ABSTRACT

There is a need for methods that provide a better understanding of bicyclists’ perceived safety and comfort on currently unavailable bicycling facilities. Different survey methods have been used to study bicyclists’ behaviour, experiences, and preferences; ranging from verbally described bicycling facilities to surveys including images and videos. Virtual Reality (VR) experiments blur the boundaries between SP and RP surveys and provide a realistic sense of design. This research introduces a novel research method and discusses the results of an experiment using a cycling simulator combined with immersive VR. Each participant bicycled along five bicycling environment on an instrumented bicycle. In total 150 participants participated in this experiment and answered a questionnaire asking about demographics,
bicycling attitudes, and perceptions and preferences after bicycling in VR. ANOVA tests discuss how each bicycling environment and ambient traffic / pedestrian volume affect perceived level of safety (PLOS) and willingness to bicycle (WTB). Results show that VR is a valuable tool to evaluate future street designs and can inform transport and urban planning.

**Keywords:** bicycling perceived level of safety, cycling simulator, virtual reality experiment, bicycle survey methods.

### 1 INTRODUCTION

Although bicycle mode share is very low in Singapore (Land Transport Authority of Singapore, 2014), the Singaporean authorities have ambitious plans to encourage bicycling by construction of more than 1000 km bicycling path network by 2040 and enable bicycling as a viable mode of transport for all road users in the future (Land Transport Authority of Singapore, 2019). Therefore, it is required to study people’s perception in different bicycling environments and evaluate their behaviour and preferences, to better plan for the development of bicycling infrastructure. However, considering the low bicycle mode share, limited bicycling experience, and scarcity of bicycle infrastructure in Singapore, the application of classic survey methods is unlikely to yield results to inform planning decisions.

Transportation engineers and planners have been attempting to estimate bicyclists’ safety, comfort, stress levels, and level of service for nearly three decades (Blanc and Figliozzi, 2016). Previous studies showed that the segment-level factors are more important than the route-level factors and safety-related factors (such as bicycle facility type and auto traffic volume) are deemed more important than comfort-related factors (such as streetscape and presence of
greenery) when studying bicycle users’ preferences (Lawson et al., 2013; Zhu et al., 2017).

Furthermore, subjective perception of safety can strongly influence travel decisions (Doorley et al., 2019; Winters et al., 2011). Therefore, it is essential to give special consideration to the subjective safety perceptions of bicyclists at the segment-level.

The following sections describe the methods that have been proposed in the literature to evaluate the quality of a segment of a road for bicycling. Despite having different names for their models, researchers are generally headed toward developing models which incorporate different sets of variables to describe the quality of service provided to bicyclists. Sections 1.1 to 1.3 discuss about different assessments models and section 1.4 summarises different survey methods in this regard.

1.1 Objective road assessment for bicycling

Various models have been proposed to evaluate road bicycling suitability or road bicycle friendliness, also known as bikeability. With the underlying objective to compare different roads, the main goal of these models is to identify how compatible a roadway is to accommodate safe, comfortable, and efficient operation of cyclists and to quantify the quality of service afforded bicyclists travelling roadway networks. One of the very first systematic attempts was to measure the operational condition of roadways to calculate bicycle safety index rating; traffic characteristic, geometric design data, intersection features, and other variables are used to derive an index which exhibits roadway desirability for safe bicycle operation (Davis, 1987; Epperson, 1994).

In a similar approach, objective roadway measurements were combined with bicycle volume to calculate an Interaction Hazard Score. This theoretical model estimates actual and perceived bicycling hazards to cyclists when sharing roadway segments with motor vehicles (Landis, 1994).

Another effort recommended roadway design guidelines that are subjectively assigned based
on traffic characteristic and type of cyclists (Wilkinson et al., 1994). Although all the
aforementioned models try to measure bicyclists’ perception of the magnitude of the hazards
(stress, risk, or conversely comfort), they all lack recognition of the bicyclists’ perspective. After
all, the decision whether a roadway is suitable for riding is taken at the individual level based on
bicyclists’ perceptions.

1.2 Bicycle stress level

The concept of bicycle stress was first developed by the Geelong Bikeplan team in Australia
(Geelong Planning Committee, 1978). Cyclists’ perspective about the adequacy of the road was
incorporated in addition to traffic characteristic and geometric design data, to pinpoint the less
comfortable roads for bicycling. Key environmental elements affecting cyclists’ stress level were
identified and values from one to five were assigned to each location to reflect the experienced
amount of stress when riding under those conditions. The word stress referred to the mental
effort while bicycling to deal with other vehicles and strain from concentration required for
riding.

A similar study later suggested a framework to individually measure the effect of traffic volume,
motor vehicle speed, and curb lane width on bicycle stress level (Sorton and Walsh, 1994). The
study included 61 participants whom were asked to rate their answers about the comfort level
for bicycling in any of the 23 road segments. Bicycle stress level was later evaluated for young,
casual, and experienced cyclists. However, due to the small sample size, the results were not
statistically validated. The results of this experiment showed that cyclists can recognise
differences in levels of traffic volume, motor vehicle speed, and lane width, which was reflected
in the level of stress ratings.

