cyclists were not addressed before [4]. So, current evaluation tools only cover a narrow range of street conditions and may not be applicable for all situations. In addition, bicycle facilities can increase convenience and promote cycling trips. Therefore, to evaluate streets in this case, bicycle facilities and infrastructures are more critical. Consequently, the objectives of this paper are divided into different stages.

1. Identifying the key factors that influence BLOS based on different cycling facilities that are covered by developed guidelines and literature.
2. Presenting a complete set of effective design factors for bicycle-friendly streets.
3. Identifying the weight of each proposed factor based on existing BLOS models.
4. Introducing new objectives for further studies to propose special bicycle-friendly street design model.

II. Material and Methods

In order to find design factors that have significant effects on BLOS developed guidelines and literature from different parts of the world were reviewed. Majority of guidelines for cycling in urban streets try to find needs of cyclists by utilizing scientific research and they present effective indicators with standards and descriptions based on their results. To have the majority of effective factors, the process of reviewing guidelines was continued until all indicators and standards repeated. Therefore, 23 developed guidelines from different parts of the world were reviewed in this research. This selection from various cities is useful for evaluating cycling indicators in different socio-economic contexts.

In the second step, current BLOS methods are reviewed to find the importance and weight of each factor in the existing models. Weight of each bicycle-friendly street factor can show the effectiveness of each factor. This weight is calculated by evaluating the importance of the factor for different BLOS models. When a factor is considered in several models, it means that this factor is needed to have better cycling conditions. Therefore, this factor is more effective and it may have higher weight. In addition, when a factor is more important, it has higher weight in the model. Therefore, a rating method and number of models that consider specific factors were applied to estimate the weight of each factor.

The factors in each study are ranked based on the importance of the factor for that study. These ranks are normalized by using the value of obtained rank per sum of ranks in each study. The sum of these normalized values is used to proposed special weight for each factor. These factors and their weights can be used in further studies to propose special bicycle-friendly street design model.

III. Result

Bicycle-friendly streets need design and construction of bicycle-friendly facilities. Different bicycle-friendly facilities have been proposed by various guidelines and literature to encourage people to use cycling as a transportation option. Bike route, signal, bike box, marking, slope, barrier and buffer, parking, trail crossing, pavement, grade, signage, lighting and traffic speed are effective design factors for bicycle-friendly streets that are identified by reviewing 23 developed guidelines from different parts of the world. Table I shows these factors and the references that are reviewed to identify them.

TABLE I
References for Design Factors Regarding Bicycle-Friendly Streets

F	References
1	r1, r2, r3, r4, r5, r6, r7, r9, r10, r11, r12, r13, r14, r15, r16, r17, r18, r19, r20, r21, r22, r23
2	r1, r11, r15, r19, r21, r22, r23
3	r8, r 11, r19, r23
4	r1, r3, r10, r11, r15, r18, r19, r20, r21, r22, r23
5	r19, r21
6	r9, r15, r18, r19, r20, r21, r22
7	r1, r2, r6, r7, r8, r10, r11, r13, r15, r16, r18,r19, r21, r23
8	r15, r18,r19
9	r1, r4, r6, r15, r16, r18, r19, r20, r21, r22, r23
10	r1, r19, r21
11	r1, r3, r4, r8, r9, r10, r11, r18, r19, r20, r21, r22, r23
12	r6, r11, r16, r17, r18, r19, r20, r21, r22, r23
13	r1, r3, r5, r6, r7, r9, r10, r11, r12, r13, r14, r15, r16, r17, r18, r19, r20, r21, r22, r23

References: r1- DELCAN [29], r2-City of Calgary [30], r3-Sutherland and Morrish [31], r4-City of Whittlesea [32], r5- Narrabrr Shir Council [33] , r6-City of Charles Sturt [34], r7-Heramb [35], r8-Vanderslice [36], r9-Ashland City Council [37], r10- Access Minneapolis [38], r11-CDOT [39], r12- Pima County [40], r13-City of Aurora [41], r14-Burden [42], r15- UTTIPEC [43], r16- City of NewYork [44], r17-RDM [45], r18- City of Tacoma [46], r19-Access Minneapolis [47], r20-Jakson et al. [48], r21-AASHTO [49], r22-Arup [50], r23-TBP [51]

F: 1-bike route, 2-signal, 3-bike box, 4-marking, 5-slope, 6-barriers and buffers, 7-parking, 8-trail crossing, 9-pavement, 10-grade, 11-signage, 12-lighting, 13-traffic speed

When a factor is suggested by several references, it means that this factor is more important for bicycle-friendly streets. In addition, when a factor is more important, there are more details and standards for this factor in the references. For instance, 22 from 23 references suggest standard bike routes such as shared lanes, paved shoulders, bike lanes, bike boulevards and shared use paths to have bicycle-friendly streets. There are complete details and standards for different types of bike routes in 10 references. The details and standards are semi complete for bike routes in 9 references and the rest just suggest to consider this facility in bicycle-friendly streets. Table II shows number of references regarding complete, semi complete and incomplete standards and details for each factor.

