Final Report

Investigating the Effect of Different Bike Lane Types on Bicyclists' Safety and Behavior in Baltimore City

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16. Abstract
Safety perception plays a significant role in the decision to use bicycles, often surpassing bike infrastructure in importance. The main goal of this study is to reduce the number of crashes involving pedestrians and bicyclists and improve their safety in Baltimore City by exploring the effects of different built environment features and various bike lane types. A combination of spatial analysis, an online survey of over 110 participants, and a bike simulator experiment with ten participants were used to explore these objectives. Baltimore's Census Tracts were spatially analyzed using ArcGIS Pro to determine the distribution of bike infrastructure and bicycle crashes. The Bicycle Equity Index (BEI) was utilized to evaluate vulnerable groups' access to infrastructure. The length of bike lanes and bicycle crashes were positively and significantly correlated using regression models, indicating that longer lanes are associated with a higher risk of crashes, likely due to poor design or lack of maintenance. Online survey results revealed that participants preferred physically separated bike lanes, trails, and side paths, emphasizing the need for infrastructure that separates cyclists from general traffic. Additionally, survey results revealed concerns about critical safety issues such as poor bike lane conditions, merging vehicles, and the lack of bike lanes in some areas. Considerably, respondents indicated a willingness to cycle more frequently if safety improvements were made. The bike simulator analysis supported these findings, showing that participants felt safest in lanes with physical barriers. Although shared bus-bike lanes gained popularity after the simulation, shared lanes without separation remained the least favored and were perceived as the least safe. The spatial analysis, survey, and bike simulator experiment results reveal a consistent theme: safety concerns are a significant barrier to increased cycling in Baltimore City. The lack of continuous and well-designed bike lanes, particularly in disadvantaged areas, contributes to a higher crash risk and discourages cycling as a mode of transportation. More extended bike lanes are linked to more crashes, possibly because they are poorly designed and lack safety elements like physical barriers and apparent signs. The simulator and survey results prove the need for separated bike lanes, improved lighting, and better enforcement of cyclist traffic laws.

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LIST OF ACRONYMS

DOT	Department of Transportation
FTA	Federal Highway Administration
MDOT	Maryland Department of Transportation
IVE	Immersive Virtual Environment
CMF	Crash Modification Factors
EB	Empirical Bayes
SBBLs	Shared Bus-Bike Lanes
SES	Socioeconomic Status
BEI	Bicycle Equity Index
ACS	American Community Survey
GLMs	Generalized linear models
OLS	Ordinary Least Squares
BS	Bike simulators
IRB	Institutional Review Board
VR	Virtual Reality

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Investigating the Effect of Different Bike Lane Types on Bicyclists' Safety and Behavior in Baltimore City

ABSTRACT

Safety perception plays a significant role in the decision to use bicycles, often surpassing bike infrastructure in importance. The main goal of this study is to reduce the number of crashes involving pedestrians and bicyclists and improve their safety in Baltimore City by exploring the effects of different built environment features and various bike lane types on. A combination of spatial analysis, an online survey of over 110 participants, and a bike simulator experiment with ten participants were used to explore these objectives. Baltimore's Census Tracts were spatially analyzed using ArcGIS Pro to determine the distribution of bike infrastructure and bicycle crashes. The Bicycle Equity Index (BEI) was utilized to evaluate vulnerable groups' access to infrastructure. The length of bike lanes and bicycle crashes were positively and significantly correlated using regression models, indicating that longer lanes are associated with a higher risk of crashes, likely due to poor design or lack of maintenance. Online survey results revealed that participants preferred physically separated bike lanes, trails, and side paths, emphasizing the need for infrastructure that separates cyclists from general traffic. Additionally, survey results revealed concerns about critical safety issues such as poor bike lane conditions, merging vehicles, and the lack of bike lanes in some areas. Considerably, respondents indicated a willingness to cycle more frequently if safety improvements were made. The bike simulator analysis supported these findings, showing that participants felt safest in lanes with physical barriers. Although shared bus-bike lanes gained popularity after the simulation, shared lanes without separation remained the least favored and were perceived as the least safe. The spatial analysis, survey, and bike simulator experiment results reveal a consistent theme: safety concerns are a significant barrier to increased cycling in Baltimore City. The lack of continuous and well-designed bike lanes, particularly in disadvantaged areas, contributes to a higher crash risk and discourages cycling as a mode of transportation. More extended bike lanes are linked to more crashes, possibly because they are poorly designed and lack safety elements like physical barriers and apparent signs. The simulator and survey results prove the need for separated bike lanes, improved lighting, and better enforcement of cyclist traffic laws.

Keywords: Bicycle safety, Bike Lanes, Bike Infrastructure

1. INTRODUCTION

Bicycling is a healthy, affordable, and environmentally friendly mode of transportation (*1*). It also impacts physical activity levels, obesity, cardiovascular health, and morbidity (*2*). Many government agencies and public health organizations promote bicycling to enhance individual health and mitigate the adverse effects of car use, such as air pollution, carbon emissions, congestion, noise, and traffic hazards (*3*, *4*). In recent years, transportation planning agencies and public health organizations have shown a growing interest in promoting bicycling as a means of transportation or recreation. This is due to the increasing recognition of the societal and environmental advantages associated with bicycling (*5*).

Previous studies indicate that the health benefits of bicycling far exceed the health risks from traffic injuries, contradicting the widespread misperception that bicycling is a dangerous activity (*2*). According to previous studies, as bicycling levels increase, injury rates fall, making bicycling safer and providing even more considerable net health benefits (*2*, *6*). Building bike lanes in the urban street network is one of the most direct ways to establish a cyclist-friendly environment (*7*). In addition, bikeable communities ensure more equitable access to goods, services, and reacreation because bicycling presents an inexpensive choice of transportation to citizens (*5*).

Safety perception plays a significant role in the decision to use bicycles, and it is often more important to potential users than the infrastructure itself (*1*). According to the U.S. Department of Transportation (DOT) and Federal Highway Administration (FTA), most fatal and severe injury bicyclist crashes occur at non-intersection locations. Nearly one-third of these crashes occur when motorists overtake bicyclists, as the speed and size difference between vehicles and bicycles can result in serious injury. Many people hesitate to ride a bicycle because they fear crashes like this. Bicycle facilities can mitigate or prevent interactions, conflicts, and crashes between bicyclists and motor vehicles and create a network of safer roadways for bicycling (*8*).

Most people will not ride a bicycle if they do not believe they have a safe and comfortable place to do so (*9*, *10*). Early efforts to dedicate space for bicyclists on roadways resulted in the addition of striped bike lanes adjacent to motor vehicle traffic. There is growing consensus that adding buffered bike lanes can increase bicyclists' sense of safety, and the number of on-street bike lanes protected from moving traffic by a buffer has increased considerably (*11*). Moreover, according to FTA, converting traditional or flush buffered bicycle lanes to a separated bicycle lane with flexible delineator posts can reduce crashes by up to 53%, and bicycle lane additions can reduce crashes by up to 49% (*8*).

Bicyclists prefer bike lanes, and cycling infrastructure is essential for bike usage. For example, studies have indicated that the availability of bicycle facilities (*12*, *13*), the distance between off-road bikeways and docking stations (*14*), and separated bike lanes (*15*) are essential factors impacting the demand for bikeshare and bike usage (*16*). Land-use factors also influence the demand for bicycles. The number of bikeshare trips can be increased by higher commercial land use density, mixed land use, the presence of universities, and recreational points of interest (POIs) (*16*, *17*).

1.1. Problem Statement

Pedestrians and bicyclists are some of the most vulnerable road users. Cyclists are 12 times more likely to be killed than motorists per kilometer traveled in the U.S. (*18*). Like many U.S. cities, Baltimore has experienced increased cycling over the past two decades (*19*). Efforts to promote cycling in Baltimore and improve public safety include the implementation of a bicyclists' bill of rights in 2010 and a state-enacted three-foot law that requires motorists to keep at least three feet of distance from bicyclists when passing (*18*, *20*). However, previous studies have shown that the three-foot law is not widely followed, compromising cyclist safety (*18*).

According to the Maryland Department of Transportation Crash Data (*21*), 2,793 crashes involving pedestrians occurred between 2018 and 2022, 4.6% of which were fatal. Moreover, 759 crashes with bicyclists occurred over the same period. Out of these crashes, 1.31% resulted in death (*21*). Of all crashes involving a bicyclist or pedal cyclist, over 80 percent resulted in an injury, more than twice the rate of drivers and passengers in all crashes statewide (*22*).

Bicycles are classified as vehicles on Maryland's streets, just like cars or trucks. Therefore, drivers of vehicles and riders of bicycles must share the road and do whatever it takes to keep each other safe (*22*). Bicyclists are authorized users of the roadway, and bicyclists have rights-of-way and the same duty to obey all traffic signals as motorists (*23*).

Safety perception heavily influences travelers' choice of mode, which may eventually override essential infrastructure for some riders. Although there is a correlation between bicycle infrastructure and safety perception, not much research has examined how cycling infrastructure affects perceptions of safety (*1*). This study seeks to bridge these gaps by examining how the built environment and bicycle lane infrastructure impact the safety of bicycle riders.

1.2. Goal

The main goal of this study is to reduce the number of crashes involving pedestrians and bicyclists and improve their safety in Baltimore City by exploring the effects of different built environment features on the crashes, investigating the various bike lane types, and educating the public about the advantages of bicycling. To achieve this goal, the following objectives will be pursued.

- Evaluating different bike lane types by investigating the data collected from roughly one hundred participants through an online questionnaire and an additional ten participants at the bike simulator lab of Morgan State University.
- Investigating potential reasons behind crashes involving pedestrians and bicyclists in specific areas of Baltimore City, including the effects of the neighborhood's walk score, bike lanes, the neighborhood's average household incomes, neighborhood residents' primary race, and neighborhood bicycle and pedestrian crashes and high-risk locations.

2. LITERATURE REVIEW

2.1. The Impacts of Bike Lanes on Cyclists' Safety

Bicycle lanes are the predominant type of infrastructure implemented to support bicycle use in the U.S. Previous studies suggested that bike lanes can increase bicycle use. For instance, using an exploratory analysis, Buck and Buehler (2012) aimed to investigate the determining factors of bikeshare usage of the Capital Bikeshare system in Washington, D.C. This study finds a significant correlation between bicycle lanes and Capital Bikeshare usage. It highlights the importance of population density and mixed landuses in encouraging ridership (*24*). Tilahun et al. (2007) concluded that users are willing to pay for designated bike lanes, parking on the street, bike lanes, and facilities (*25*). Hunt and Abraham (2007) demonstrated that cycling in mixed traffic on bike lanes, finding secure parking, and taking showers at the destination influence bicycle use (*26*). As bicycle lanes become increasingly popular in U.S. cities, it is essential to review the success of this intervention in improving safety (*27*).