Recent studies on bikeability and bicycle stress level experience a methodical revaluation by
taking human perception more into consideration and embed cyclists’ perceptions in an urban
design context. The rationale for this methodological shift is the belief that the involvement of
the human perception can lead to a more accurate identification of the built environment for
bicycling. Human-centric models was practised by application of bio-physiological and eye-
tracking sensors’ data to detect bicyclists’ emotions connected to bicyclists in the field (Berger
and Dörrzapf, 2018; Caviedes and Figliozzi, 2018; Zeile et al., 2016). The outcome of such studies
identifies stressful locations for bicyclists on a predefined route. Post hoc analysis of the data
from video camera attached to bicyclist, data from sensors collecting environmental attributes,
and self-expressed emotions of the bicyclist investigates specific events or situations to be
correlated to the stressful moments. However, one of the limitations of naturalistic studies is
the replicability of the field study and control for all environmental factors; meaning that it is
not feasible to replicate exactly the same conditions for every participant in real field
experiments.

1.3 Bicycle Level of Service (BLOS)

The concept of level of service was introduced by Highway Capacity Manual (HCM) and is widely
used to qualify the operational characteristics associated with various levels of vehicles or
people passing a given point during a specific time period (Harkey et al., 1998). Level of Service
(LOS) is defined as “qualitative measures that characterize operational conditions within a traffic
stream and their perception by motorists and passengers”. LOS criteria for the motorised vehicle
mode is based on performance measures that are field-measurable and perceivable by traveller.
However, the LOS criteria for pedestrian and bicycle mode are based on scores subjectively
reported by travellers indicating their perception of service quality after watching videos of
different bicycling environments (Hummer et al., 2006). Bicycling perceptions can be combined
with observed geometric and operational conditions of the roadway to indicate bicycling
comfort by defining a bicycle compatibility index (Harkey et al., 1998).
Traveller perception research is needed to determine the BLOS. Bicyclists are asked to rate the quality of service associated with a specific trip along an urban street. The letter A is used to represent the best quality of service, and the letter F is used to represent the worst quality of service (Transportation Research Board, 2016). However, HCM’s detailed methodology is not sensitive to the details of bicycle facilities on links, i.e. painted bicycle lane, striped buffers, or bicycle tracks. Furthermore, even though HCM BLOS index is a complex method that measures road performance considering safety, comfort, and operation aspects while reflecting bicyclists’ perceptions measured in the field, it lacks travellers trip characteristics such as perceptions of bicyclists travelling with their children or their friends.

### 1.4 Bicycle survey methods

Over the years, travel survey methods for bicycle research have been evolved and new research tools and approaches have been introduced. Telephone surveys are used to understand bicycling perceptions and attitudes of people. For instance, telephone surveys have been used to understand motivators and deterrents for bicycling (Winters et al., 2011) and perceptions of the build environment (Ma and Dill, 2015). Intercept surveys assess bicyclists’ views of the bicycling environment or to measure the impact of a new bicycle infrastructure (Dill et al., 2016; Standen et al., 2017). However, since only bicyclists are studied in intercept surveys, any random sample might not accurately represent the broader population of people with different concerns about bicycling. Questionnaire based surveys is another survey approach that has been used to study perceived safety of bicyclists (Lawson et al., 2013; Sanders, 2015). Simple text gives more freedom to respondents to imagine the described bicycling environment, but it might lead to biased results as too varied choices might be envisioned by different respondents that may not exist in researcher’s frame of reference.
Studying bicyclists in field is a classic approach to understand their perceptions and behaviour. Such studies might define a specific bicycling course and time block to simulate bicycling activity to study BLOS through bicyclists’ ratings (Landis et al., 1997). Mental map is a similar approach that does not specify a route and intends to evaluate the bikeability of roadways. Participants are provided with a map and are asked to draw their regularly used bicycling routes with different colours to indicate their perception of safety of that segment of the route (Manton et al., 2016). Nevertheless, the accuracy of the results is highly dependent on the memory of the participants. More recent and advanced studies in this regard are called naturalistic studies that collect bicyclists’ data using instrumented bicycles in the field. Participants are recruited to commute with an instrumented bicycle for a period of time to examine their bicycling behaviour (Dozza and Werneke, 2014; Werneke et al., 2015). Nevertheless, these partially controlled field studies fail to uniformly replicate all ambient factors for all participants. In addition, due to field-specific difficulties and time-demanding nature of such studies, the sample size of them are relatively small which makes them incapable to lead statistically representative results.

Stated preference surveys are heavily used in the literature to identify bicyclists’ perceptions and preferences. There are several ways beyond simple text to communicate imaginary designs with respondents in surveys: images have been used to study bicyclists’ route choice behaviour (Axhausen and Smith Jr, 1986), bicycle infrastructure preferences (Caulfield et al., 2012), bicycle path separation type from motorised vehicles (McNeil et al., 2015), and perceived comfort and safety of bicycling (Sanders, 2016) of hypothetical scenarios. Short video clips of the intended bicycle infrastructures were implemented in surveys to provide a better understanding of bicycling for participants (Hummer et al., 2006; Parkin et al., 2007; Tilahun et al., 2007). Computer-generated simulations were initially implemented into surveys to represent a cost effective alternative to traditional field research methods. In one of the very first attempts, perceived risk of cyclists and drivers was elicited for variations in lane conditions, vehicle speeds,
and vehicle volumes (Hughes and Harkey, 1997). With recent advances in Virtual Reality (VR) technology, application of VR as an empirical research tool for bicycle research has become more popular (Abadi et al., 2019; de Leeuw and de Kruijf, 2015; Nazemi et al., 2019; Xu et al., 2017). VR experiments blur the boundaries between stated preference and revealed preference surveys and provide a realistic sense of design to better evaluate subjective perceptions and preferences for bicycling in different environments.

