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ABSTRACT

Several methods exist for quantifying the quality of service provided by a roadway from a bicyclist's perspective; however, many of these models do not consider physically protected bike lanes and, of those that do, none is based on empirical data from the US. This is problematic as engineers, planners, and elected officials are increasingly looking to objective performance measures to help guide transportation project design and funding prioritization decisions. This paper addresses this gap by presenting a cumulative logistic model to predict user comfort on protected bike lanes developed from data collected during in-person video surveys. The surveys were conducted in Portland, OR with video footage gathered in Chicago, IL, Portland, OR and San Francisco, CA. The model is for road segments only and not signalized intersections. It complements the *Highway Capacity Manual 2010* level-of-service methods by providing an analysis procedure for a facility type that is not currently included in the manual. The model indicates that the type of buffer, direction of travel (one-way vs. two-way), adjacent motor vehicle speed limit, and average daily motor vehicle volumes are all significant predictors of bicyclist comfort in protected bike lanes. The model predicts a mean value of 'A' or 'B' on an A (most comfortable) – F (least comfortable) scale for all protected bike lane clips used in the survey. Consistent with previous research findings, survey respondents report that protected bike lanes are generally more comfortable than other types of on-street infrastructure.

INTRODUCTION

Long popular in northern Europe, protected bike lanes (PBLs)—also known as "cycle tracks" or "separated bike lanes"— are seeing a surge of installations in the United States. Around 80 such facilities had been built by 2011, but another 61 protected bike lanes have been built since then, an increase of approximately 76% *(1)*. One of the expected primary benefits of protected bike lanes is that they provide a higher level of comfort over a standard bike lane that is only delineated by an inches-wide painted stripe. Indeed, previous research has shown that people prefer bicycling facilities that are physically separated from traffic to standard bike lanes *(2-7)*.

The most recent edition of the *Highway Capacity Manual* (HCM) contains analysis procedures for measuring the level-of-service (LOS), also referred to as quality of service, provided by an urban roadway to bicyclists *(8)*. The method uses different design and operating features of the roadway segment (e.g. width, motor vehicle volumes and speeds) to assess an LOS grade of A (best) to F (worst). These procedures are used by planners and engineers to recommend how existing streets could be retrofitted or new streets designed to better serve people on bicycles (and other modes). However, the current HCM does not include methods that address protected bike lanes, only conventional striped bike lanes, shoulders, and shared streets. There are other methods for predicting comfort from a bicyclist's perspective that do consider protected bike lanes, but they are either based on expert opinion *(9, 10)* or on surveys in Denmark *(11)* and it is not clear if their results correspond to the actual perceptions of the American traveling public.

This paper fills in some of this gap by presenting the results of an experiment to predict user comfort on protected bike lanes using surveys conducted in the United States. The resulting model is for road segments only and not signalized intersections. Data were collected for model development using a procedure similar to the HCM *(12)* and Danish methods *(11)*. The surveys were conducted in Portland, OR with video footage gathered in Chicago, IL, Portland, OR and San Francisco, CA. Video surveys have previously been shown to be an effective substitute for field surveys involving individuals actually riding on the study facilities *(13)*. They also allow for a large group of individuals to view multiple locations that might otherwise be impossible to recreate in a field study. The model could be used to supplement the current HCM to consider a wider range of options for improving the environment for bicycling.

The remainder of this paper is organized as follows. The paper begins with a brief review of prior research related to measuring comfort for bicyclists. The following section describes the process for filming and selecting the clips and administering the surveys. The collected data on user comfort ratings are used to develop models to predict user comfort based on variables related to motor vehicle traffic, roadway characteristics, and facility characteristics. To partially validate the model, the model is applied and the results are compared to self-reported comfort levels of cyclists who were intercepted on protected bike lanes as part of another independent, but related, research effort. A simple example application is then presented. Finally, conclusions and limitations of the model are presented. A more detailed project summary and additional analysis can be found in the corresponding author's master's thesis *(14)*.

PRIOR RESEARCH

Constructing protected bike lanes may be a means to attract more individuals to bicycle because they reduce the perceived risk of bicycling. Several surveys have shown that people prefer bicycling facilities that are physically separated from traffic to standard bike lanes *(*2-7*)*. In a study of Danish residents, Jensen *(15)* found that 45% of the respondents said that they felt "very safe" when bicycling on protected bike lanes, as opposed to about 30% for standard bike lanes, and just over 10% for shared streets. This study also found an increase in bicycle and moped (which also use the infrastructure) volumes of 18-20% on streets where protected bike lanes were constructed. Finally, a study of protected bike lanes in Washington, D.C. found that bicycle volumes increased by over 200% during the p.m. peak hour after the installation of the lanes and that surveyed bicyclists generally reported feeling more comfortable riding in the lanes than they had riding on the street before *(16).*

Researchers and practitioners have developed a number of quality-of-service (QOS) models for bicyclists *(8-12, 17-28)*. The six most relevant methods are summarized in Table 1. Of these, four use regression-based models using an 'A' – 'F' scale and two employ categorical indices producing final numeric scores. Most of the regression-based models used ordinary least squares (OLS), though one used logistic regression. Only the Danish LOS and the Level of Traffic Stress approaches consider protected bike lanes, and, of those two, only the Danish model is based on empirical data. The US models were developed with inputs from 150-200 participants and the Danish model includes results from over 400 participants.