The identified factor can be included in the complete set of effective design factors for bicycle-friendly streets if at least one guideline suggests complete details and standards for that factor. Table III shows the complete set of effective design factors for bicycle-friendly streets and suggested references for their standards and details.

TABLE II
COMPLETE, SEMI COMPLETE AND INCOMPLETE STANDARDS AND DETAILS FOR EACH FACTOR

Standards and details	Factors 1	2	3	4	5	6	7	8	9	10	11	12	13
IC	3	2	1	5	0	2	5	1	4	1	6	3	5
SC	9	2	2	3	0	1	3	1	2	0	4	4	0
C	10	3	3	4	2	4	6	1	5	2	4	2	15

Factors: 1-bike route, 2-signal, 3-bike box, 4-marking, 5-slope, 6-barriers and buffers,7-parking, 8-trail crossing, 9-pavement, 10-grade, 11-signage, 12-lighting, 13- traffic speed.

IC = incomplete, SC = semi complete, C = complete.

TABLE III
THE COMPLETE SET OF EFFECTIVE DESIGN FACTORS FOR BICYCLE-FRIENDLY STREETS AND STANDARDS' REFERENCES

Design factors	Standards' References
1	r1, r4, r5, r7, r9, r10, r11, ..., r23
2	r11, r19, r21, r22, r23
3	r8, r11, r13, r18, r19
4	r4, r10, r18, r19, r20, r21, r22
5	r19, r21
6	r9, r18, r19, r21, r22
7	r6, r7, r8, r15, r16, r18, r19, r21, r23
8	r18, r19
9	r15, r16, r18, r19, r21, r22, r23
10	r19, r21
11	r8, r15, r18, r19, r20, r21, r22, r23
12	r6, r11, r16, r17, r19, r21
13	r5, r6, r9, r10, r11, ..., r23

References: r1- DELCAN [29], r2-City of Calgary [30], r3-Sutherland and Morrish [31], r4-City of Whittlesea [32], r5- Narrabrr Shir Council [33] , r6-City of Charles Sturt [34], r7-Heramb [35], r8-Vanderslice [36], r9-Ashland City Council [37], r10- Access Minneapolis [38], r11-CDOT [39], r12- Pima County [40], r13-City of Aurora [41], r14-Burden [42], r15- UTTIPEC [43], r16- City of NewYork [44], r17-RDM [45], r18- City of Tacoma [46], r19-Access Minneapolis [47], r20-Jakson et al. [48], r21-AASHTO [49], r22-Arup [50], r23-TBP [51].

Design factors: 1-bike route, 2-signal, 3-bike box, 4-marking, 5-slope, 6-barriers and buffers, 7-parking, 8-trail crossing, 9-pavement, 10-grade, 11-signage, 12- lighting, 13-traffic speed.

Among these factors some of them have more impacts on BLOS. In the next step, the importance and weight of each factor for existing BLOS models is estimated to find the weight of design factors for bicycle-friendly streets. Most of current BLOS models are reviewed in this step. The weights are estimated by evaluating the importance of the factor for current BLOS models. Therefore, the design factors that are considered by current BLOS models are ranked from the lowest to the highest for each model based on the importance of the factor for each study. The importance of the factors can be identified by the coefficients, emphasizes or points that are considered for factors in the models. The ranks are normalized for each study by using the value of obtained rank per sum of ranks in each study. Table IV shows ranks and normalized ranks for the factors in the current BLOS models.

This complete set of effective design factors for bicycle-friendly streets and their weights can be used in further studies to propose special bicycle-friendly street design model. In addition, this complete set considers cyclists as users of streets who have special needs and facilities and includes a wide range of cycling facilities. Therefore, this complete set can be used to propose new practical measures for BLOS that cover the majority of facilities and infrastructures. Fig. 1 shows the strength of each factor for further special bicycle-friendly street design and evaluation models based on the proposed complete set of effective design factors. The weights of design factors show that bike route, traffic speed, pavement and barriers and buffers are the most effective design factors for bicycle-friendly streets (refer Fig. 1).