Considering different survey methods for bicycle research, there might be potential discrepancies between participants’ perceptions. The results of a research found differences in ratings given to videotapes versus real-field observations. There were also difficulties in discerning environmental properties, such as lane width variations in different locations while watching videotapes (Harkey et al., 1998). In addition, existing literature discusses how there is a difference between objective and perceived measurements of a road that leads to mixed findings of the relationship between the travel behaviour and built environment studies (Ma and Dill, 2016). Furthermore, a good bicycling environment may mean different environmental attributes for different people and for different trip purposes. This mismatch can be overcome by immersive VR through a more human-centred approach surveying participants with various sociodemographic characteristics.

A major difference of the present research from previous studies is that due to the scarcity of bicycle infrastructure and bicycling experience in Singapore, application of classic survey methods might lead to unreliable results. Therefore, some variables such as ability to pass other bicyclists—that has an effect on perceived level of service—was of no interest. This paper aims to understand Singaporean’s bicycling perceptions and preferences through a new method by using a cycling simulator combined with virtual reality. Capabilities and limitations of virtual reality for bicycle research is investigated and the results provide implications for planning of the local bikeway network.
The method outlined in this research includes using a cycling simulator combined with immersive VR (Schramka et al., 2017). Different data is collected from each participant: 1- participants’ speed, pedaling, breaking, and head movement activities while bicycling in VR, 2- participants answers given to a questionnaire before and after bicycling in VR, 3- participants’ physiological response collected through the whole experiment by an EDA sensor attached to their wrists. This approach provides a consistent condition for all the participants, as the experiment can be repeated under the exact same conditions for each individual. Short bicycling durations in VR requires limited workload and ensures the validity of the EDA sensor data (Vlakveld et al., 2015). Furthermore, synchronisation of the cycling simulator data, EDA sensor data, and retracing other road users’ positions in VR, relative to the bicyclists, can be done fairly easily, while it has been reported as one of the difficulties of naturalistic studies (Berger and Dörrzapf, 2018). Analysis of EDA data is the ongoing research and is out of the scope of this paper.

Participants bicycle through different bicycling environments. There are four Likert scale questions on WTB and five Likert scale questions on PLOS after each scene that estimate an individual, subjective impression of the rider’s environment. Participants are provided with their previous answers given to the safety questions to be able to give relative answers and modify them.

2.1 Experiment design

A $5 \times 2$ mixed design was used with bicycling environment as within-subject factor and pedestrian / traffic volume as between-subject factor. Each participant cycled through all the five bicycling environments (sidewalk next to pedestrians, painted bicycle path on the sidewalk, painted bicycle path on the road, roadside next to vehicles, and segregated bicycle path) using
a cycling simulator, but experienced either low traffic volume or high traffic volume. Two different sequences for the bicycling environments were designed to account for learning and ordering effects.

The experiment questionnaire was refined two times by conducting pilot tests before the main experiment. A researcher facilitated the whole process of the experiment for each participant. Participants were encouraged to reflect on their accumulating experience while proceeding through the experiment. Participants were provided with their previous answers given to each question for the previous bicycling environments and hence could re-grade as they completed each bicycling environment.

2.2 Bicycling course
The designed bicycling course included representative traffic conditions, road typologies and land development forms present in residential areas of Singapore. The bicycling course is approximately 380 meters long and located in a 4-lane urban street (2 lanes in each direction) which can be frequently found in Singapore. This stretch of road is composed of two links and a 3-leg uncontrolled intersection in between. The course configuration is shown in Figure 1. There are 5 bicycling environments designed for this experiment. The specifications of each bicycling environment are shown in Figure 2. It should be noted that the cross-sectional distance of the designs is the same for all designs.
<table>
<thead>
<tr>
<th>Environment</th>
<th>Bicyclist viewpoint in VR</th>
<th>Geometric design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segregate bicycle path</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>Roadside</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>Painted bicycle path on the road</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>Painted bicycle path on the sidewalk</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>Sidewalk</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

**Figure 2.** Bicycling environments, bicyclist viewpoint in VR, and geometric designs
Participants were exposed to two traffic volumes: 500 veh/hr/ln for the low volume case and 1500 veh/hr/ln for the high volume case. Cars were traveling with an average speed of 50 km/hr for the bicycling environments closer to the road, including the segregated bicycle path. There is a bus passing the slower lane every 20 seconds with the speed of 50 km/hr. Bus frequency was intentionally defined high to make sure that participants experience passing of at least one bus during the short bicycling time in each bicycling environment. In addition to creating different vehicular volumes, two cases of high and low pedestrian volumes for bicycling environments for the case of bicycling on the sidewalk was also devised.

Considering HCM composition of road segments to links and intersection, this study’s purpose is to evaluate link PLOS (and not intersections) for each bicycling environment. Accordingly, the participants were instructed to disregard the conditions at the middle intersection. Questions ask about the safety of the environment which is usually the common perspective articulated by road users to express how well a particular street or road accommodates their travel with a bicycle. The participants evaluated the safety of the bicycling environments by giving ratings on 7-point scale Likert questions. There are five questions after each bicycling in each environment that ask about safety due to number of pedestrians, proximity to pedestrians, volume of passing vehicles, proximity to passing vehicles, and being worried about occasional pedestrians or vehicles that might potentially come to their bicycling path.