Developing and expanding bike lanes is increasingly associated with enhanced safety for cyclists. Numerous studies suggest that bike lanes reduce crashes involving cyclists by providing a dedicated space for bicyclists, thereby minimizing conflicts with motor vehicles. For instance, a survey by Pucher and Buehler (2016) analyzed data from several cities with well-established bike lane networks and found that bike lanes significantly reduced the rate of cyclist crashes. Additionally, protected bike lanes were associated with a substantial decrease in fatalities and injuries, indicating the effectiveness of physical separation between cyclists and motor vehicles (*28*, *29*). Moreover, the presence of bike lanes has been linked to changes in cyclists' behavior, further contributing to their safety. Research by Dill and McNeil (2013) showed that cyclists in cities with bike lanes were more likely to follow traffic rules and were less inclined to engage in risky behavior, such as riding on sidewalks or in unpredictable patterns. This behavioral shift was attributed to the clear distinction provided by bike lanes, which offered cyclists a safer and more predictable route (*30*). Furthermore, Jacobsen (2003) found that an increase in the number of cyclists on the road, often spurred by the presence of bike lanes, contributed to what he termed the "safety in numbers" effect, where the likelihood of crashes decreased as the number of cyclists increased due to heightened awareness among motorists (*31*).

A growing body of evidence suggests that installing bicycle lanes is an effective and low-cost approach to reducing the crash risk for cyclists in a given city (*32*). For instance, using computer vision techniques to detect the speed and trajectory of over 9,000 motor vehicles at an intersection to analyze the effects of bicycle lanes on traffic speeds, Younes et al. (2024) discovered that a delineator-protected bicycle lane (marked with traffic cones and plastic delineators) resulted in a 28% reduction in average maximum speeds and a 21% decrease in average speeds for vehicles turning right. Painted-only bike lanes were similarly associated with a modest 11-15% reduction in speed, but only for cars turning right. These findings point to a significant additional advantage of bike lanes. By acting as a traffic calming measure, delineated bicycle lanes may reduce the risk and severity of crashes for pedestrians and other road users (*33*). To understand bicyclists' behavioral and physiological responses efficiently and safely, Guo et al. (2023) used a bicycle simulator within an immersive virtual environment (IVE), and their results show that the protected bike lane design received the highest perceived safety rating and exhibited the lowest average cycling speed (*34*).

Park et al. (2015) evaluated Crash Modification Factors (CMFs) for adding bike lanes using both observational before-and-after studies with the Empirical Bayes (EB) method and cross-sectional analyses. They also developed simple and complete CMFunctions to describe how CMFs relate to roadway characteristics. Based on this analysis, they concluded that adding bike lanes to urban arterials has positive safety effects (i.e., CMF < 1) for all crashes, including those involving bicycles. Adding a bike lane was more effective in reducing bike crashes than for all crashes (*35*). Moreover, Kondo et al. (2018) used Bayesian conditional autoregressive logit models to relate the odds that a bicycle injury crash occurred on a street segment in Philadelphia, PA, between 2011 and 2014. Their findings showed that bicycle lanes led to a 48% reduction in crashes in streets segments adjacent to 4-exit intersections, a 40% reduction in streets with one- or two-way stop intersections, and a 43% reduction in high traffic volume streets. The presence of bicycle lanes was not associated with a change in crash odds at intersections with less or more than four exits, at 4-way stop and signalized intersections, on one-way streets and streets with trolley tracks, or on streets with low-moderate traffic volume. The effectiveness of bicycle lanes therefore depends most on the configuration of the adjacent intersections and the volume of vehicular traffic (*32*). The effectiveness of bicycle lanes appears to depend most substantially on the configuration of the adjacent intersections (*36*).

However, a cross-sectional study was conducted to document the frequency and rate of obstructions in protected bike lanes throughout Manhattan, NYC. Three obstructions within the bicycle lanes were coded: object, pedestrian, and vehicle. A total of 233 obstructions in the protected bike lanes were observed in this study. The standard type of obstruction was objects, which accounted for 53.2% of obstructions and ranged through zones. People were the second most common obstruction, which accounted for 28.3% of the obstructions. Vehicles accounted for the remaining 18.5% of the obstructions. The findings of this study indicate that even in "protected" lanes, bikers may be forced into traffic or approach parked cars, increasing the risk of being "doored" (*37*).

Marquez et al. (2021) studied how the characteristics of bike lanes influence safety perception and the intention to use bicycles as a feeder mode to BRT, using Bogota as a case study. The results showed that providing colored pavement, buffers with planters, or buffers with safe hit posts increases riders' perceptions of safety and enhances their desire to use bicycles as a feeder mode for BRT (*1*). Aside from efficiency and safety, integrating two modes of transportation in the same place raises questions about interactions between buses and bicycles. Shared bus-bike lane (SBBL) design should prioritize efficiency and safety for both buses and riders. SBBLs have been difficult to deploy in underdeveloped nations due to a lack of standardized design and limited resources to adapt to local conditions via research. Cazorla (2017) examines design guidelines for SBBLs used in Europe, North America, and Australia, concluding that the type of cycling infrastructure, alignment within the SBBL, and lane width are the parameters that should be considered to ensure the safety and efficiency of these two modes. Increasing public transportation and cycling ridership is dependent not only on the quality of the built infrastructure but also on the coordination of the design, operation, enforcement, and proper use of the infrastructure, as well as the measures put in place to discourage the use of personal vehicles (*38*).

2.2. Social and Environmental Characteristics

A considerable amount of work has been devoted to studying the effects of socioeconomic characteristics and infrastructure on the use of bicycles (*1*). Evidence from the literature indicates that infrastructure is crucial in enhancing human perceptions of safety while cycling (*39*, *40*). Empirical data consistently shows that protected facilities enhance individuals' perception of bicycle safety (*41*). Studies based on discrete choice models show that personal characteristics, such as gender, age, and education level, significantly affect bicycle use. Typically, males and educated people are more likely to use a bicycle. People between 25 and 45 tend to use a bike more than other age cohorts. Factors related to household income, car and bicycle ownership, and demography are additional determinants (*1*).

Even in areas with increased levels of bicycling, a significant "gender gap" in bicycling in the U.S. remains, with men outnumbering women bicyclists by two or three to one (*42*). A study used survey data from a comprehensive evaluation of protected bike lanes in five large U.S. cities (Austin, TX; Chicago, IL; Portland, OR; San Francisco, CA; and Washington, DC) that included survey responses of 1,111 intercepted bicyclists and 2,283 residents. Both men and women overwhelmingly felt that the lanes increased their safety while riding in them. Women were also more likely to indicate that the new protected lane had improved their overall levels of bicycling (*43*). Generally, women's trips are significantly shorter than their male counterparts, and despite more trip chaining than men, women travel fewer annual miles, regardless of mode (*44*). Moreover, women are less likely to prefer off-street paths than men, ostensibly because of heightened personal security concerns despite the lack of danger from automobiles (*42*).

Despite the increasing prominence of equity discussions in bicycle planning and advocacy, statements on inequalities in bike lane access have often needed more empirical evidence. By examining whether area-level sociodemographic characteristics are associated with the presence and extent of bike lanes in 22 large U.S. cities, Braun et al. (2019) focused on dedicated on-street bike lanes—including unprotected, buffered and protected—given their dual provision of both traffic separation and destination connectivity, as well as their status as a signal of public investment in some regions of a community. Their study showed that disadvantaged block groups (i.e., those with lower socioeconomic status (SES) and higher proportions of minority residents) had significantly lower access to bike lanes (*45*). The social impacts of bike lanes extend beyond improving cyclist safety, which is vital in promoting equity and community well-being. Bike lanes can enhance mobility options for low-income communities and reduce transportation barriers, as cycling offers an affordable and accessible alternative to driving. Research has demonstrated that bike lanes can contribute to greater inclusivity, particularly in underserved neighborhoods, where residents often rely more heavily on non-motorized transport. Furthermore, bike lanes help normalize cycling as a legitimate mode of transportation, increasing visibility and acceptance of cyclists across all socioeconomic groups, which fosters a culture of shared road use and respect among diverse road users (*10*, *46*).

Overall, previous studies emphasize bike lanes' importance in improving cyclist safety and ridership. Studies have shown that bike lanes, particularly protected ones, significantly reduce cyclist crashes and enhance safety. However, the effectiveness of bike lanes can vary depending on the surrounding infrastructure, traffic volume, and design, with factors such as intersection configuration and lane obstructions influencing their safety outcomes. In conclusion, while bike lanes offer significant benefits for cyclists' safety and inclusivity, their design, placement, and maintenance are crucial to maximizing their effectiveness. The integration of bike lanes into urban infrastructure not only enhances cycling safety but also contributes to broader goals of sustainability, mobility equity, and community well-being.

3. DATA AND METHODOLOGY

3.1. Methodology

The research team conducted several analyses in three different sections. First, a spatial analysis was performed, then a survey was distributed and analyzed. Lastly, a bicycle simulation was conducted.

3.1.1. Spatial Analysis Methodology

This study used ArcGIS to conduct several spatial analyses to investigate bike infrastructure's impact on Baltimore City's safety. First, this study used the Bicycle Equity Index (BEI) to identify who benefits from current bicycle networks and who is disadvantaged.

3.1.1.1. Bicycle Equity Index (BEI)

To investigate access to bicycle infrastructure from the equity point of view, this study adapted the methodology of the Bicycle Equity Index (BEI), developed by Rachel Prelog for the League of American Bicyclists (*47*). This study will consider several variables:

- Percentage of minority population (non-white and/or Hispanic)
- Percentage of low-income population (below poverty)
- Percentage of the elderly population (65 and older)
- Percentage of youth population (under 18)
- Percentage of the zero-vehicle household population

To obtain the variables mentioned earlier, this study used the United States Census Bureau's American Community Survey (ACS) (*48*) five-year estimate (2017-2021) data for race and Hispanic origins (*49*), poverty level status (*50*), population variables (*51*), and household size by number of vehicles available (*52*). The index can help communities detect gaps and make better decisions. The BEI is built using the five indicators from the ACS data source. To combine various indicators into a single BEI assessment, the z-scores of each indicator were calculated. Positive z-scores indicate a more significant proportion of an indicator than the regional mean. The BEI was calculated by adding the z-scores from all five indicators. However, only positive z-scores were employed in the index creation, and negative scores were turned to zero. This prevented indicators with negative z-scores (values below the average) from reducing the effect of other indicators (*47*). Additionally, all indications were given equal weight, meaning none were more crucial for determining equity than the others. The z-score statistic is calculated using **Equation 1**, where x is the raw score, μ is the population mean, and σ is the population standard deviation:

$$z = (x - \mu) / \sigma \tag{1}$$

3.1.1.2. Regression Model

The bicycle-involved crash data, bike lanes, and BEI data are imported into ArcGIS Pro. Next, a spatial joint is conducted to associate each bike lane (polyline) and bicycle-involved crashes (points) with the Census Tracts (polygon) in Baltimore City. This will assign crashes and bike lanes to sociodemographic attributes from the Census Tract and aggregate the data at the Census

Tract level. The Summarize-Within and Intersect tools in ArcGIS Pro were used to calculate the number of crashes and the total length of bike lanes within a Census Tract.

Regression analysis is used for two purposes: to provide a simple outline to examine the relationship among a group of variables and to predict the dependent variable and future outcome. Generalized linear models (GLMs) are a class of linear-based regression models developed to handle varying types of error distributions. These models are highly beneficial for data types that may not conform to what is typically expected given Gaussian expectations or assumptions (*27*). The model can generally be expressed as **Equation 2**, where n represents the sample size, y denotes the dependent variable, X is the explanatory variable, β is the unknown regression coefficients, and ε is the error term.

$$y = \boldsymbol{X}\beta + \varepsilon \quad (2)$$

$$r_i = y_i - \hat{y}_i \quad i=1, 2, \ldots, n \quad (3)$$

$$\hat{\beta}_{OLS} = \arg\min_{\beta} \sum_{i=1}^{n} r_i^2(\beta) \quad (4)$$

Based on the estimated coefficients $\hat{\beta}$, the dependent variable can be estimated as $\hat{y}$. The residual ri is then calculated for each observation based on **Equation 3**. A typical regression analysis relies on the Ordinary Least Squares (OLS) method, which computes the model's coefficients to minimize the sum of squared residuals, as indicated in **Equation 4**. Regression analysis provides a simple outline to examine the relationship among variables. Multiple linear regressions were conducted to find the most satisfactory result using bicycle-involved crashes at the Census Tract as the dependent variable, bike lane length at the Census Tract, and BEI variables as independent variables.