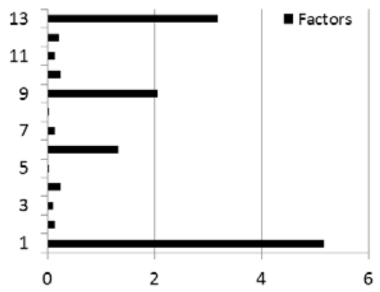

Fig. 1 The weight of each design factor. Factors: 1-bike route, 2-signal, 3-bike box, 4-marking, 5-slope, 6-barriers and buffers, 7-parking, 8-trail crossing, 9-pavement, 10-grade, 11-signage, 12-lighting, 13-traffic speed

IV. DISCUSSION AND CONCLUSIONS

Ample of previous studies consider BLOS based on the facilities that are designed for motorized vehicles, but cyclists like pedestrians and other special users need their own infrastructures. This research is of value since it provides a foundation for considering cyclists as significant street users with special facilities. In addition, considerable studies in BLOS have used complicated methods that are not applicable for designing and improvement process in different contexts and they only support a narrow range of cycling facilities. To overcome these shortcomings, this study tries to identify a wide range of cycling facilities based on various literature and developed guidelines. The final complete set of effective design factors for bicycle-friendly streets that is introduced in this study is a combination of universal factors that are proposed by developed guidelines. This complete set can be a foundation for bicycle-friendly streets design and evaluation models that are easy to follow and can be linked to the design process. Therefore, it is a comprehensive and easy to follow methodology to improve streets and guidelines which suits universal applications. Various cycling facilities are rated in this method so this model may also be used to prioritize financial resources. This method has the potential to be developed for other streets' users LOS based on similar process. This model can extend street guidelines towards complete streets by adding all users.

Furthermore, for model optimization, adding new local factors and guidelines may enhance BLOS and design models that are achieved by this method in case of localization. This method uses guidelines and current BLOS models to indicate and prioritize the factors. Validity of these factors and their weights can be tested by other methods like relationship models in various contexts.

TABLE IV
WEIGHTS OF DESIGN FACTORS FOR BICYCLE-FRIENDLY STREETS BASED ON CURRENT BLOS MODELS

BLOS Models		1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
Mozer [14]	R	2.00					1.00							1.00	4.00
	NR	0.50					0.25							0.25	1.00
Dixon [15]	R	3.00					1.00			2.00				2.00	8.00
	NR	0.38					0.13			0.25				0.25	1.00
Landis [52]	R	2.00								1.00				1.00	4.00
	NR	0.50								0.25				0.25	1.00
Landis et al. [24]	R	3.00					1.00			4.00				2.00	10.00
	NR	0.30					0.10			0.40				0.20	1.00
Turner et al. [53]	R	1.00								1.00				1.00	3.00
	NR	0.33								0.33				0.33	1.00
Harkey et al. [21]	R	3.00					2.00							1.00	6.00
	NR	0.50					0.33							0.17	1.00
Noe¨l et al. [28]	R	4.00					2.00			1.00	2.00			3.00	12.00
	NR	0.33					0.17			0.08	0.17			0.25	1.00
Petritsch et al. [54]	R	3.00								1.00				2.00	6.00
	NR	0.50								0.17				0.33	1.00
Jensen [16]	R	3.00					1.00							2.00	6.00
	NR	0.50					0.17							0.33	1.00
NCHRP [55]	R	3.00								1.00				2.00	6.00
	NR	0.50								0.17				0.33	1.00
Asadi-Shekari et al [7]	R	9.00	4.00	3.00	7.00	1.00	5.00		1.00	7.00	2.00		6.00	8.00	53.00
	NR	0.17	0.08	0.06	0.13	0.02	0.09		0.02	0.13	0.04		0.11	0.15	1.00
Asadi-Shekari [56]	R	10.00	4.00	3.00	7.00	1.00	5.00	9.00	1.00	7.00	2.00	8.00	6.00		63.00
	NR	0.16	0.06	0.05	0.11	0.02	0.08	0.14	0.02	0.11	0.03	0.13	0.10		1.00
FDOT [57]	R	3.00								1.00				2.00	6.00
	NR	0.50								0.17				0.33	1.00
Sum	R	49.00	8.00	6.00	14.00	2.00	18.00	9.00	2.00	26.00	6.00	8.00	12.00	27.00	187.00
	NR	5.17	0.14	0.10	0.24	0.03	1.32	0.14	0.03	2.06	0.24	0.13	0.21	3.18	13.00

1-bike route, 2-signal, 3-bike box, 4-marking, 5-slope, 6-barriers and buffers, 7-parking, 8-trail crossing, 9-pavement, 10-grade, 11-signage, 12- lighting, 13-traffic speed, R: rank, NR: normalized rank.

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