2.3 Participants

Participants were mainly recruited from the National University of Singapore and the Land Transport Authority (LTA) of Singapore. The experiment was successfully completed by 150 participants including 79 women ($M_{age} = 27.04$, $SD_{age} = 9.55$) and 71 men ($M_{age} = 27.75$, $SD_{age} = 7.37$). Student participants were informed by an advertisement posted in the university website. LTA employees were invited to participate by sending an e-mail explaining the experiment held
at the LTA campus. Students were compensated with S$ 15 cash and LTA employees were compensated with S$ 15 vouchers for about 45 minutes of their time.

3 RESULTS

Table 1 outlines the demographic characteristics of the sample. Bicycle ownership was 47% and 62% of the participants stated that they used bike sharing system in Singapore. Bicycle is used as a commute mode by 3% of the participants and 62% never commute by bicycle. Considerable data for each bicycling environment were collected to permit extensive hypothesis testing of both within-subject and between-subject comparisons. Since each of the 150 participants cycled through all five bicycling environments with 76 and 74 participants experiencing high and low traffic / pedestrian volumes, the most stable and reliable analyses are based on the combined pairs of observation within each of these two groups. Since each participant bicycled through all environments, repeated-measures analysis of variance (ANOVA) tests were performed to analyse bicycling environment as a within-subject factor. Vehicular and pedestrian volumes were analysed separately as a between-subject variable by one-way ANOVA tests to study the effect of vehicle / pedestrian volume on PLOS and WTB. The dependent variables are self-expressed answers given to questions regarding bicyclists’ PLOS. Pairwise comparisons of estimated marginal means were conducted to identify significant effects. Tukey HSD adjustments were used for post hoc pairwise comparisons of estimated marginal means. A significance level of 0.05 was adopted. R software was used for data analysis.
Table 1. Demographic characteristics of the participants

<table>
<thead>
<tr>
<th></th>
<th>Women (n = 79)</th>
<th></th>
<th>Men (n = 71)</th>
<th></th>
<th>Total (n = 150)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency</td>
<td></td>
<td>Frequency</td>
<td></td>
<td>Frequency</td>
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<tr>
<td></td>
<td>Percentage</td>
<td></td>
<td>Percentage</td>
<td></td>
<td>Percentage</td>
<td></td>
</tr>
<tr>
<td><strong>Bicycle availability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Bicycle ownership</td>
<td>33</td>
<td>42</td>
<td>37</td>
<td>52</td>
<td>70</td>
<td>47</td>
</tr>
<tr>
<td>Bike sharing usage</td>
<td>47</td>
<td>60</td>
<td>47</td>
<td>66</td>
<td>94</td>
<td>62</td>
</tr>
<tr>
<td><strong>Commute mode (multiple choice)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walk</td>
<td>36</td>
<td>46</td>
<td>29</td>
<td>41</td>
<td>65</td>
<td>43</td>
</tr>
<tr>
<td>Bicycle</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>10</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>Public transport</td>
<td>77</td>
<td>97</td>
<td>64</td>
<td>90</td>
<td>141</td>
<td>94</td>
</tr>
<tr>
<td>Taxi or private hire car</td>
<td>6</td>
<td>8</td>
<td>3</td>
<td>4</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Car</td>
<td>7</td>
<td>9</td>
<td>10</td>
<td>14</td>
<td>17</td>
<td>11</td>
</tr>
<tr>
<td>Shuttle</td>
<td>3</td>
<td>4</td>
<td>7</td>
<td>10</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td><strong>Bicycling frequency as commute mode</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Never</td>
<td>58</td>
<td>74</td>
<td>35</td>
<td>49</td>
<td>93</td>
<td>62</td>
</tr>
<tr>
<td>4 to 6 times per year</td>
<td>11</td>
<td>14</td>
<td>13</td>
<td>18</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>2 to 3 times per month</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Once a week</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>2 to 4 times per week</td>
<td>1</td>
<td>1</td>
<td>10</td>
<td>14</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>Everyday</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>6</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td><strong>Estimated commute time by bicycle</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less than 15 minutes</td>
<td>8</td>
<td>10</td>
<td>15</td>
<td>21</td>
<td>23</td>
<td>15</td>
</tr>
<tr>
<td>15 to 30 minutes</td>
<td>8</td>
<td>10</td>
<td>5</td>
<td>7</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>30 to 45 minutes</td>
<td>6</td>
<td>8</td>
<td>3</td>
<td>4</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>More than 45 minutes</td>
<td>33</td>
<td>42</td>
<td>30</td>
<td>42</td>
<td>63</td>
<td>42</td>
</tr>
<tr>
<td>I don’t know how long it would take</td>
<td>24</td>
<td>30</td>
<td>18</td>
<td>26</td>
<td>42</td>
<td>28</td>
</tr>
<tr>
<td><strong>Driving license and driving frequency</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>No, I don’t have a driving license</td>
<td>41</td>
<td>52</td>
<td>21</td>
<td>30</td>
<td>62</td>
<td>41</td>
</tr>
<tr>
<td>Yes, but I don’t drive</td>
<td>12</td>
<td>15</td>
<td>7</td>
<td>10</td>
<td>19</td>
<td>13</td>
</tr>
<tr>
<td>Yes, less frequent than twice a year</td>
<td>9</td>
<td>11</td>
<td>1</td>
<td>1</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Yes, twice a year</td>
<td>8</td>
<td>10</td>
<td>4</td>
<td>6</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>Yes, once a month</td>
<td>4</td>
<td>5</td>
<td>8</td>
<td>11</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>Yes, once a week or more frequent</td>
<td>5</td>
<td>7</td>
<td>30</td>
<td>42</td>
<td>35</td>
<td>23</td>
</tr>
<tr>
<td><strong>Bicycle accident</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preventative from more bicycling</td>
<td>9</td>
<td>11</td>
<td>5</td>
<td>7</td>
<td>14</td>
<td>9</td>
</tr>
</tbody>
</table>
3.1 Perceived level of safety (PLOS)