TABLE 1 Summary of Select Bicycle QOS Methods

Method	Form	# of Participants	# of Study Sites[1]	Considers Protected Bike Lanes?
Highway Capacity Manual 2010 LOS *(12)*	OLS Regression	145	30	No
Danish LOS *(11)*	Logistic Regression	407	56	Yes
Florida Department of Transportation LOS *(20-22)*	OLS Regression	60-150[2]	21-30[2]	No
FHWA Bicycle Compatibility Index *(24)*	OLS Regression	202	78	No
Level of Traffic Stress *(9)*	Index	Not based on observational data		Yes
San Francisco Bicycle Environmental Quality Index *(10)*	Index	Not based on observational data		Partially

[1]Not all sites shown at each viewing
[2]Includes multiple studies

Data Collection

Most of the methods are based on participant surveys completed after watching videos. Frequently this involves recording video of different routes and/or intersections and showing them to participants in some type of controlled environment (e.g. a room with a projector, screen, and speakers) (3, *11*, *12*, *13*, *19*, *23*, *24*, *25*) or via an internet survey (*27*). These videos are usually filmed from a moving bicycle (3, *11*, *12*, *13*, *19*, *23*, *25*), but they may also be recorded on a camera in a car (*27*) or a stationary camera (*24*). Field surveys, where individuals ride and then rate each segment or intercept surveys are also used. While field rides provide complete immersion for the participants, video surveys are often preferred to avoid the potential risks that come with placing individuals in potentially dangerous conditions (*12*, *13*, *24*) and because of the opportunity to control the conditions experienced by all participants (*24*).

Factors Considered

The most commonly considered factors include speeds of adjacent motor vehicles *(8-11, 17-22, 24, 28)*, the width of the space available for bicyclists (e.g. bike lane width, shared lane width) *(8-11, 18-22, 24, 25, 27)*, the type of facility available *(8-11, 18, 19, 24, 26)*, and motor vehicle volumes *(8, 10, 11, 17-22, 24)*. The width of the outside motor vehicle lane is also sometimes included *(8, 11, 17, 22, 24)*.

User Demographic Influences on Comfort Perceptions

User demographics are typically not included in predictive LOS models, though research often finds correlations between comfort level and some personal characteristics. Jensen *(11)* found no significant correlation between demographics and scores; though his study did observe that men and younger individuals generally felt more comfortable. Tilahun, et al. *(3)* found that gender and age produced similar trends in their utility model but were not significant predictors at the 95% confidence level. However, Petritsch, et al. *(13)* found age and gender to both be significant predictors in their work to develop the Florida Department of Transportation (FDOT) LOS model (again with men and younger individuals providing more comfortable ratings). The studies have produced more definitive results in terms of the impact that bicycling experience has on comfort ratings, finding that that more experienced riders are typically more comfortable than less experienced riders at a significant level *(17, 22, 24)*. Dowling et. al *(12)* also found statistically significant differences in their results based on the metro area the survey took place in; however, Harkey, et. al. *(24)* found no difference in scores among the three metro areas they surveyed.

METHODOLOGY

This research employed a video survey approach to data collection. As suggested in the literature, it is preferred to field rides because it is more efficient and allows people to rate conditions not found locally and has been found to produce comparable results to field rides *(13)*. The resulting model produced by the data is verified with intercept survey responses from a different project studying protected bike lanes *(29)*.

Video Collection and Production

High-definition video was taken while biking along each study site using a GoPro® Hero 3 camera at eye level mounted to a bike's handlebars using a metal post. Audio was recorded by using an external stereo microphone with a windscreen. The author rode each study route at a speed of 10-14 miles-per-hour (MPH) while filming, which is about the speed of an average bicyclist *(30)* and comparable to previous efforts *(11, 12, 25, 27)*.

One of the challenges to using a fixed-metal pole for the camera mount is that it doesn't dampen road vibration well. To mitigate this effect, each of the chosen clips was post-processed to smooth the bumpiness of the video using iMovie 2009. This program is effective at smoothing slight bumps; however the roughness of the pavement still shows on clips from routes with significant cracking or otherwise rough surfaces. After the fact, it was discovered that selecting a lower frame rate for filming would have improved the ability of the program to smooth the video clips.