3.1.2. Survey

To reach the goal of this study, an online survey was designed using the online platform Qualtrics (*53*). Online surveys can prevent items from being skipped, be used to contact groups that are difficult to reach, and encourage honesty in online questionnaires (*54*). The research team conducted an IRB-approved survey (#24/03-0076) (**APPENDIX D**). The purpose of the IRB review is to assure, both in advance and by periodic review, that appropriate steps are taken to protect the rights and welfare of humans participating as subjects in the research. The survey was distributed from May 9 – June 18, 2024. A total of 114 participants completed the study. Next, the answers were monitored individually, and the authors removed inattentive respondents from the final data set. Lastly, the final clean dataset includes 110 responses.

3.1.3. Bike Simulator

This study used a high-fidelity bike simulator at the Safety and Behavioral Analysis (SABA) Center at Morgan State University to evaluate different bike lane types. Bike simulators (BS) are typically used to observe how a rider reacts to hypothetical events or functions that cannot be tested safely in an actual bicycle (*55*, *56*). **Figure 1** shows the bike simulator.

Figure 1 Bike Simulator at SABA Lab, Morgan State University

Ten participants were recruited from Morgan State University. Participants rode in a simulated virtual environment modeled to scale from a real-world street with different types of bike lanes. The research team conducted an institutional review board-approved (IRB-approved) driving task (#24/03-0076) (**APPENDIX D**). The purpose of the IRB review is to assure, both in advance and by periodic review, that appropriate steps are taken to protect the rights and welfare of humans participating as subjects in the research. To determine the impacts of their experiences on their riding behaviors, participants were asked to complete a pre-survey questionnaire, ride for approximately ten minutes in various simulated scenarios, and then complete a post-survey questionnaire. First, the observer gave the participants a brief description of the simulator to familiarize them with its environment. The 10 participants also reviewed the procedure before riding the bike simulator.

The participants rode five scenarios, each one-kilometer-long network. A major three-lane road (three 12-foot lanes) with a speed limit of 55 mph was designed using virtual reality (VR) Studio software. A level of service B, i.e., light traffic, was used in these scenarios. Traffic flow and density were the same in all five scenarios. The first scenario is a shared lane; participants and motor vehicles share the same roadway without dedicated bike space. The second scenario is a separated bike lane, which provides a designated space for cyclists, separated from vehicle traffic by a buffer, such as a curb or space, creating a safer environment for biking by keeping vehicles at a distance. The third scenario is a separate bike lane with barriers. This lane further increases safety by including physical barriers, such as posts or bollards, between cyclists and motor vehicle traffic, preventing vehicles from creeping into the bike lane. The fourth scenario is a bike lane with green pavement marking. This bike lane is highlighted with green pavement, providing clear visual cues to cyclists and drivers and enhancing visibility and awareness, especially at intersections or conflict zones. The fifth scenario is shared bus-bike lanes, and while space is dedicated for both modes, cyclists need to navigate the lane while accommodating slower, larger buses.

3.2. Data

3.2.1. Spatial Data

The data for bike facilities in Baltimore City were retrieved from the Baltimore City Department of Transportation. They depict the the city's existing bike facilities as recognized by Baltimore City Department of Transportation's Bike Baltimore program of the (*57*). **Figure 2** shows different types of bike lanes in Baltimore City.

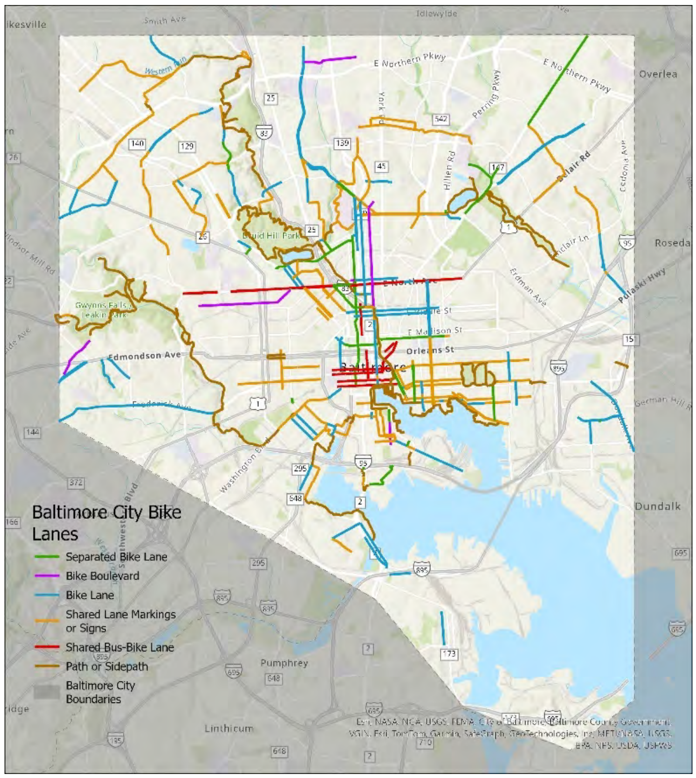


Figure 2 Different Types of Bike Lanes in Baltimore City

Maryland Crash Data were retrieved from Maryland.gov and Maryland State Police (*58*) from 2022 to 2023. The total number of crashes in Baltimore City during these two years is **32,110**. **Table 1** shows the crash summary for both total crashes and bicycle-involved crashes in Baltimore City.

Table 1 Crash Summary (2022-2023)

	Total Crashes		**Bicycle Involved Crashes**	
	2022	**2023**	**2022**	**2023**
Fatal Crashes	49	43	1	0
Injury Crashes	5,063	5,085	93	90
Property Damage Crashes	11,074	10,796	22	20
Total Crashes	16,186	15,924	116	110

There were 16,186 crashes in 2022 and 15,924 crashes in 2023. **Figures 3** and **4** show heat maps of all crashes in Baltimore over these two years involving all vehicles and bicycles, respectively. The heatmaps indicate varying frequencies of crashes across the city, with red and yellow areas signifying regions with a high crash density and blue and purple areas indicating lower a crash density.

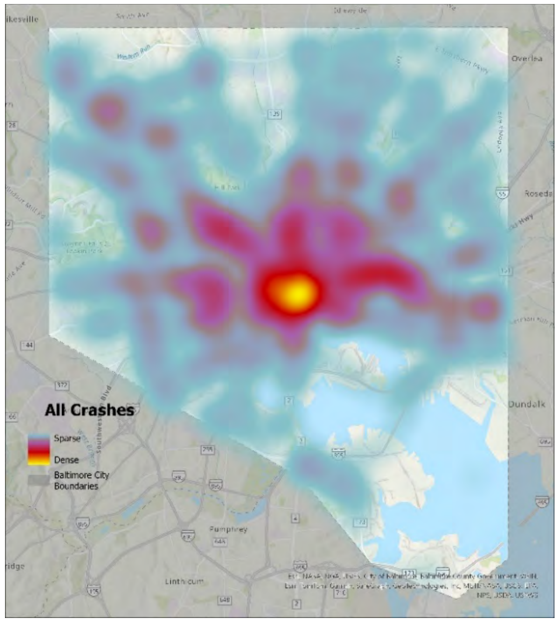


Figure 3 Heat Map of All Crashes in Baltimore City

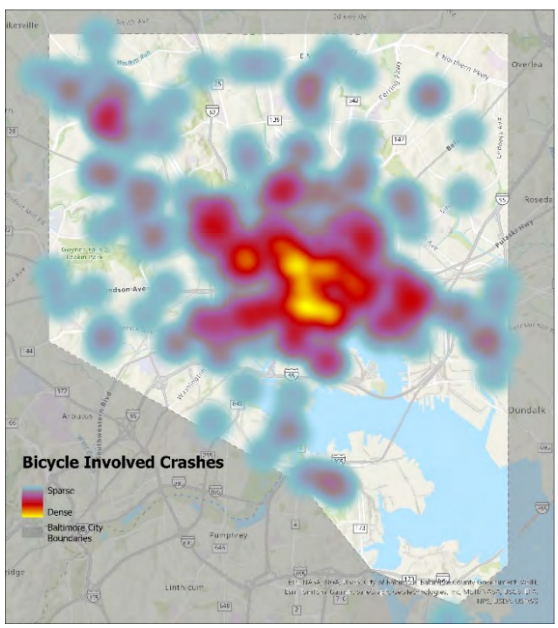


Figure 4 Heat Map of Bicycle Involved Crashes in Baltimore City

At the Census Tract level, the sociodemographic data for the median household income, race, etc., were retrieved from the U.S. Census Bureau's ACS 2018-2022 five-year estimates (*59*). **Figure 5** shows the median income, and **Figure 6** shows the race at the Census Tract level.

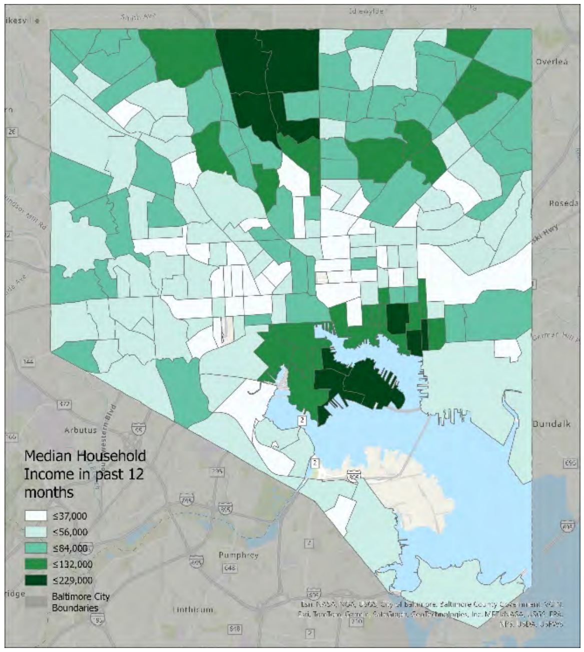


Figure 5 Household Median Income

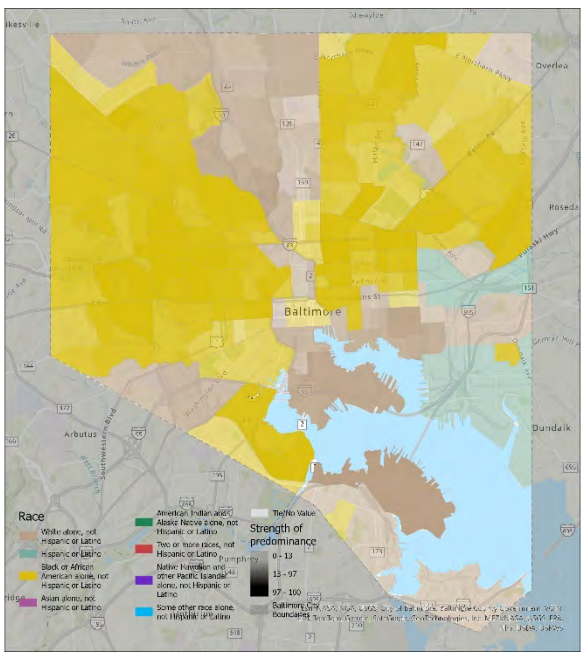


Figure 6 Household Race in Baltimore City

3.2.2. Survey Data

The survey consists of three sections. The first section collected basic information about the respondents, including age, gender, education, etc. The second section is related to cycling habits and was split into two sections: one for respondents who used bike lanes in Baltimore City before and one for respondents who did not. The results showed that 49 participants (more than 44%) had previously used bike lanes in Baltimore City. **Table 2** shows the sociodemographic information of respondents. Most respondents were female undergraduate students between 18 and 24 years old.