Participants were asked five questions after bicycling in each environment regarding bicycling PLOS. These questions are focused on the influence of pedestrian/traffic volume and proximity to other road users on PLOS to later investigate the key concerns of bicyclists in each bicycling environment. Mean (M) and standard deviation (SD) values of PLOS for each bicycling environment is presented in Table 2. Participants reported higher mean PLOS values for bicycling on the painted bicycle path on the sidewalk due to proximity to pedestrians (MPLOS, Low volume = 5.09, SD PLOS, Low volume = 1.61; MPLOS, High volume = 4.55, SD PLOS, High volume = 1.87) compared to PLOS values for bicycling on the painted bicycle path on the road due to proximity to vehicles (MPLOS, Low volume = 4.57, SD PLOS, Low volume = 1.75; MPLOS, High volume = 4.46, SD PLOS, High volume = 1.65). Lowest mean PLOS values are reported for bicycling on the roadside due to proximity to traffic stream (MPLOS, High volume = 1.95, SD PLOS, High volume = 1.36; MPLOS, Low volume = 2.09, SD PLOS, Low volume = 1.42) and participants were most worried about occasional vehicles that might potentially come to their path in the same bicycling environment (MPLOS, High volume = 6.25, SD PLOS, High volume = 1.23; MPLOS, Low volume = 6.22, SD PLOS, Low volume = 1.30).

Table 2. Mean and standard deviation values of PLOS for each bicycling environment.

<table>
<thead>
<tr>
<th>Question</th>
<th>Descriptive statistics</th>
<th>Segregated bicycle path</th>
<th>Roadside</th>
<th>Painted bicycle path on the road</th>
<th>Painted bicycle path on the sidewalk</th>
<th>Sidewalk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Did you feel safe due to proximity to pedestrians?</td>
<td>M 6.86 (0.34)</td>
<td>Low volume 6.66 (0.75)</td>
<td>Low volume 6.74 (0.70)</td>
<td>Low volume 5.09 (1.61)</td>
<td>Low volume 2.88 (1.60)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD 6.88 (0.43)</td>
<td>High volume 6.41 (1.36)</td>
<td>High volume 6.57 (0.91)</td>
<td>High volume 4.55 (1.87)</td>
<td>High volume 2.41 (1.58)</td>
<td></td>
</tr>
<tr>
<td>Did you feel safe due to the number of pedestrians?</td>
<td>M 6.88 (0.37)</td>
<td>Low volume 6.69 (0.84)</td>
<td>Low volume 6.84 (0.44)</td>
<td>Low volume 4.64 (1.78)</td>
<td>Low volume 2.76 (1.57)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD 6.87 (0.41)</td>
<td>High volume 6.37 (0.95)</td>
<td>High volume 6.58 (0.80)</td>
<td>High volume 3.84 (1.89)</td>
<td>High volume 2.24 (1.51)</td>
<td></td>
</tr>
<tr>
<td>Did you feel safe due to proximity to cars?</td>
<td>M 6.66 (0.58)</td>
<td>Low volume 2.09 (1.42)</td>
<td>Low volume 4.57 (1.75)</td>
<td>Low volume 6.64 (0.54)</td>
<td>Low volume 6.49 (1.73)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD 6.75 (0.66)</td>
<td>High volume 1.95 (1.36)</td>
<td>High volume 4.46 (1.65)</td>
<td>High volume 6.47 (0.96)</td>
<td>High volume 6.34 (1.08)</td>
<td></td>
</tr>
<tr>
<td>Did you feel safe due to volume of the cars?</td>
<td>M 6.62 (0.66)</td>
<td>Low volume 2.77 (1.75)</td>
<td>Low volume 4.73 (1.72)</td>
<td>Low volume 6.66 (0.58)</td>
<td>Low volume 6.51 (1.90)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD 6.67 (0.70)</td>
<td>High volume 2.21 (1.53)</td>
<td>High volume 4.53 (1.82)</td>
<td>High volume 6.50 (0.79)</td>
<td>High volume 6.33 (1.91)</td>
<td></td>
</tr>
<tr>
<td>Were you worried about the occasional pedestrian coming to your path?</td>
<td>M 2.22 (1.66)</td>
<td>Low volume 6.32 (1.30)</td>
<td>Low volume 4.86 (1.81)</td>
<td>Low volume 4.65 (1.88)</td>
<td>Low volume 6.05 (1.34)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD 2.29 (1.73)</td>
<td>High volume 6.25 (1.23)</td>
<td>High volume 4.95 (1.60)</td>
<td>High volume 5.00 (1.69)</td>
<td>High volume 6.12 (1.37)</td>
<td></td>
</tr>
</tbody>
</table>
Repeated-measures ANOVA tests were used to determine the effects of bicycle environment on mean PLOS for low and high volume scenarios separately. One-way ANOVA tests evaluate the answers given to five questions after bicycling at each environment. Post hoc Tukey’s HSD tests were conducted for pairwise comparisons. Only important statistically significant comparisons are discussed.