Site Selection

Two general groups of sites were selected for this project: protected bike lanes to be used for model development and sites of more common infrastructure types (e.g. standard bike lanes, shared streets, and off-street paths) to be used for comparison (reference) purposes. The primary goal in selecting protected bike lane sites was to include a variety of different buffer types and have both one-way and two-way facilities represented. Candidate sites were limited to those present in cities being traveled to for a separate project (i.e. Chicago, Portland, and San Francisco). Reference sites were chosen to determine how individuals would perceive their comfort biking on protected bike lanes as compared to more common situations.

An initial list of 20 clips ranging from 21 to 30 seconds in length was selected for showing, for a total video running time of less than 15 minutes. The project team determined after the first survey that three of the clips were providing redundant information about user comfort and they were replaced by three other clips to provide a greater variety of facilities.

The selected clips cover a range of facility types, as shown in Figure 1. Some of the clips are taken from the same, or similar, location on a given street in order to determine if the number of motor vehicles passing the bicyclist in the adjacent motor vehicle lane influences participant ratings. Average daily traffic (ADT) volumes for each facility are from official City or State counts.

FIGURE 1 Screenshots and Select Characteristics of Survey Clips

Survey Administration

The survey instrument was designed to make it comparable to previous methods, to be simple and easy to understand, and to collect enough demographic information to examine potential biases in the sample. Respondents were asked to rate each clip on a scale from 'A' (extremely comfortable) to 'F' (extremely uncomfortable). The 'A' through 'F' scale is intuitively understood by most people and is comparable to the six point scales used in the *HCM 2010* and Danish LOS methods *(8, 11)*. Participants are also asked to provide basic demographic information.

The survey was administered in-person three times. The first two surveys took place during the weekly Portland Farmer's Market located at the Portland State University (PSU) campus on November 16 and 23, 2013. There are several farmer's markets in the Portland area, but the one held at PSU is the largest. It was chosen as a location for the survey because it attracts a wide range of people, in terms of age, gender, and bicycling habits. Given that it was late in the season, so most other regional markets had closed, and one of the weekends was before Thanksgiving, it was expected that the market would be drawing from around the region and not just inner Portland.

The survey itself was conducted in a room in the PSU student union building, set-up with a projector, screen and external sound system. Lights were turned off in the room and the audio was turned up to a volume that represented actual traffic conditions. The clips were played on a continuous loop with the clip number appearing before each one started, so participants were instructed to find the first clip number that appeared after they entered the room on their grading sheet and begin from there, continuing until they came back to where they started. The room was set up so that individuals walking in and out of the room were out of the view of the seated participants. Eight-seconds of grading time were provided after each clip. Participants were recruited through signs placed outside of the entrance to the student union where the Farmer's Market was taking place that advertised the survey. Participants were offered a $5 token to be spent at the Farmer's Market in exchange for their participation in the survey.

The third and final in-person survey took place at the Oregon Museum of Science and Industry (OMSI) on December 4, 2013. The survey coincided with the monthly OMSI After Dark event, in which the museum is only open to those age 21 years or older. This event was chosen because it eliminated the difficulty of trying to recruit participants with children and because it is popular, drawing hundreds of guests from around the area. The set-up and process at OMSI was similar to the farmer's market.

Validation Survey Data

A separate project the authors were involved in collected comfort ratings from individuals who have ridden on different protected bicycle facilities *(29)*. Data from these surveys (labeled here the "intercept survey") are used to validate the model developed using the video-based survey data. Over, 3,230 individuals bicycling on protected bike lanes in Austin, TX; Washington, DC; San Francisco, CA; Portland, OR; and Chicago, IL completed a survey about their experience with the protected bike lane they were riding on after being handed a postcard with a link to the online survey.

Although the respondents rated their comfort on the protected bike lane in a similar fashion to those who watched the videos, the results from intercept survey are not necessarily directly comparable to the results from this video survey. In particular, the intercept survey questions cover the entire length of the facility that the respondent has ridden, encapsulating signalized intersections and changing conditions (i.e. different buffer types facility), whereas the video survey did not include any signalized intersections and the clips show only uniform sections. Also, the intercept survey only includes individuals who currently ride on the facility, so it does not capture individuals who do not currently bicycle.

RESULTS

Participants

A total of 221 individuals participated in the survey (146 at the market and 75 at OMSI). The resulting sample provides a wide range of participants in terms of age, gender, and bicycle riding experience. Table 2 summarizes the demographics of participants. The sample generally represents a wide range of individuals, comparable to, or more diverse than, previous studies. However, it skews toward younger persons and those who bicycle more frequently than the general population, despite the efforts to recruit broadly.