Table 2 Sociodemographic Information of Respondents

Variable	Bike Lane Users	Bike Lane Non-users
Age	-	-
Less than 18	0%	3.28%
18-24 years old	24.49%	24.59%
25-34 years old	30.61%	26.23%
35-44 years old	30.61%	26.23%
45-54 years old	10.20%	16.39%
55-64 years old	4.08%	0%
65 or more	0%	3.28%
Gender		
Male	48.98%	68.85%
Female	51.02%	27.87%
Prefer not to say	0%	3.28%
Race		
White	16.33%	18.03%
Black or African American	67.35%	80.33%
Asian	16.33%	1.64%
Education		
Less than high school graduate	0%	1.640%%
High school graduate, including GED	6.12%	11.48%
Some college or associate's degree (e.g., AA, AS)	20.41%	13.11%
Bachelor's Degree (e.g., BA, AB, BS)	22.45%	16.39%
Graduate or professional degree (e.g., MA, MS, MED, Ph.D.)	51.02%	57.38%
Cycling Usage		
Daily	8.16%	1.64%
Weekly	20.41%	3.28%
Monthly	16.33%	0%
Rarely	42.86%	22.95%
Never	12.24%	72.13%
Bicycle Type		
Conventional bike	61.22%	21.31%
E-bike	14.29%	6.56%
Shared Bike (Spin, Lime, etc.)	16.33%	6.56%
Road Bike	2.04%	1.64%
None above	6.12%	63.93%

Table 2 highlights significant differences in sociodemographic characteristics and cycling habits between respondents who used bike lanes in Baltimore City and those who did not. Most bike lane users were female (51.02%) compared to non-users. The age distribution shows that the majority of bike lane users were between 25 and 44. Cycling usage patterns also differ, with bike lane users showing more frequent riding habits—8.16% ride daily and 20.41% weekly—whereas non-users ride much less frequently, with 72.13% never using a bike. Conventional bikes are the most popular among both groups, but a greater diversity of bike types is seen among lane users, including e-bikes and shared bikes.

3.2.3. Bike Simulator Data

The pre-survey and post-survey (**Appendix B and C**) were designed as part of a simulation study to assess preferences and perceptions regarding various bike lanes in Baltimore. Respondents were presented with multiple-choice questions showcasing five bike lane configurations offered in the bike simulator (**Figure 7**).

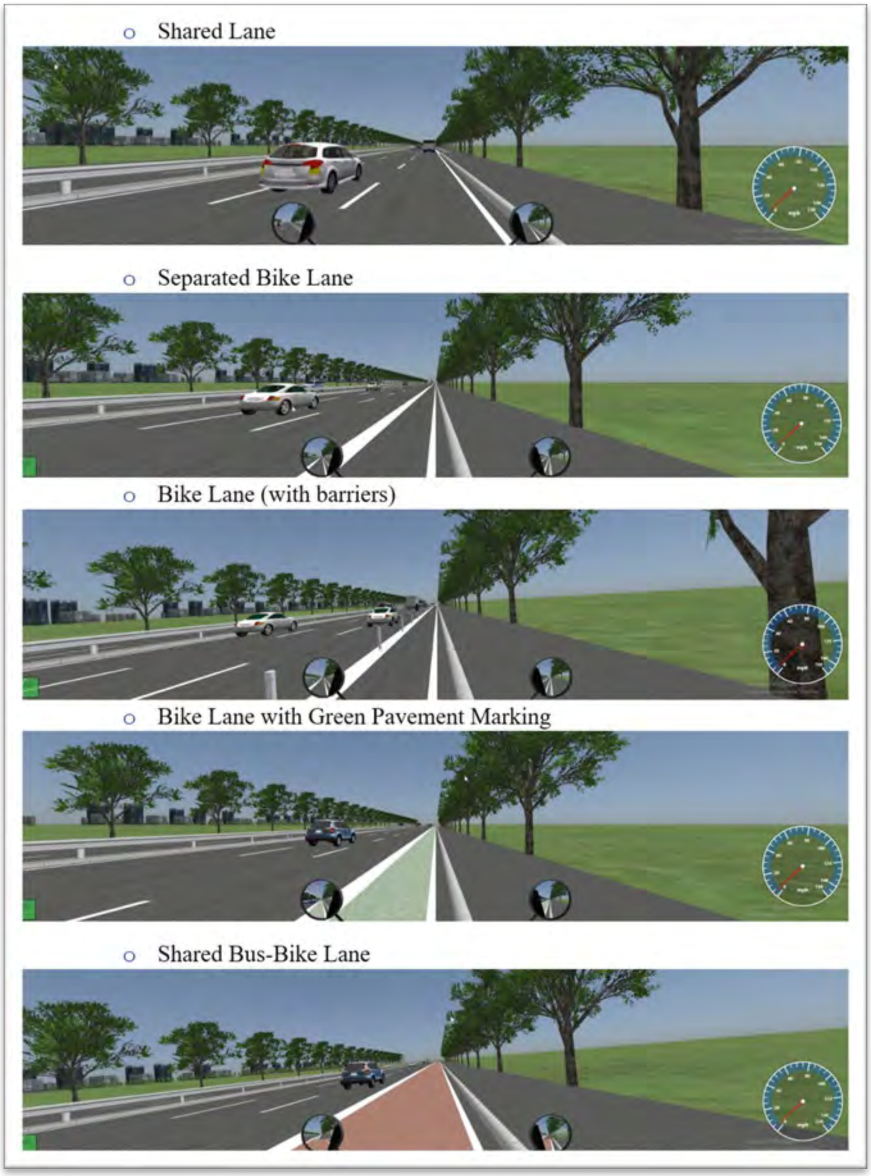


Figure 7 Different Types of Bike Lanes Presented in The Survey

Each bike lane type was represented visually to allow participants to differentiate between the configurations. Respondents were asked to indicate their preferences and feelings of safety regarding each lane type before and after participating in the simulation study. Key questions included:

- Which type of bike lane do you prefer to use the most and least in Baltimore before and after the simulation study?
- Which type of bike lane do you feel is the safest and least safe to use in Baltimore before and after the simulation study?

This approach allowed us to gauge initial impressions and any shifts in perception following the simulation, providing insight into the factors influencing users' preferences for specific bike lane designs.

4. RESULTS

4.1. Spatial Analysis Results

4.1.1. Bicycle Involved Crashes

The distribution of crashes in Baltimore City, as shown by the heat map, exhibits several notable patterns:

1. High Concentration in the City's Center: The densest areas of crashes, indicated by the red and yellow zones, are concentrated in the central parts of Baltimore. This suggests that the highest volume of crashes occur in the city's core, likely due to higher traffic volumes, increased pedestrian and bicycle activity, and potentially more complex road networks.
2. Decreasing Density Moving Outward: As you move away from the central areas, the crash density diminishes, transitioning to blue and purple zones. This indicates fewer crashes in outer and suburban neighborhoods, possibly due to lower traffic volumes, simpler road designs, and more residential zoning.
3. Geographic Influences: The map suggests frequent crashes near crucial transportation corridors and densely populated regions. Areas near downtown Baltimore and regions with high commercial and residential activity levels will likely see the highest incidents. In contrast, areas near the outskirts, particularly near bodies of water like the harbor and less densely developed areas, experience significantly fewer crashes.
4. Potential Clusters Along Major Roads: The spread of crash density suggests the presence of specific corridors or roads where crashes might be more frequent. These could be major arterials, highways, or roads with significant traffic flow or safety issues that result in higher crash frequencies.

This distribution highlights the need for targeted safety interventions in central Baltimore, where the crash risk appears much higher. It also suggests that planners and policymakers focus on road safety measures, such as improved traffic management, bike lane expansion, pedestrian safety enhancements, or speed reductions in these dense areas.

4.1.2. Bicycle Equity Index

Areas of more significant disadvantages that might benefit from investments in bicycle infrastructure can be identified by combining the z-scores of all BEI Indicators. **Figure 8** demonstrates the results of the BEI and the spatial distribution of BEI scores. Areas with brighter shades have a lower need for bike infrastructure, and the darker census tracts have a higher need for bikeshare infrastructure. Notable neighborhoods are located on the west, east, and south sides. **Figure 8** shows that areas with higher bike infrastructure need more bike lanes.

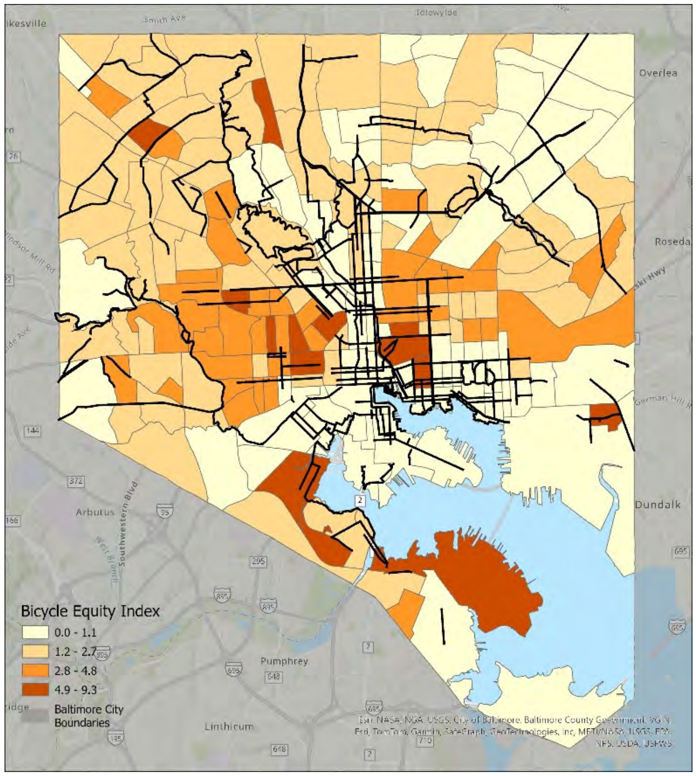


Figure 8 Bicycle Equity Index and Bike Lanes in Baltimore City

4.1.3. Regression Model

The results of the linear regression model are presented in **Table 3**. The regression model results show several factors have a statistically significant relationship with the number of bicycle-involved crashes at the census tract level. The length of the bike lane is positively and significantly associated with bicycle-involved crashes, suggesting that more extended bike lanes may correspond with a higher number of crashes, possibly due to increased cyclist activity in areas with more infrastructure. Additionally, the percentage of households with no vehicles is positively and significantly associated with bicycle crashes, indicating that areas with more car-free households might experience more bicycle traffic and, consequently, more crashes. Other variables, such as the percentage of the population under 18 and over 65, have negative but non-significant relationships with bicycle-involved crashes.