In the first step, differences between the effects of proximity to traffic / pedestrians and volume of traffic / pedestrians on PLOS between different bicycling environments were inspected for different bicycling environments. Pairwise comparison analyses showed that participants felt safer bicycling on the segregated bicycle path compared to bicycling on the painted bicycle path on the road and roadside, due to proximity to cars and due to traffic volume ($P < 0.001$).

Although, similar vehicular volumes were defined for all the three aforementioned bicycling environments. The difference in mean PLOS deemed to be greater for scenarios with high traffic volume in comparison with low volume scenarios. Compared to roadside bicycling, bicyclists had a higher PLOS considering proximity to cars and volume of cars while bicycling on the painted bicycle path on the road ($P < 0.001$). This difference was more strongly perceived for high volume scenario, even though the volume of the passing cars were exactly the same for these two bicycling environments. Furthermore, bicyclists were more worried about occasional cars that might potentially come to their path, when bicycling on the roadside as compared to painted bicycle path on the road ($P < 0.001$).

For the cases of bicycling on the sidewalk, mean values of PLOS due to proximity to pedestrians and due to number of pedestrians were higher when bicycling on the painted bicycle path compared to bicycling on the sidewalk shared with pedestrians ($P < 0.001$). Nevertheless, the number of the pedestrians for both bicycling environments were exactly the same. The difference in mean PLOS found to be smaller for scenarios with high pedestrian volume in comparison with low pedestrian scenarios. Bicyclists were less worried about the pedestrians...
that might potentially come to their path while bicycling on the painted bicycle path on the sidewalk ($P < 0.001$) with a larger difference for low volume of pedestrian scenario.

In the second step, the influence of proximity to traffic / pedestrians and volume of traffic / pedestrians on PLOS within each bicycling environment were investigated by performing one-way ANOVA tests. PLOS did not significantly differ due to proximity to motorised vehicles and volume of motorised vehicles for both high volume and low volume scenarios in segregated bicycle path, painted bicycle path on the road, and roadside bicycling. No significant difference was observed for BLOS due to proximity to pedestrians and volume of pedestrians when bicycling on the sidewalk and painted bicycle path on the sidewalk.

In the final step, mean PLOS scores are statistically compared between the low volume and high volume scenarios to more specifically study the role of ambient traffic volume and pedestrian volume on safety perceptions. When comparing each individual factor affecting PLOS in low volume to its counterpart in high volume scenarios, one-way ANOVA test revealed that neither of the factors were different from each other. However, for the painted bicycle path on the sidewalk made a distinction in PLOS of bicyclists between low and high number of pedestrians at the 0.15 significance level. When studying main factors affecting PLOS within each bicycling environment, there found to be only one significant difference in mean PLOS due to proximity to pedestrians and number of pedestrians for bicycling on the painted bicycle path on the sidewalk ($P < 0.001$). Other comparisons between proximity to motorised vehicles and volume of motorised vehicles did not lead to significant differences.

### 3.2 Willingness to bicycle (WTB)

There are four questions on WTB after each VR scene. These questions inspect how likely would it be for each participant to consider bicycling in that environment. Questions enquire about the duration of bicycling, bicycling accompanying a 10-year-old child which requires more safety,
and bicycling at night with the same traffic conditions, but less light and visibility. Mean (M) and standard deviation (SD) values of WTB for each bicycling environment is presented in Table 3.

Highest mean WTB for all four questions relate to the segregated bicycle path. Segregated bicycle path is followed by painted bicycle path on the sidewalk for less than 10 minutes rides and more than 10 minutes rides. Least average WTB scores are given to roadside environment bicycling with a child, bicycling at night, and bicycling for more than 10 minutes. Bicycling on the sidewalk shared with pedestrians accompanying a child and during nights was also found to be unpopular after roadside bicycling. The results of the mean ratings given to the WTB between low volume and high volume scenarios are mixed and no specific pattern was observed.

Mean WTB ratings for less than 10 minutes was not significantly different from each other while comparing segregated bicycle path to painted bicycle path on the road, and sidewalk to painted bicycle path on the sidewalk at 0.05 level. Bicyclists were least willing to bicycle for less than 10 minutes on the roadside compared to all other bicycling environments (P < 0.001). The difference for less than 10 minutes WTB values was significant between bicycling on the segregated bicycle path and bicycling on the sidewalk shared with pedestrians for high volume scenarios (P < 0.001).