TABLE 2 Participant Demographics

Demographic Characteristic	Summary
Age	18-89 years; Mean = 36 years; Interquartile Range = 27-44 years
Gender	Female = 52% (n=115)
Riding Frequency	6+/week = 6% (n=14) 3-5x/week = 20% (n=44) 1-2x/week = 16% (n=35) 1-2x/month = 34% (n=75) Never = 23% (n=50) No Response = 1% (n=3)
Access to a Working Bicycle	Yes = 79% (n=175)
Would Like to Bicycle More Often	88% Strongly/Somewhat Agree (n=194)

Demographic Influences on Scores

Correlations between scores and demographics were analyzed in order to determine what types of biases may exist within the sample. Age (R=0.06, p=0.01) and riding habits (R=-0.10, p<0.01) are weakly correlated with the scores of individual clips, with scores tending to worsen as age increases and improve as riding frequency increases. Gender (R=0.03, p=0.11) is not significantly correlated with the score for individual clips, indicating there is no statistical difference in the ratings provided by men compared to women.

Mean Comfort Score by Facility Type

Figure 2 shows the mean score by facility type for all video clips. The relative preference for different facility types is mostly consistent with previous route preference research *(3, 4, 30).* The exception to this is that the bike lane with parking facility type is ranked higher than the two-way protected bike lane and the bike boulevard (a low-volume shared-use street with traffic calming and diversion features and signage and markings to promote bicycle use - see Figure 1). This is possibly a function of only one clip representing a bike lane with parking and it is on a residential collector with a 25 MPH speed limit. Also, the ratings for the bike boulevard clip have the largest standard deviation in the study, indicating a wide range of comfort with the facility shown in this clip, and the median score for the bike boulevard is the same, ‘B,’ as the bike lane with parking clip and most of the two-way protected bike lane clips.

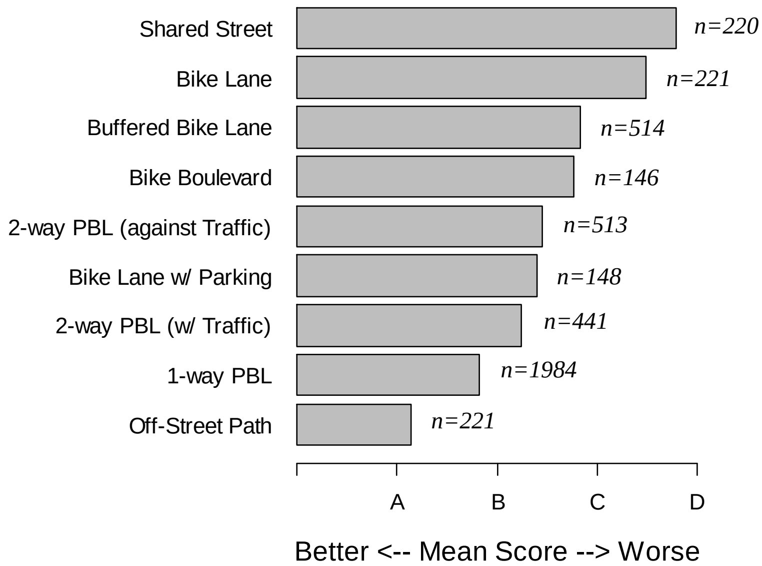

FIGURE 2 Mean Score by Facility Type

An ANOVA test reveals that on the whole, the difference in mean scores by facility type is significant ($p < 0.01$). A Tukey post-hoc analysis of the ANOVA shows that most facility types are significantly different from each other at 95% confidence level. There are a few exceptions, notably for protected bike lanes that the difference in scores for riding against or with motor vehicle traffic on a two-way facility is not significant. This indicates that contraflow riding may not significantly influence comfort on a two-way protected bike lane.

Protected Bike Lane Characteristics

The median score for all protected bike lane clips is either 'A' or 'B.' A Tukey post-hoc analysis of an ANOVA of buffer type and score reveals that most buffer types are significantly different from each other at the 95% confidence level. The exceptions to this are raised/parking and parked cars and raised/parking and posts. There is only one clip that has a raised facility, so the sample size is small.

Pearson correlations are estimated for a number of other variables to determine how well they might predict changes in rider comfort. These variables include motor vehicle volume and speed, unsignalized conflict density, number of travel lanes, and buffer width. On their own, all of the variables are weakly correlated with comfort ratings. The low correlation values do not necessarily mean these variables are not important for predicting bicyclist comfort. Instead, they indicate that the relationship between these characteristics and comfort may be complex with some level of interdependency between variables.

Model Development

A series of cumulative logistic models (CLM) are developed. Logistic regression is preferred to OLS regression because the residuals from ordered response data are often non-normally distributed, which violates one of the assumptions of OLS regression, and OLS regression can predict values outside the allowable range (i.e. one to six).The proportional odds assumption underlying the CLM model has been approximately met in the dataset. The CLM model predicts the probability that a user will provide a given comfort score for a facility. This can also be interpreted as the percentage of the population that would view the facility at a given comfort rating. A single score for the facility can be determined based on when the cumulative probability reaches a certain threshold or a weighted average of the predicted distribution. Jensen *(11)* recommends reporting the median value; however, this threshold can be modified to an agency's goals (e.g. if the desire is to have facilities that are comfortable for 75% of the population, then the threshold could be set to 75%).