Table 3 Regression Model Results

Coefficients:					
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	0.64	0.32	2.00	0.05	*
Bike Lane Length	0.37	0.05	7.36	0.00	***
Household with No Vehicle	0.02	0.00	3.49	0.00	***
Age Under 18	-0.02	0.01	-1.70	0.09	.
Age Above 65	-0.20	0.12	-1.66	0.10	.
--- Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1'' **1**					

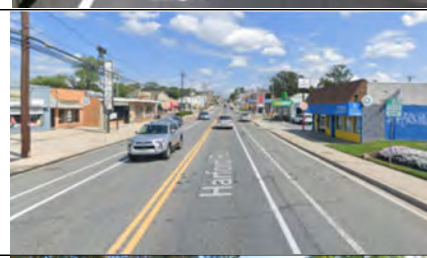
4.2. Survey Analysis Results

4.2.1. Bike Lanes Users

4.2.1.1. Bike Lanes Preference

Participants were asked which bike lane they have used most often in Baltimore. **Table 4** shows the results. The results show that paths or side paths were the most used bike lane type in Baltimore City, with 30.66% of participants selecting this option. In contrast, shared lane markings or signs were the least used type, accounting for 14.66% of responses, while shared bus-bike lanes were chosen by 21.33% of participants, making them the second most used ones.

Table 4 Different Types of Bike Lanes Used in Baltimore City

Bike Lane Type	Bike Lane Type	Percentage
Shared Lane Markings or Signs		14.66%
Separated Bike Lane		16%
Bike Lane		17.33%
Path or Sidepath		30.66%
Shared Bus-Bike Lane		21.33%

Participants were asked about their preference for separate bikes or shared lanes with vehicles. The overwhelming majority of respondents (87.75%) prefer separated bike lanes from traffic, indicating a strong desire for dedicated cycling infrastructure that is physically separated from vehicle lanes. Only a tiny percentage (4.08%) prefer shared lanes with vehicles, suggesting that few people are comfortable sharing the road with cars. Additionally, 8.16% of respondents expressed no preference, indicating some flexibility in their choice of bike lane type.

4.2.1.2. Safety

Users were asked how safe they felt using bike lanes in Baltimore City on a scale of 1 to 5. **Figure 9** shows the results. Many respondents think using bike lanes in Baltimore City is only moderately safe. The highest percentage of respondents rated their sense of safety as a two on the scale (31.25%), followed closely by those who rated it a three (29.16%).

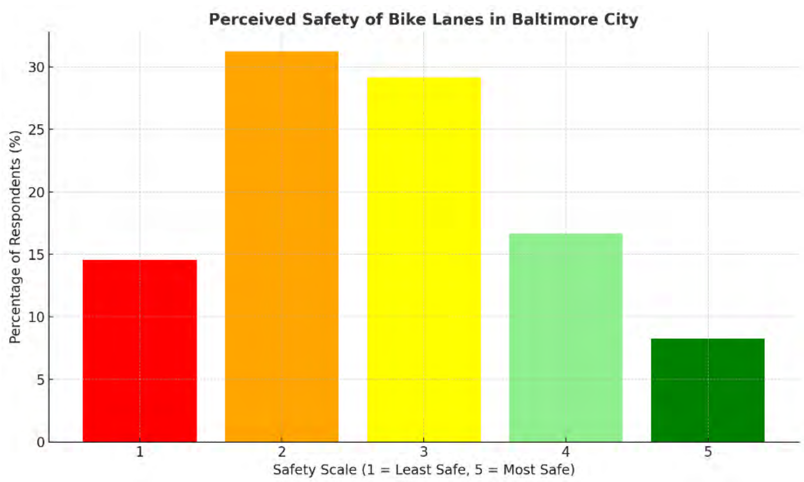


Figure 9 Perceived Safety of Bike Lanes

Table 5 shows the results of several safety concerns and participants' responses. According to the results, the most common safety concern for bike lane users in Baltimore City is a lack of bike lanes in some places, with 18.79% indicating this issue. Other significant problems include turning cars (15.78%) and merging traffic (15.03%). Other significant complaints are dooring by parked automobiles and poor road surfaces, cited by around 13-15% of respondents. Less often stated difficulties include debris in the lane, a lack of signage or markings, and insufficient illumination, all of which contribute to cyclists' overall safety challenges.

According to **Table 5**, 20.4% of respondents had been involved in a crash or near-crash while pedaling in a Baltimore City bike lane, whereas 79.6% have not. Regarding helmet use, just 14.28% of respondents always wear one, while a more significant number (48.97%) use one occasionally. According to the results, bikers in Baltimore City frequently encounter obstructions that restrict bike lanes, such as parked cars and people. Nearly half of the respondents (48.97%) reported sometimes facing these challenges, while 32.65% encountered them regularly. Notably, none of the respondents reported never meeting an impediment, indicating that this is a widespread concern for cyclists in the city. The research shows that feeling unsafe due to the lack of signals and drivers not anticipating cyclists in bi-directional bike lanes on one-way streets is a prevalent concern. A significant proportion of respondents (34.69%) reported feeling unsafe regularly, showing that this problem is common.

Table 5 Safety Concerns Questions Results

Safety Concerns	
Choices	**Percentage**
Dooring by parked cars	13.53%
Merging traffic	15.03%
Turning vehicles	15.78%
Debris in the lane	9.77%
Poor road surface	15.03%
Lack of bike lanes in some areas	18.79%
Lack of signage or markings	6.76%
Lack of lighting	5.26%
Being involved in a crash or near-crash while cycling in a bike lane in Baltimore City	
Yes	20.4%
No	79.6%
Wearing a helmet while biking	
Always	14.28%
Often	32.65%
Sometimes	48.97%
Rarely	4.08%
Never	0%
Encountering obstacles blocking bike lanes (parked cars, debris, pedestrians, etc.)	
Always	14.28%
Often	32.65%
Sometimes	48.97%
Rarely	4.08%
Never	0%
The lack of signals and drivers not anticipating cyclists in bi-directional bike lanes on one-way streets	
Always	10.20%
Often	34.69%
Sometimes	34.69%
Rarely	12.24%

Table 6 shows the bike lane users' opinion on built environment features that would most improve bike lane safety (Rank 1-5, with 5 being the most important). According to the data, bike lane users prefer various built environment measures for improving bike lane safety in Baltimore City. Rumble strips separating bike lanes from traffic are the most critical element, according to 63.26% of respondents who prioritized it. Raised crosswalks at bike lane intersections are similarly highly regarded, with 40.81% of respondents thinking that they are the most significant. Improved street lighting along bike paths is another major priority, with 42.85% of respondents selecting it as the most critical aspect. Dedicated bike parking facilities, while still significant, were chosen as the top priority by just 22.44% of respondents, showing less importance than other characteristics. This indicates a substantial preference for infrastructure that improves physical security and visibility.

Table 6 Bike Lane Improvement Priorities (With 5 Being Most Important)

	1	2	3	4	5
Dedicated bike parking areas	10.20%	18.36%	30.61%	18.36%	22.44%
Improved street lighting along bike routes	2.04%	8.16%	14.28%	32.65%	42.85%
Raised crosswalks at bike lane intersections	2.04%	6.12%	20.40%	30.61%	40.81%
Rumble strips separating bike lanes from traffic	2.04%	6.12%	8.16%	20.40%	63.26%

Other safety concerns bike lane users mention include narrow bike lanes, unavailability of physical barriers separating bikers, aggressive and distracted drivers, and disconnectivity of the bike lane network in the city. According to the findings, bike lane users feel safer bicycling in the mornings, afternoons, off-peak hours, and on weekends, most likely owing to less traffic and a decreased risk of collisions with automobiles.

4.2.1.3. Accessibility and Quality

Participants were asked how accessible bike lanes are from their residences or workplaces. The data indicates that most respondents (63.26%) find bike lanes accessible from their homes or workplaces. A smaller portion of respondents (18.36%) report that bike lanes are either very accessible and not accessible at all. A question was asked about the quality of bike lanes in Baltimore City. **Figure 10** shows the results. This chart highlights that most respondents rated the bike lanes as "Fair" (59.18%). At the same time, only a small portion considered them "Excellent" (6.12%), suggesting that most people view the quality as mediocre, with room for improvement.

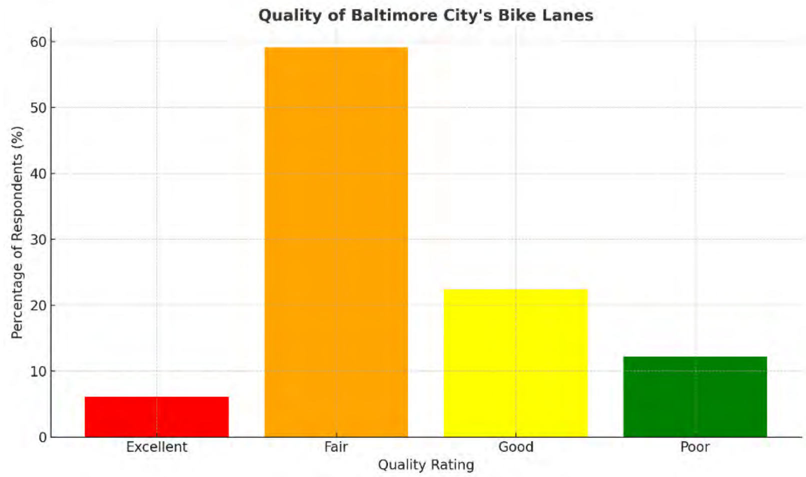


Figure 10 Quality of Bike Lanes

Table 7 shows that the most effective way to encourage more riding in Baltimore would be to construct additional separated bike lanes, which 31.93% of respondents identified as their top priority. Improved bike lane signs and markings were the second most popular option (22.68%), followed by enhanced lighting (18.48%) and increased enforcement of cyclist-related traffic rules (15.12%). Furthermore, several respondents emphasized the need for broad bike lanes with buffer spaces and street-cleaned bike lanes, highlighting the need for infrastructure improvement to make cycling safer and more desirable.

Table 7 Factors Encouraging Bikers to Cycle More in Baltimore City

More separated bike lanes	31.93%
Improved signage and markings for bike lanes	22.68%
Educational programs on cycling safety for both cyclists and motorists	12.60%
Improved lighting	18.48%
Increased enforcement of traffic laws related to cyclists	15.12%

The suggestion section raised various concerns, including the need for a more connected bike lane network. Respondents preferred broader roadways with buffer areas and bollards to separate bike lanes from vehicles on narrower routes. Some respondents said that automobiles frequently fail to spot bikers, resulting in unsafe situations. Others noted that current bike lanes must be used and linked to desirable locations like parks and lakes. The lack of access to safe routes restricts the usage of bike lanes, particularly for leisure purposes like riding to Lake Montebello. Overall, the bike lane users highlight the critical need for improved infrastructure, connectivity, visibility, and safety measures to promote safe and accessible cycling in the city. Specific areas in Baltimore where participants feel bike lanes could be expanded or improved are:

- Around and through Morgan State University
- The areas of the city where there are no large parks with bike paths. And near schools for kids who bike.
- North Avenue
- Mount Royal Terrace

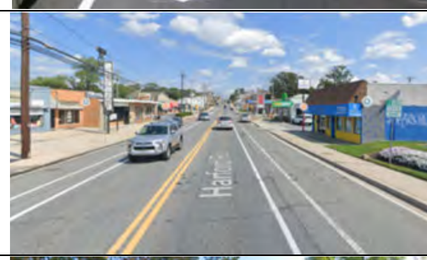
- East Cold Spring Lane
- York Road
- 33rd Street

4.2.2. Non-Users

4.2.2.1. Bike Lanes Preference

Participants were asked which bike lane they preferred to use in Baltimore. **Table 8** shows the results. Most participants (52.38%) preferred to use paths or side paths for cycling in Baltimore City, making it the most favored option. Shared lane markings or signs were the least preferred, with only 2.38% of respondents selecting them.