<table>
<thead>
<tr>
<th>Question</th>
<th>Descriptive statistics</th>
<th>Segregated bicycle path</th>
<th>Roadside</th>
<th>Painted bicycle path on the road</th>
<th>Painted bicycle path on the sidewalk</th>
<th>Sidewalk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Will you consider cycling for less than 10 minutes?</td>
<td>M (SD)</td>
<td>Low volume</td>
<td>High volume</td>
<td>Low volume</td>
<td>High volume</td>
<td>Low volume</td>
</tr>
<tr>
<td>Will you consider cycling for more than 10 minutes?</td>
<td>M (SD)</td>
<td>Low volume</td>
<td>High volume</td>
<td>Low volume</td>
<td>High volume</td>
<td>Low volume</td>
</tr>
<tr>
<td>Will you consider cycling accompanying a 10-year-old, more than 10 minutes?</td>
<td>M (SD)</td>
<td>Low volume</td>
<td>High volume</td>
<td>Low volume</td>
<td>High volume</td>
<td>Low volume</td>
</tr>
<tr>
<td>Will you consider cycling at night, more than 10 minutes?</td>
<td>M (SD)</td>
<td>Low volume</td>
<td>High volume</td>
<td>Low volume</td>
<td>High volume</td>
<td>Low volume</td>
</tr>
</tbody>
</table>

Table 3. Mean and standard deviation values of WTB for each bicycling environment.
Pairwise comparisons WTB for more than 10 minutes were significant for all combinations between environments except for the contrast between painted bicycle path on the sidewalk and painted bicycle path on the road for both low and high volume scenarios, and segregated bicycle path and painted bicycle path on the sidewalk in low volume scenario. Greater variations were observed in WTB accompanying a child and WTB during night, especially for high volume scenarios; interestingly, WTB ratings for both measurements in low volume scenarios were not significantly different from each other, for segregated bicycle path and painted bicycle path on the sidewalk, and for sidewalk and painted road comparisons that shows similar concerns of bicyclists for bicycling accompanying a child and bicycling at night in low volume conditions. All other comparisons are significantly different from each other ($P < 0.001$) which explicitly indicate bicyclists’ preferences of specific environments.

Comparison of sidewalk and painted bicycle path on the sidewalk shows how the WTB values for more than 10 minutes, WTB accompanying a child, and WTB at night are significantly different from each other ($P < 0.001$), for both low and high volume scenarios. Comparison of painted bicycle path on the sidewalk and painted bicycle path on the road provides evidence that there is no meaningful difference between WTB for less than 10 minutes and WTB for more than 10 minutes. However, the contrast of WTB accompanying children and WTB at night reveals that there is a significant difference between these two measurements ($P < 0.001$), regardless of the volume of pedestrians / traffic.

When comparing the WTB within each bicycling environment, no meaningful differences were observed for segregated bicycle path (i.e. bicyclists felt equally the same regarding WTB questions). An average rating of 4.18 and 4.04 was given to bicycling on the roadside for less than 10 minutes, for low ambient volume and high ambient volume, respectively. Other WTB scores were significantly lower than these values ($P < 0.001$). Similar pattern was observed for painted bicycle path on the road. However, no significant difference between mean WTB values
for less than 10 minutes and for more than 10 minutes was seen, which divulges the fact that bicyclists felt comfortable bicycling on this bicycle facility and would not mind to bicycle for longer periods of time. Painted bicycle path on the sidewalk received highest WTB rating following segregated bicycle path while there was only one marginally significant difference between the answers given to WTB for less than 10 minutes and WTB with a child ($P < 0.05$). Concerns regarding bicycling with a child and bicycling at night resulted in significantly lower WTB measurements compared to bicycling for less than 10 minutes and more than 10 minutes on the sidewalk ($P < 0.001$).

4 DISCUSSION

Sufficient number of participants in this experiment provides a robust qualitative and quantitative interpretation of the data. Primary analysis of the results revealed that the main safety concern for bicycling on the sidewalk deals with the presence of pedestrians, while vehicular traffic stream makes bicyclists feel unsafe when riding closer to the road. PLOS judgements due to proximity to motorised traffic is correlated to the distances of the bicyclists to traffic stream as shown in Figure 2, and confirms that relative distances in virtual reality are correctly perceived while bicycling in VR (Nazemi et al., 2018). However, these results might be biased by bicyclists’ overall perceived safety being provided a more separated bicycling environment. Segregated bicycle path was perceived as the most safe bicycling environment due to proximity to motorised vehicles and volume of motorised vehicles, followed by painted bicycle path on the road. Bicyclists were most worried about other road users that might potentially come to their path when riding on the roadside, followed by sidewalk bicycling shared with pedestrians.

Traffic volume of the roadway affects bicycling risk as riders are more prone to accidents. Motorised vehicle flow rate is also a data source to determine the quality of service of a link.
This study showed that the volume of the motorised vehicles also affects bicyclists’ perceived safety by capturing higher mean PLOS values for high volume scenarios as compared to low volume. In general, participants felt safer and less worried about other road users for bicycling in low pedestrian / traffic bicycling environments. However, the differences were not statistically significant and such weak discrepancies in mean PLOS scores between low volume and high volume scenarios might root in the between-subject experimental design of the factor ambient volume.

Regardless of volume, highest ratings have been given to WTB on the segregated bicycle path for all the four questions, which is in agreement with the previous research results (Caulfield et al., 2012; Damant-Sirois et al., 2014). Bicyclists were equally willing to bicycle for less than 10 minutes, for more than 10 minutes, accompanying a child, and during night on the segregated bicycle path which nominates this bicycling environment as the ideal option. Painted bicycle path on the sidewalk was also found to be an ideal environment if bicyclists are to ride accompanying their children or bicycling during nights. The difference in mean WTB for the segregated bicycle path and painted bicycle path on the sidewalk compared to other environments were significant.