Table 3 summarizes the range of variables included in the survey that could be used to estimate the models. Other variables were considered but excluded from the model after exploration. These include facility width, pavement condition, and the density of unsignalized conflicts (e.g. driveways). There is not enough variation in the facility width of the sample protected bike lanes to include this variable in the model. Pavement condition is commonly used in other models; however it is also sometimes excluded because it is not readily available data and not under the control of designers *(11, 27)*. For these latter reasons, it is also excluded here. Unsignalized conflict density is not included in the final models because this information is not typically readily available and it can be difficult to collect for a large study area. The range of the number of driveways on each segment is also limited.

TABLE 3 Model Variable Summary

Factor	Number of Clips with Factor	Number of Unique Facilities with Factor
Planter Buffer	3	1
Posts Buffer	3	3
Parked Cars Buffer	8	3
Raised w/ Parking Buffer	1	1
1-Way	10	6
2-Way	5	1
25 MPH MV Speed	9	3
30 MPH MV Speed	5	3
35 MPH MV Speed	1	1
2 Travel Lanes	11	6
3 Travel Lanes	4	2
Average Daily Traffic (ADT) Volume	Mean 12,160 St. Dev= (5,635), Range 4,380 – 28,160	

Three models are presented in Table 4. The first two, A and B, use only variables for which data are likely to be readily available to practitioners:

- Buffer type
- Facility type (1-way vs. 2-way)
- Motor vehicle speed
- Number of motor vehicle travel lanes
- *ADT (as a substitute for number of motor vehicle travel lanes)*

These listed variables also have some of the highest Pearson correlation values with the comfort scores for either all protected facilities or one-way protected facilities only. Further, the latter three variables are among the most commonly included items in other models. The third model, C, is an exploratory model determined by the statistical software package, R, using stepwise regression and drawing on a wider range of possible variables *(31-34)*. The purpose of Model C is to compare how a model that draws on a wider range of variables, some of which may be difficult to gather, performs with respect to Models A and B, which are limited to the variables listed above.

All three models are statistically significant predictors of comfort rating at the 95% confidence level ($p<0.01$ for all three compared to the null model using a chi-squared test). Model B has the lowest deviance and all of its coefficients are significant predictors at the 95% confidence level. Model C produces inconsistent results as compared to the other two models (i.e. the Parked Car buffer has a positive coefficient). Therefore, the discussion below focuses on Model B. Note that because lower scores are better (A=1, F=6) the interpretation of the signs on the coefficients are such that negative signs mean improved comfort scores.

TABLE 4 Cumulative Logistic Regression Model Results

Variable[1]	**Model A Coefficient/(odds ratio)**	**Model B Coefficient/ (odds ratio)**	**Model C Coefficient/(odds ratio)**
Planter Buffer	-1.99/(0.14)**	-2.13/(0.12)**	-0.89/(0.41)*
Parked Car Buffer	-1.26/(0.28)**	-1.38/(0.25)**	0.87/(2.39)
Raised/ Parking[2] Buffer	-0.35/(0.70)	-0.70/(0.50)**	1.13/(3.09)
Two-Way Facility	1.24/(3.44)**	1.12/(3.08)**	0.93/(2.55)**
MV Speed	-0.01 (0.99)	n/a	n/a
# of MV Lanes	-0.30 (0.74)**	n/a	n/a
ADT (1,000 vehicles/day) * MV Speed	n/a	-0.001 (1.00)**	n/a
ln(MV Volume in Adjacent Lane (Veh/hr))	n/a	n/a	0.50/(1.65)**
ln(Buffer Width)	n/a	n/a	-0.13/(0.28)
MV Volume in Adjacent Lane (Veh/hr) * Buffer Width	n/a	n/a	0.09/(1.00)
Intercept: A-B	-2.05	-1.60	0.50
Intercept: B-C	-0.40	0.05	2.15
Intercept: C-D	1.09	1.53	3.65
Intercept: D-E	2.09	2.54	4.65
Intercept: E-F	3.15	3.60	5.71
Log Likelihood	-3,305	-3,230	-3,295

Note that because lower scores are better (A=1, F=6), negative signs on coefficients mean improved comfort scores.
[1]The reference facility has a posts buffer and is a one-way protected bike lane
[2]Parking is not expected to be occupied often
*Significant at the 95% confidence level
**Significant at the 99% confidence level

Interpretation of the model coefficients allows us to predict how changing one (or more) features of the protected lane would affect comfort levels. The baseline or "reference" facility is a one-way lane with flexposts in the buffer. For example, in Model B, changing the buffer from the baseline to a planter increases the odds of an individual rating a facility one grade better by approximately 730% ((1/odds ratio) – 1). Adding a mostly-occupied buffer of parked cars increases the odds 300%, and raising the lane slightly above the street grade with an unoccupied parking buffer increases the odds 100%. Conversely, the odds of an individual rating the facility one letter grade worse increase by about 208% if it is a two-way protected bike lane. A one unit change in ADT (1,000) multiplied by motor vehicle speed has minimal impact on the odds of an individual's rating changing.