Table 8 Different Types of Bike Lanes Preferred to Use in Baltimore City

Bike Lane Type	Bike Lane Type	Percentage
Shared Lane Markings or Signs		2.38%
Separated Bike Lane		10.71%
Bike Lane		17.85%
Path or Sidepath		52.38%
Shared Bus-Bike Lane		14.28%

None		2.38%

Participants were asked about their preference for separate bikes or shared lanes with vehicles. Most respondents (81.97%) prefer separated bike lanes from traffic, indicating a strong desire for dedicated cycling infrastructure that is physically separated from vehicle lanes. Only a small percentage (8.20%) prefer shared lanes with vehicles, suggesting that only some people are comfortable sharing the road with cars. Additionally, 9.84% of respondents expressed no preference, indicating some flexibility in their choice of bike lane type.

4.2.2.2. Safety

Table 9 highlights numerous major safety concerns for cyclists in Baltimore City from non-users' points of view. The most critical concerns are merging traffic (18.68%), turning vehicles (16.66%), and poor road surfaces (15.65%), demonstrating that cyclists suffer great dangers from vehicle interactions and infrastructure quality. Other prominent difficulties include parked automobile dooring (13.63%) and a lack of bike lanes in some regions (13.13%). Fewer respondents cited debris in the lanes (6.06%), a lack of signs (9.09%), or illumination (7.07%) as their top worries. Surprisingly, 24.6% of non-users have been engaged in or observed a bicycle-involved crash or near-crash, highlighting the dangers cyclists confront on Baltimore's streets.

Significantly, 78.69% of participants expressed interest in cycling activities if they felt more secure using bike lanes, underscoring the robust association between perceived safety and cycling behavior in the urban area.

Table 9 Safety Concerns Questions Results

Safety Concerns	
Choices	**Percentage**
Dooring by parked cars	13.63%
Merging traffic	18.68%
Turning vehicles	16.66%
Debris in the lane	6.06%
Poor road surface	15.65%
Lack of bike lanes in some areas	13.13%
Lack of signage or markings	9.09%
Lack of lighting	7.07%
Being involved in or witnessed a bicycle-involved crash or near-crash in Baltimore City	
Yes	24.6%
No	75.4%
Encountering obstacles blocking bike lanes (parked cars, debris, pedestrians, etc.)	
Always	6.5%
Often	27.86%
Sometimes	34.42%
Rarely	9.83%
Never	21.31%
More likely to consider cycling if you felt safer using bike lanes	

Yes	78.69%
No	21.31%

Table 10 shows non-users opinions on built environment features that would improve bike lane safety (Rank 1-5, with 5 being the most important). According to the data, they prefer various built environment measures for improving bike lane safety in Baltimore City. Rumble strips separating bike lanes from traffic are the most critical element, according to 63.93% of respondents who prioritized it. Improved street lighting along bike routes is also highly regarded, with 49.18% of respondents considering it the most essential feature. Dedicated bike parking areas are another major priority, with 40.98% of respondents selecting it as the most critical aspect.

Table 10 Bike Lane Improvement Priorities (With 5 Being Most Important)

	1	2	3	4	5
Dedicated bike parking areas	14.75%	19.67%	21.31%	13.11%	40.98%
Improved street lighting along bike routes	6.55%	8.19%	8.19%	27.86%	49.18%
Raised crosswalks at bike lane intersections	6.55%	8.19%	19.67%	26.22%	39.34%
Rumble strips separating bike lanes from traffic	8.19%	4.91%	6.55%	16.39%	63.93%

4.2.2.3. Accessibility and Quality

Participants were asked about bike lane accessibility from their residences or workplaces. The data indicates that 42.62% find bike lanes to be somewhat accessible or not accessible at all. A smaller portion of respondents (14.76%) report that bike lanes are accessible. A question was asked about the quality of bike lanes in Baltimore City. **Figure 11** shows the results. This chart highlights that most respondents rated the bike lanes as "Fair" (54.10%). At the same time, only a tiny portion considered them "Excellent" (3.28%), suggesting that most people view the quality as mediocre, with room for improvement.

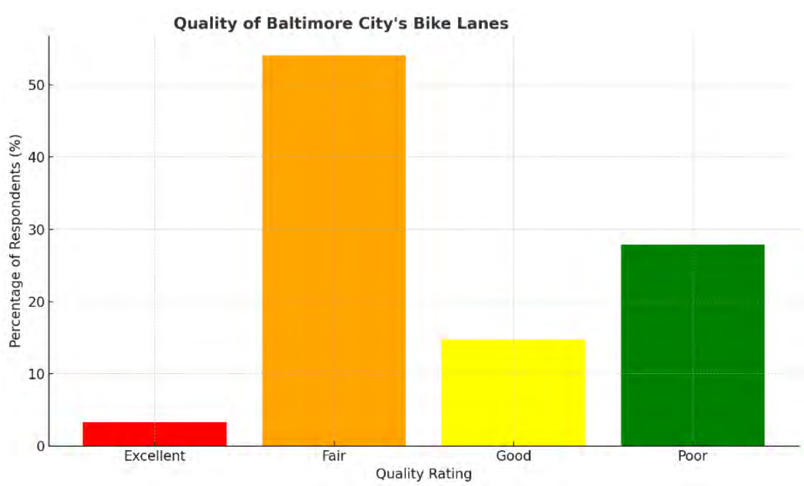


Figure 11 Quality of Bike Lanes

Table 11 shows that the most effective way to encourage non-users to ride more in Baltimore would be to construct additional separated bike lanes, which 34.69% of respondents identified as their top priority. Improved bike lane signs and markings were the second most popular option (19.04%), followed by enhanced lighting (18.36%) and increased enforcement of cyclist-related traffic rules (15.64%). Other answers include increased enforcement of all traffic laws, not just those related to cyclists.

Table 11 Factors Encouraging Bikers to Cycle More in Baltimore City

More separated bike lanes	34.69%
Improved signage and markings for bike lanes	19.04%
Educational programs on cycling safety for both cyclists and motorists	12.24%
Improved lighting	18.36%
Increased enforcement of traffic laws related to cyclists	15.64%

In the suggestion section, various concerns were raised, including making sure that biking is safe and accessible to all people in the city and not just to a select few neighborhoods in the area. Improving the connection between public transportation and bike lanes in Baltimore could connect neighborhoods and city/county residents better, potentially increasing job opportunities, revenue, etc. Specific areas in Baltimore where participants feel bike lanes could be expanded or improved are:

- Northern parkway
- Around John Hopkins University and Morgan State University
- Charles and Saint Paul Street
- Northeast Baltimore City/ County Neighborhoods (Cedonia, Cedmont, Overlea, Fullerton, Moravia, Frankford, Bel Air-Edison)

4.3. Bike Simulator Analysis Results

The first question in the pre-survey questionnaire asked the participants which type of bike lane they preferred to use in Baltimore the most. The same question was asked of the participants after the simulation to examine the difference between their preferences after the experiment. **Figure 12** shows the results of the first question.

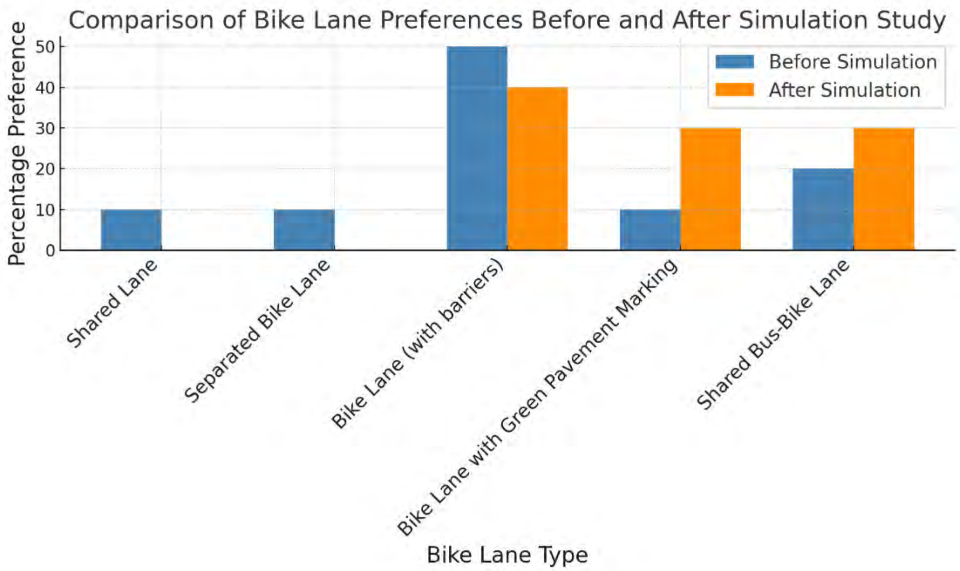


Figure 12 The Most Preferred Bike Lanes Before the Simulation

The results showed that before the simulation, the bike lane (with barriers) was the most preferred bike lane, with 50% of the respondents choosing it as their top choice. The shared bus-bike lane followed, with 20% of the respondents selecting it. After the simulation, the preference shifted significantly, with the bike lane (with barriers) still being the favorite but dropping to 40%. The shared bus-bike lane increased in preference to 30%, showing a more favorable view after the simulation. The bike lane with the green pavement marking also gained popularity, with 30% of respondents preferring it.

The second question in the pre-survey questionnaire asked the participants which type of bike lane they least preferred to use in Baltimore. The same question was asked of the participants after the simulation to examine the difference between their preferences after the experiment. **Figure 13** shows the results of the first question.