The comparison of the abovementioned environments to each other for low volume scenarios did not show distinct preferences of bicyclists, which indicates the influence of the ambient volume of other road users on the WTB. Same comparison for less than 10 minutes in high volume scenarios reveals a meaningful concern of the bicyclists for riding next to the pedestrians. However, this concern has been alleviated by the introduction of a painted bicycle path on the sidewalk. In addition, pairwise comparison of painted bicycle path on the sidewalk and sidewalk led to distinct differences that implies the added value of the painted bicycle path on the sidewalk. Comparison of painted bicycle path on the road and painted bicycle path on the sidewalk showed that there is no meaningful preference of WTB between these two
environments for bicycling for both less than 10 minutes and for more than 10 minutes. Bicycling
duration made a significant difference in answers to WTB on the sidewalk shared with
pedestrians since bicyclist showed more interest on bicycling for shorter durations ($P < 0.001$).
Bicyclists felt less willing to bicycle accompanying a child compared to bicycling for less than 10
minutes alone on a painted bicycle path on the sidewalk in high volume scenarios. This marginal
difference in mean WTB ratings shows that bicyclists are still concerned about safety and
comfort issues riding next to a lot of pedestrians and this bicycle facility might not encourage
them to bicycle with children. The results show that bicyclists were willing to bicycle alone for
less than 10 minutes, more than 10 minutes, and during night on the painted bicycle path on
the road. However, they are not willing to bicycle with a child in the same environment.
Therefore, if the intention of the authorities is to enable bicycling for everyone, the solution
would be a segregated bicycle path or a painted bicycle path on the sidewalk.

If rating 4 (out of 7) imputes the border between a yes and no answer to WTB, the following
conclusions can be derived: if bicyclists are to bicycle for less than 10 minutes to their
destinations, they all consider bicycling regardless of infrastructure type and volume level.
However, if the duration of the bicycling is extended to more than 10 minutes, a shift in WTB
occurs for roadside bicycling and crowded sidewalks. Bicyclists are willing to bicycle for less than
10 minutes, more than 10 minutes, and during night on a painted bicycle path on the road, but
there is a shift in WTB for bicycling accompanying a child. Bicyclists stated that they would
bicycle only for less than 10 minutes on the sidewalk, and they are not interested to bicycle for
more than 10 minutes, accompanying a child, and during night.

5 PRACTICAL IMPLICATIONS

This study tried to provide a better understanding of the proposed bicycle environment choices
to participants by using VR tool. Due to restrictions with regards to VR immersion duration to
avoid motion sickness and mental overload, a short bicycling course was designed. In addition, for similar reasons, the steering activity was not activated in this study which has an impact on PLOS; participants were bicycling but they could not have any potential accidents with pedestrians or vehicles. The developed VR model did not include the interactions between the participant and other road users due to technological limitations.

This research focuses only on the bicyclists’ viewpoint on measuring the PLOS, which can be considered as an indicator for perceived quality of service. Procedures for assessing the impact of bicyclists on other road users’ (i.e. pedestrians and motorised vehicles) quality of service are not considered. This study focuses on road links only, excluding intersections. Different types of intersections should also be studied to reach a comprehensive understanding of the PLOS of a segment of a road. Nevertheless, the link-based evaluation is regularly practiced by transportation agencies as it is less data required and at the same time produces results that are generally reflective of bicyclist perceptions of service along the roadway, especially for networkwide evaluations. Weather conditions may also affect bicyclists’ WTB, especially in tropical countries, which was not included in this study. Participants were asked about WTB accompanying a child and WTB at night, which are not implemented in VR and still require imagination. These conditions can be implemented in VR, but they were discarded to reduce survey length and number of participants.

6 CONCLUSIONS

This paper presents the results of an experiment to study bicyclists’ PLOS and WTB using a cycling simulator combined with immersive VR. Traditional methods study bicyclists’ perceptions and preferences using surveys including video clips or by conducting naturalistic experiments. The former often offer a weak representation of the bicycling environment, while the latter lacks validity of the sensor results and reproducibility of creating consistent conditions.
for all participants. In contrast, a cycling simulator and VR proved to be a reliable tool to study cyclists’ perceptions of the environment by providing a close-to-reality representation of the possible future scenarios. The proposed method establishes a novel and innovative framework for bicyclist-centric research, and improves subjective understanding and interpretation of non-existing designs. Furthermore, this approach enables close observation of cyclists’ behaviour and responses at different occasions while bicycling in a controlled setting, which can be used for further behavioural studies.

The results of this study support a better understanding of bicyclists and potential bicyclists’ needs and preferences which can be considered as a source of information to help improving bicycle infrastructure development and bicycling quality. However, there are still questions regarding the validity of the results compared to real world conditions, which need further clarification. How can data collection process become faster and less tedious? What should be done to enhance bicycling experience in VR and reduce motion sickness effects? What is the relative importance of bicyclists’ sociodemographic attributes, perceptions of the bicycling environment, and bicycle facility preferences compared to traffic characteristic and geometric design data in the overall service quality of the bicycle facility and subsequently the decision to bicycle. What is the added value of using the proposed method compared to traditional survey methods in this line of research?

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