Model B is selected for further evaluation. Figure 3 compares the predicted distribution of responses for each protected bike lane clip from Model B to the observed distribution of responses from the video survey. As inspection of the figure reveals, the selected model predicts distributions that are relatively similar to what is observed in the video surveys. Although not shown, the model also correctly predicts the median score for all fourteen clips.

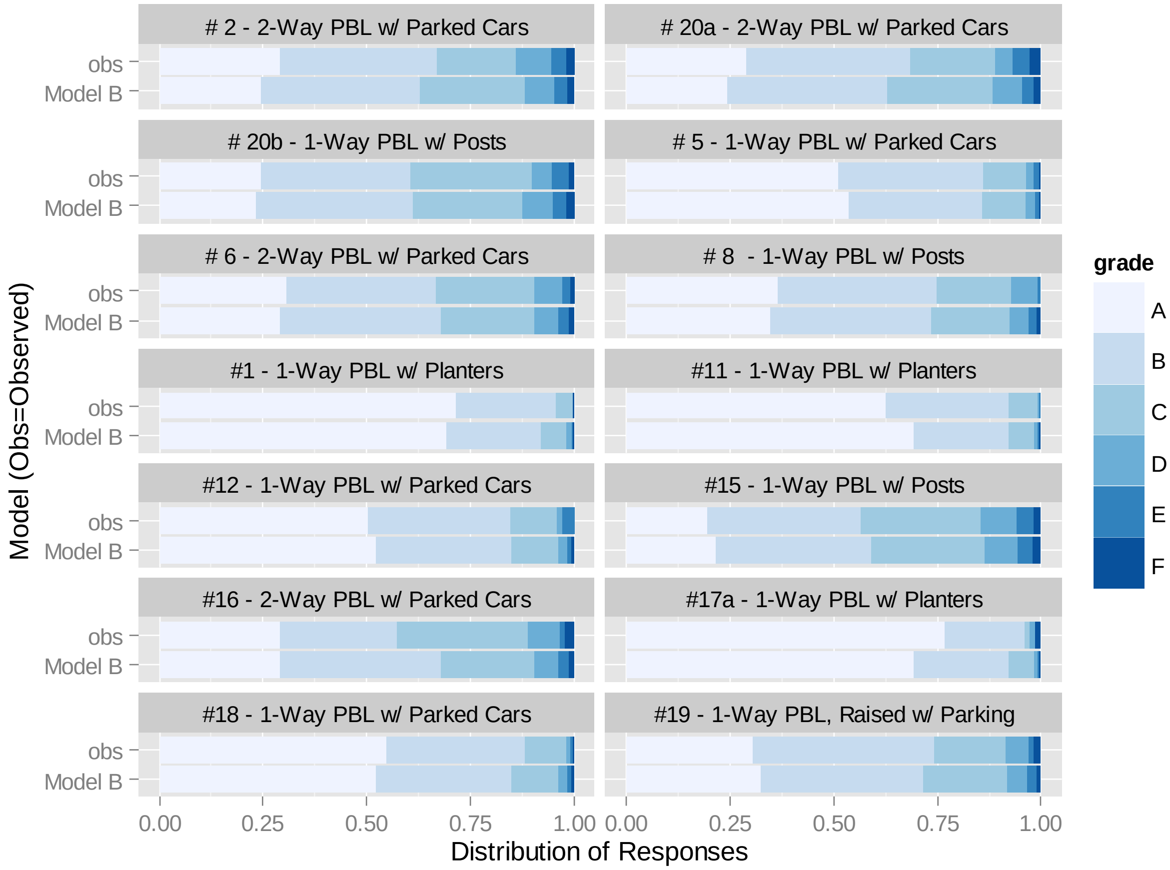

FIGURE 3 Predicted vs. Observed Distributions

Model Validation

The model was validated using the intercept survey described previously in the methodology section and the Danish LOS model *(11)* for road segments. The results are shown in Figure 4. In the figure, "Obs" is the distribution of responses from the intercept survey respondents, "Model B" is the results of applying Model B to the facilities the bicyclists were intercepted on, and "Danish" is the results from applying the Danish LOS model for road segments to the surveyed facilities. Note that there is also a Danish model for intersections, but it is not used here in order to provide a direct comparison to Model B.