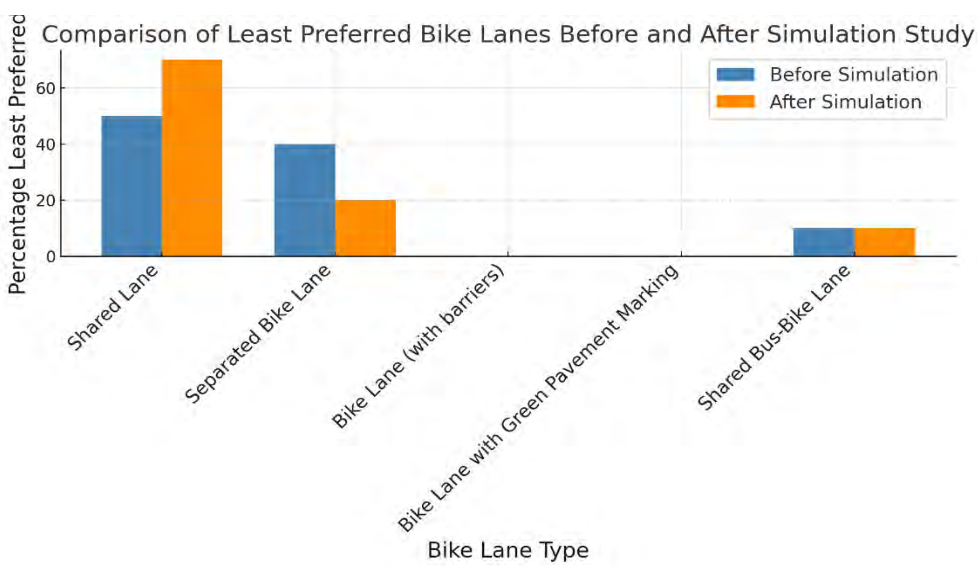


Figure 13 The Least Preferred Bike Lanes Before the Simulation

Before the simulation, the results showed that the shared lane was the least preferred by 50% of respondents. The separated bike lane followed, with 40% of the respondents listing it as their least preferred option. The shared bus-bike lane was the least preferred for 10% of respondents. After the simulation, the shared lane increased to be the least preferred, jumping to 70%. After the simulation, the separated bike lane was least preferred among 20% of respondents, showing some positive shift in perception. The shared bus-bike lane remained consistent, with 10% still listing it as their least preferred. The simulation seemed to reinforce a negative perception of the Shared Lane, while the perception of the separated bike lane improved after the experience.

The third question in the pre-survey questionnaire asked the participants which type of bike lane they felt was safest to use in Baltimore. The same question was asked of the participants after the simulation to examine the change in their preferences after the experiment. **Figure 14** shows the results of the first question.

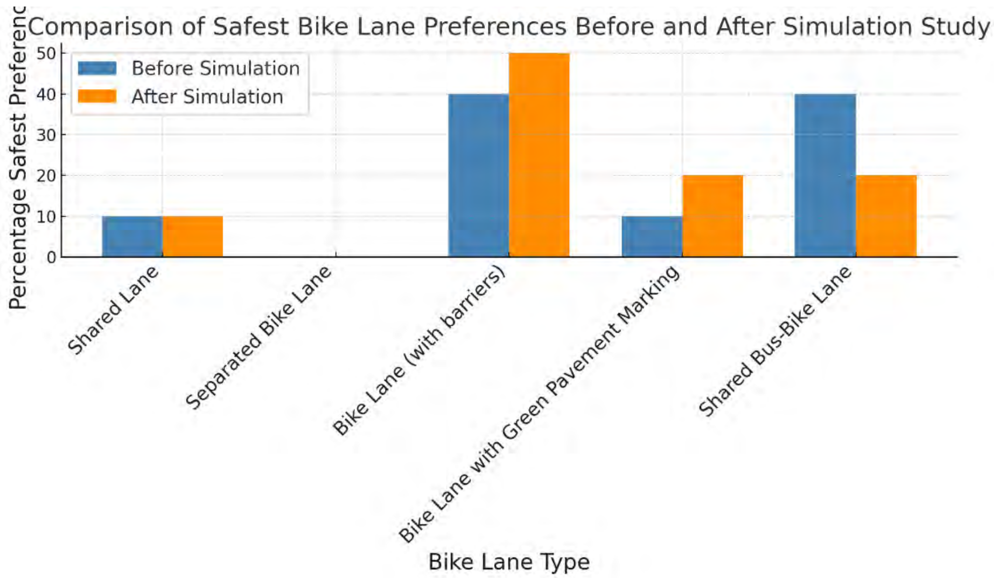


Figure 14 The Safest Bike Lanes Before the Simulation

Results show that before the simulation, both the bike lane (with barriers) and the shared bus-bike lane were considered to be safest by 40% of the respondents. The bike lane with the green pavement marking and shared lane garnered 10% of responses. After the simulation, the bike lane (with barriers) became the clear favorite, as 50% of respondents chose it as the safest option. The bike lane with green pavement markings and the shared bus-bike lane were each selected by 20% of the respondents. The shared lane maintained its 10% rating. This shift indicates that respondents favored bike lanes, such as barriers, that provided higher physical protection after the simulation. In contrast, other bike lanes saw smaller increases or maintained similar levels of perceived safety.

The fourth question in the pre-survey questionnaire asked the participants which type of bike lane they felt safest and the least safe to use in Baltimore. The same question was asked of the participants after the simulation to examine the difference between their preferences after the experiment. **Figure 15** shows the results of the first question.

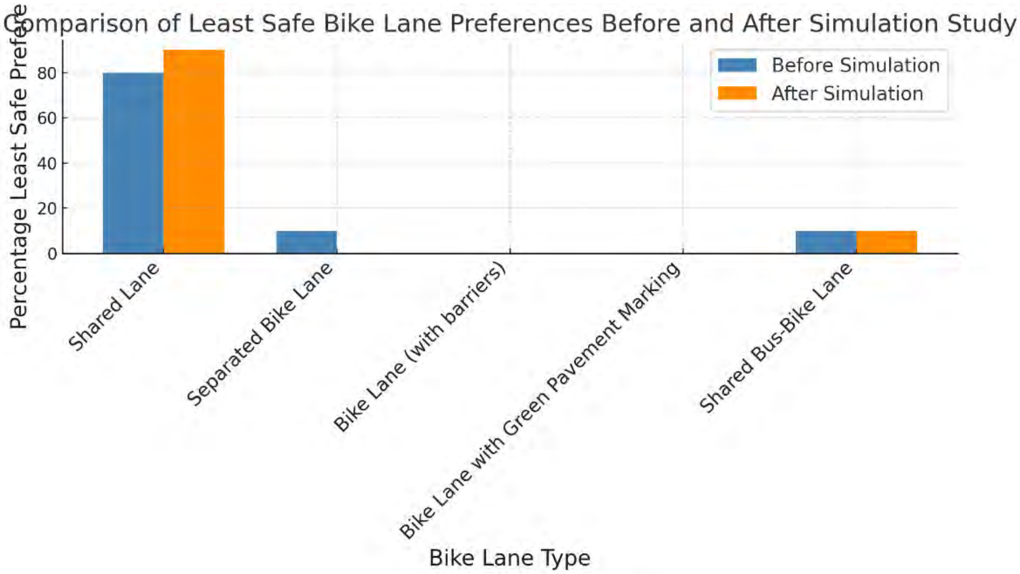


Figure 15 The Least Safe Bike Lanes Before the Simulation

Before the simulation, 80% of respondents felt the shared lane was the least safe option. The separated bike lane and the shared bus-bike lane were viewed as the least safe by 10% of respondents. After the simulation, the shared lane increased perception as the least secure, rising to 90%. The shared bus-bike lane maintained its 10% ranking as the least safe. The other bike lane types, including separated bike lanes and bike lanes with barriers, saw no change in their ratings. This suggests that the simulation may have reinforced perceptions of the shared lane as the least safe option, with other configurations maintaining or solidifying their relative positions regarding safety concerns.

5. DISCUSSION

This study's spatial analysis identifies key locations in Baltimore City that are high in bicycle-related collisions. Downtown Baltimore has the highest overall concentration of crashes, including crashes involving bicycles, indicating that densely populated metropolitan regions are more likely to have higher crash rates. This may be caused by more significant vehicle and bicycle traffic and more complex road systems and crosswalks. Additionally, the Bicycle Equity Index (BEI) highlights differences in bike infrastructure accessibility among neighborhoods with different socioeconomic conditions. According to the BEI analysis, vulnerable groups—including minorities, those with low incomes, children, and the elderly—generally reside in locations with less access to infrastructure for safe riding. These locations, frequently found in the suburbs or less developed sections of the city, feature fewer bike-friendly road layouts and protected bike lanes. In addition to discouraging cycling as a means of transportation, this lack of infrastructure increases risk for cyclists in these locations. Thus, the geographical analysis highlights an equity problem, as underprivileged neighborhoods are deprived of the safety benefits of well-planned bike infrastructure.

The findings of the regression model provide an understanding of the relationship between the number of bicycle-related crashes and presence of bike lanes, which is positive and significant. Although more extended bike lanes may be expected to reduce crashes by providing more dedicated space for cyclists, this finding suggests that the number of crashes increases as bike lane length increases. There might be several reasons for this, including the fact that more extended bike lanes may expose bikers to more significant risks of collisions or that more extended bike lanes may draw more cyclists. Another interpretation might be that the bike lanes' design could be insufficient for the traffic they are meant to accommodate, with inadequate protection or unclear signage contributing to accidents. This finding highlights the importance of expanding bike lane networks and ensuring they are designed with adequate safety measures to reduce crash risk. The research emphasizes how important it is for bike lanes to remain continuous; lengthier lanes are only advantageous if they are consistent, well-integrated into the entire traffic system, and have sufficient safety measures. Even when there is a significant amount of total lane length, areas with disjointed or poorly constructed lanes may unintentionally put bicyclists in greater danger.

The survey analysis provides insightful information on the experiences and perceptions of safety among bikers in Baltimore City. According to the data, most participants ranked separated bike lanes and pathways or side paths highly, indicating a significant need for cycling infrastructure that keeps cyclists apart from motorized traffic. Safety is still a vital worry, and frequent problems include poor road conditions, merging vehicles, and the absence of bike lanes in certain places. The comparison between bike lane users and non-users in Baltimore City shows noticeable differences in preferences and usage of various bike lanes.

Among bike lane users, paths or side paths were the most frequently used option, with 30.66% of participants selecting them, while the second most used type was the shared bus-bike lane, at 21.33%. In contrast, non-users overwhelmingly preferred paths or side paths, with 52.38% selecting this as their preferred option for cycling, indicating a stronger preference for this safer and more protected type of infrastructure. Additionally, non-users showed a lower preference for shared bus-bike lanes (14.28%) than users, who were more willing to use this type of lane. Shared lane markings or signs were the least preferred and used by both groups. The high preference for separated lanes among non-users highlights the importance of safe and dedicated cycling infrastructure to encourage broader participation in biking.

These results are consistent with the geographical analysis as there is a greater likelihood of safety problems in high-density metropolitan areas that lack suitable infrastructure. Furthermore, the survey results show that individuals are more inclined to think about cycling if they feel safer, with 78.69% saying they would want to ride more often if safety measures were taken. Promoting the number of segregated bike lanes, upgrading the lighting and signage, and enforcing traffic regulations more strictly are all important recommendations for promoting safety. The survey results also bring to light several pressing safety concerns. Lack of bike lanes in some areas, poor road conditions, merging traffic, and turning cars were identified as bicyclists' top three safety concerns. These worries align with results from previous studies that indicate the riskiest places for cyclists to be at crossroads and portions of roads where they must share space with cars. The respondents also highlighted the need for better-designed infrastructure and more extensive coverage of bike lanes around the city.

The survey results provide insightful information about Baltimore City neighborhoods, where respondents felt significant upgrades to the city's bike infrastructure were required. Many respondents mentioned specific streets and communities with inadequate bike lanes or infrastructure, heightening the feeling of risk when cycling. Participants emphasized the need for better bike infrastructure near Morgan State University. Morgan State University is in a part of the city with few bike lanes and inadequate maintenance. Several respondents noted the inadequate bike infrastructure in Baltimore's northeastern and northwest regions. These areas frequently lack bike lanes, and the roads can be unsafe because of fast-moving vehicles and a lack of safety measures for cyclists.