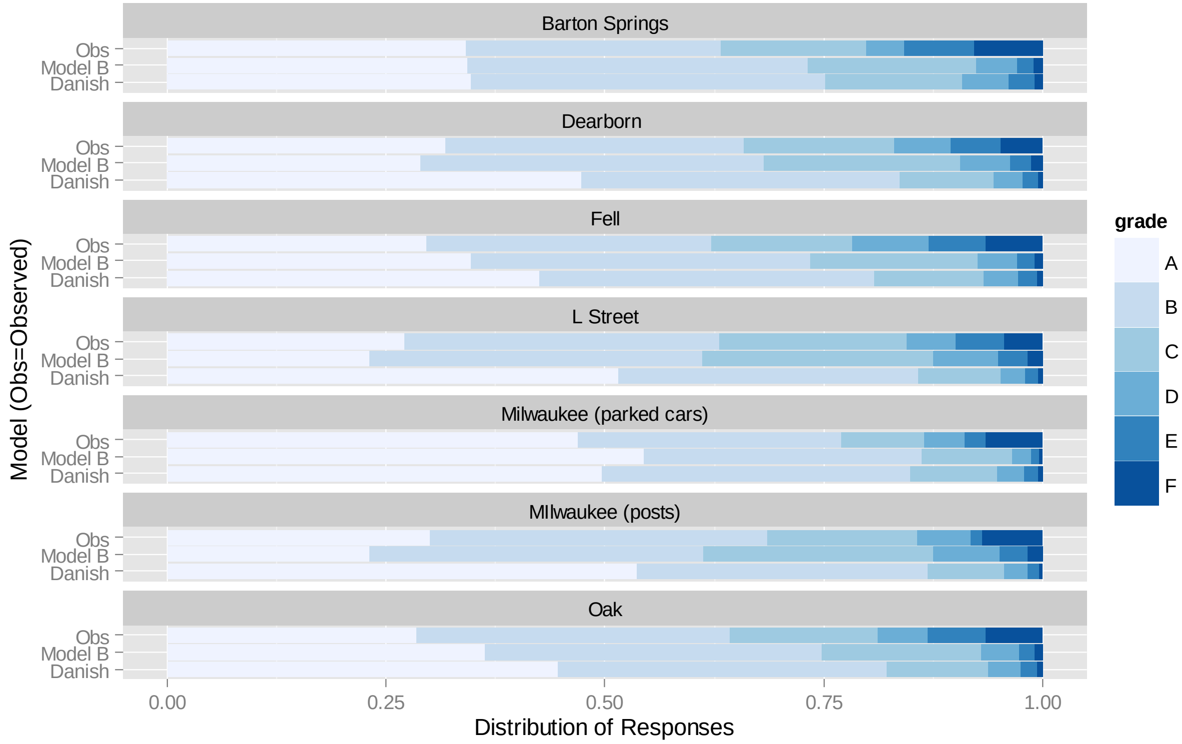

FIGURE 4 Predicted vs. Observed Responses – Intercept Facilities

Predictions from the two models generally approximate the frequencies observed in the surveys. While neither model includes signalized intersections, Model B generally tracks closer to the observed frequencies (especially for the 'A' and 'B' grades) than does the Danish model. As noted above, the intercept survey method covered the entire length of the protected lane, including signalized intersections, so it is not a perfect source for validation. Both models underestimate the 'D'-'E'-'F' scores which most likely indicates that a user's perceived comfort on the entire facility is significantly affected by the experience at intersections.

It is important to note that while there is some overlap between the facilities in the validation attempt and model development, the models are applied to a few facilities that were not included in the model development. Barton Springs Road (Austin, Texas) and L Street (Washington, DC) are not included in the video survey. Neither is Oak Street (San Francisco, California), but it is similar to Fell Street, which is shown in the video survey, as they share similar designs and form a couplet. Milwaukee Avenue (Chicago, Illinois) is shown in the video surveys, but only with a posts buffer. Given that Model B predicts frequency distributions similar to what is shown from the surveys of these facilities, the model appears to be transferable to other facilities that are within the same ADT range (approximately 8,000 to 30,000 vehicles/day), same speed range (25-35 mph), and feature the same buffer types (i.e. parked cars, posts, or planters) as those included in the video survey. It may also be more applicable to American facilities than the Danish model, but further analysis using the Danish intersection model would be required to verify this.

EXAMPLE APPLICATION

To demonstrate the application of the model, a simple example is presented. A jurisdiction is considering adding a protected bike lane to a three-lane one-way street with an ADT of 11,000 vehicles per day that has on-street parking but no bike facilities. Using *HCM 2010* methodology, such a street would have a link LOS of 'D' for bicycling. Assuming sufficient width to remove a travel lane and replacing it with a one-way protected bike lane with a parked car buffer, application of the model would be as follows:

Probability of an 'A' rating = $1/(1+e^{(-(-1.60)-1.38-0.001*(30*11,000/1,000))}) = 0.53$

$p(B) = 1/(1+e^{(-(0.05)-1.38-0.001*(30*11,000/1,000))}) - 0.53 = 0.32$

$$p(C) = 1/(1+e^{(-(0.05)-1.38-0.001*(30*11,000/1,000))}) - (0.53 + 0.32) = 0.11$$

$$p(D) = 1/(1+e^{(-(2.54)-1.38-0.001*(30*11,000/1,000))}) - (0.53 + 0.32 + 0.11) = 0.03$$

$$p(E) = 1/(1+e^{(-(3.60)-1.38-0.001*(30*11,000/1,000))}) - (0.53 + 0.32 + 0.11 + .03) = 0.01$$

$$p(F) = 1 - (0.53 + 0.32 + 0.11 + .03 + 0.01) = 0$$

In summation, the model estimates that about 53% of people rate it an 'A,' 32% a 'B,' 11% a 'C,' 3% a 'D,' 1% an 'E,' and <1% 'F'. The new LOS could be reported as 'A' using the median value predicted by the model or as a "B" (1.67) using the weighted average of the predicted distribution.

DISCUSSION

The recommended model (B) uses variables that are readily available for most collector-level and above roadways. Application of the model was compared to comfort scores on intercept survey data from another project of actual bicyclists on a variety of protected bike lanes. The predicted median comfort ratings and distributions of those ratings are generally similar to the responses from the survey.

The model is only valid for the following situations:

- ADT volume of approximately 9,000 to 30,000 vehicles per day
- Speed limit between 25 and 35 MPH
- Buffer type is posts, parked cars, raised surface with an unoccupied parking lane, or planters

This model can be used to complement the *HCM 2010* methodology when protected bike lanes are being considered. For situations that fall outside the range of this model, the Danish LOS model provides a useful substitute.

A significant limitation of this study is the variety of protected bike lanes used in the clips. Due to logistical constraints and the limited number of protected bike lane installations in the US, study sites for this project were limited to the Portland area and a few locations in Chicago and San Francisco. The ability to show a wider variety of facilities was further limited by the desire to show multiple clips from the same facility in order to isolate the impact of motor vehicle traffic on user comfort in the video, to include reference video clips of more common bicycling infrastructure, and to limit the survey to about 15 minutes. Most notably, there are multiple video clips of a two-way facility; however, they are all from Dearborn Street in downtown Chicago. Therefore, the two-way dummy variable in the model is based on one facility in a dense urban environment. Additionally, the planter and raised with unoccupied parking buffer types are represented by only one facility and that the parking buffer is unoccupied in the video is a limitation in that this situation will only exist in specific situations (e.g. residential areas in the daytime). Another significant limitation of this study is that it does not include intersections. This was an intentional decision made in order to isolate the variables that influence segment level comfort. The buffer alongside a protected bike lane necessarily disappears at intersections, making it seem likely that comfort is likely to be less through an intersection. Finally, the sample used in this survey is relatively young in age, rides more frequently than the general population.

Surveys were conducted only in Portland, Oregon, but we believe the results are generally transferable across the US. Previous studies *(12, 24)* have produced conflicting results on whether the location of a survey impacts results. The one study that found a difference among locations noted that respondents in areas with a metro population of greater than one million (i.e. San Francisco, California and Chicago, Illinois) generally had lower levels of comfort than smaller areas (i.e. College Station, Texas and New Haven, Connecticut) *(12)*. Finally, there are a limited number of protected bike lanes in the Portland metropolitan area and many of the respondents do not bicycle frequently, so do we not expect biases due to familiarity with this type of treatment.

CONCLUSIONS

This paper presented a mathematical model to predict how comfortable a bicyclist is likely to feel riding in a protected bike lane under various conditions. This work is a unique contribution in that there are currently no such models to predict bicyclist comfort in protected bike lanes that are based on data from the U.S. The final recommended model, a cumulative logistic model, predicts the probability that a user will provide a given comfort score for a facility. This can also be interpreted as the percentage of the population that would view the facility at a given comfort rating; thereby providing a more complete picture of the facility's performance than can be ascertained from a mean score provided by a simple linear model. A single score can be reported based on the critical threshold desired by the agency (i.e. a policy that the score is based on a certain percentile of the population viewing the facility at that score or better).

Future research related to quantifying bicyclist comfort in protected bike lanes should focus on intersection treatments. Given the narrow range of median values for the protected bike lane clips, the utility of a more robust effort to create a segment model may not be as high as creating an intersection model. There are several different intersection treatments in use today, which is likely indicative of a limited understanding of how well they perform in regards to bicyclist comfort, among other factors. Such an effort should be modeled after this study and other previous efforts. Ideally, an intersection model would eventually be combined with a segment model to provide a complete picture of an entire route. The model created for this project only includes protected bike lanes. A comprehensive model incorporating all types of bicycle facilities should be created. The resulting model should be either a simple index model or a cumulative logistic model using readily available data. It should also incorporate other types of bicycle facilities not covered in most models, such as buffered bike lanes.

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