The pre-and post-simulation survey results provide valuable insights into how participants' preferences for bike lanes changed after experiencing the simulation. Before participating in the simulation, most participants said they preferred bike lanes with barriers because they thought that was the safest choice. On the other hand, shared bus-bike lanes had a noticeable increase in popularity following the simulation experience. Participants felt more comfortable with these lanes after experiencing them in a controlled environment. The simulation also reinforced negative perceptions of shared lanes without physical separation from vehicle traffic, with 90% of participants identifying them as the least safe option post-simulation. This implies that being physically separate from cars significantly increases cyclists' sense of safety. Using simulations to change people's opinions about specific bike lane designs may be a promising avenue of future research and education initiatives.

Several key themes emerge across the spatial, survey, and bike simulator analyses. First, the geographical and survey data consistently show that dedicated, physically segregated bike lanes are necessary, with mixed-traffic lanes and insufficient infrastructure posing a safety concern. These results are further supported by the results of the bike simulator, which demonstrates that riders felt most safe in lanes with physical barriers. The study's findings highlight how critical it is to increase and improve Baltimore City's bike infrastructure, especially in locations with limited infrastructure coverage and a high crash risk.

The spatial analysis also clarified that targeted actions are required in specific neighborhoods. For instance, safer bike lanes, improved lighting, and more obvious signage would all be beneficial additions to the infrastructure in Baltimore, where crashes occur most frequently. New bike lane projects could focus on improving accessibility and safety for underprivileged communities in less developed areas. By expanding bike lane networks and assuring their optimal safety design, these focused enhancements might potentially reduce the hazards found in the regression model.

6. SUMMARY AND CONCLUSION

Safety perception plays a significant role in the decision to ride a bicycle. and it may become more important for potential users than the bike infrastructure. This study aimed to investigate how different types of bike lanes impact the safety and behavior of riders in Baltimore City. The study examined how different built environment factors affect bicycle crashes and how infrastructure design might promote safer riding settings and higher ridership.

Data was collected in several ways. First, the research team conducted a spatial analysis. Next, the research team surveyed over 110 participants via an online questionnaire to investigate bike lanes in Baltimore City. Finally, ten participants used a bike simulator at Morgan State University to reach the goals of this study. The research was carried out using survey analysis, geographical analysis, and bike simulator experiments.

ArcGIS Pro was used to conduct spatial analysis, which evaluated the distribution of bike infrastructure and bicycle-related crashes among Baltimore City's Census Tracts. Heat maps were created to analyze areas with varying levels of crash incidents. Moreover, to investigate access to bicycle infrastructure from an equity perspective, this study adopted the Bicycle Equity Index (BEI) methodology. Finally, using the variables developed by the spatial analysis of the study, a regression model was conducted to examine the relationship between bicycle-involved crashes and other sociodemographic and built environment factors.

In addition, an online survey was designed and distributed using the online platform Qualtrics. The study aimed to gather opinions on the safety of bike lanes from cyclists and non-riders, as well as preferences for various types of bike lanes and places in Baltimore in need of infrastructure improvements. In addition to recording participants' impressions both before and after the exercise, the bike simulator offered a secure setting for them to test various bike lane configurations.

The spatial analysis identified downtown Baltimore as a crash hotspot, with higher densities of bike-related crashes occurring in central, densely populated areas. These results aligned with the Bicycle Equity Index (BEI), which showed that vulnerable groups, including low-income and minority groups, have less access to safe cycling infrastructure. Furthermore, the regression model found a positive and significant correlation between the length of bike lanes and bike-related collisions. It suggests that while more extended bike lanes may accommodate more cyclists, they might also increase exposure to crash risks if not designed and maintained correctly.

Most survey respondents felt safer when physically isolated from moving cars, as seen by their significant preference for segregated bike lanes, trails, and side routes. Safety is still a considerable concern, and frequent problems include poor road conditions, merging vehicles, and the absence of bike lanes in certain places. The comparison between bike lane users and non-users in Baltimore City shows noticeable differences in preferences and usage of various bike lanes. The survey also revealed that most participants would be more likely to cycle if they felt safer on the roads, reinforcing the need for infrastructure improvements.

The bike simulator results align with the survey results, revealing that participants felt most secure in bike lanes with physical barriers. The study also showed that participants' choices changed after using the simulator to explore various lane types; following the simulation, a majority said they preferred shared bus-bike lanes. However, the shared lane was still considered the least safe and least favored option before and after the simulation.

The spatial analysis, survey, and bike simulator experiment results reveal a consistent theme: safety concerns are a significant barrier to increased cycling in Baltimore City. The lack of continuous and well-designed bike lanes, particularly in disadvantaged areas, contributes to a higher crash risk and discourages cycling as a mode of transportation. More extended bike lanes are linked to more crashes, possibly because they are poorly designed and lack safety elements like physical barriers and apparent signs. The simulator and survey results prove the need for separated bike lanes, improved lighting, and better enforcement of cyclist traffic laws.

7. APPENDIX A. QUESTIONNAIRE

Hello!

Thank you for participating in this survey. We are studying the effects of different bike lane types on bicyclists' safety and rider behaviors in Baltimore City. This study is conducted by Dr. Mansoureh Jeihani, Dr. Eazaz Sadeghvaziri, and Ms. Ramina Javid.

Any information obtained concerning this study that can identify you will remain confidential. If you have any questions, please do not hesitate to contact us at Mansoureh.Jeihani@morgan.edu, Eazaz.Sadeghvaziri@morgan.edu, or rajah1@morgan.edu.

Please feel free to share this survey with others. Your participation is of great importance in this study. If you have any questions, please do not hesitate to contact us. Thank you for your participation, which is important to this study.

Thank you!

1. What is your Age?
   - Less than 18
   - 18-24 years old
   - 25-34 years old
   - 35-44 years old
   - 45-54 years old
   - 55-64 years old
   - 65 and more

2. What is your Gender?
   - Male
   - Female
   - Prefer not to say
   - Other (Please specify)

3. What is your Race?
   - American Indian or Alaska Native
   - Native Hawaiian or Other Pacific Islander
   - Asian
   - Black or African American
   - White

4. What is the highest level of education you have completed?
   - Less than high school graduate
   - High school graduate, including GED

- Some college or Associate's degree (e.g., AA, AS)
- Bachelor's Degree (e.g., BA, AB, BS)
- Graduate or professional degree (e.g., MA, MS, MED, Ph.D., MD, DDS)

5. What is your current state of residence?

6. What is the zip code of your residence?

7. How often do you cycle in Baltimore City?
   - Daily
   - Weekly
   - Monthly
   - Rarely
   - Never

8. What type of bicycle do you ride most often?
   - Conventional bike
   - E-bike
   - Shared Bike (Spin, Lime, etc.)
   - None
   - Other (Please Specify)

9. Have you ever used a bike lane in Baltimore City?
   - Yes
   - No

Skips to question number 27 if the respondent answered "No"

10. Which type of bike lane have you used most often in Baltimore?
    - Shared Lane Markings or Signs

    - Separated Bike Lane

- Bike Lane

- Path or Sidepath

- Shared Bus-Bike Lane

- Other (Please Specify)

11. On a scale of 1 (Not Safe) to 5 (Very Safe), how safe do you feel using bike lanes in Baltimore?
    - 1
    - 2
    - 3
    - 4
    - 5

12. In your experience, what are the biggest safety concerns you face while using bike lanes in Baltimore City? (Select all that apply)

- ☐ Dooring by parked cars
- ☐ Merging traffic
- ☐ Turning vehicles
- ☐ Debris in the lane
- ☐ Poor road surface
- ☐ Lack of bike lanes in some areas
- ☐ Lack of signage or markings
- ☐ Lack of lighting
- ☐ Other (Please Specify)

13. Have you ever been involved in a crash or near-crash while cycling in a bike lane in Baltimore City?
    - Yes
    - No

14. Are bike lanes in Baltimore well-marked and visible on the roads?
    - Yes
    - No

15. How often do you encounter obstacles in bike lanes? (Parked cars, debris, pedestrians, etc.)
    - Always
    - Often
    - Sometimes
    - Rarely
    - Never

16. How often do you wear a helmet while biking?
    - Always
    - Often
    - Sometimes
    - Rarely
    - Never

17. Are there specific intersections or areas where you feel less safe while biking?
    - No
    - Yes (Please specify the location)

18. In your opinion, which of the following built environment features would most improve bike lane safety? (Rank 1-5, with 5 being most important)

	1 (Least Important)	2	3	4	5 (Most Important)
Dedicated bike parking areas					
Improved street lighting along bike routes					
Raised crosswalks at bike lane intersections					
Rumble strips separating bike lanes from traffic					

19. How accessible are bike lanes from your residence or workplace?
    - Very Accessible
    - Somewhat Accessible
    - Not Accessible

20. Do you prefer separated bike lanes from traffic or shared lanes with vehicles?
    - Separated Lanes
    - Shared Lanes
    - No Preference

21. Overall, how would you rate the quality of Baltimore City's bike lanes?
    - Excellent
    - Good
    - Fair
    - Poor

22. Are there specific areas in Baltimore where you feel bike lanes could be expanded or improved?
    - No
    - Yes (Please specify the location)

23. Do you feel safer biking during specific times of the day?
    - No
    - Yes (Please specify the time)

24. What improvements to Baltimore's bike infrastructure would most encourage you to cycle more? (Select all that apply)
    - More separated bike lanes
    - Improved signage and markings for bike lanes
    - Educational programs on cycling safety for both cyclists and motorists
    - Improved lighting
    - Increased enforcement of traffic laws related to cyclists

- Other (Please Specify)

25. How often do you feel unsafe due to the lack of signals and vehicle drivers not anticipating cyclists in bi-directional bike lanes on one-way streets?
    - Always
    - Often
    - Sometimes
    - Rarely
    - Never

26. Do you have any additional comments or suggestions for improving bike lane safety in Baltimore City? (If not, Please type N/A)

If participants answered "No" to question #9, they would answer the following questions:

27. Which type of bike lane have you used most often in Baltimore?
    - Shared Lane Markings or Signs

    - Separated Bike Lane

    - Bike Lane

- Path or Sidepath

- Shared Bus-Bike Lane

- Other (Please Specify)

28. In your experience, what are the biggest safety concerns you face while using bike lanes in Baltimore City? (Select all that apply)

- ☐ Dooring by parked cars
- ☐ Merging traffic
- ☐ Turning vehicles
- ☐ Debris in the lane
- ☐ Poor road surface
- ☐ Lack of bike lanes in some areas
- ☐ Lack of signage or markings
- ☐ Lack of lighting
- ☐ Other (Please Specify)

29. Have you ever been involved in or witnessed a bicycle-involved crash or near-crash in Baltimore City?
    - Yes
    - No

30. Are bike lanes in Baltimore well-marked and visible on the roads?
    - Yes
    - No

31. How often do you encounter obstacles blocking bike lanes (parked cars, debris, pedestrians, etc.)?
    - Always
    - Often
    - Sometimes
    - Rarely
    - Never

32. In your opinion, which of the following built environment features would most improve bike lane safety? (Rank 1-5, with 5 being most important)

	1 (Least Important)	2	3	4	5 (Most Important)
Dedicated bike parking areas					
Improved street lighting along bike routes					
Raised crosswalks at bike lane intersections					
Rumble strips separating bike lanes from traffic					

33. Thinking about your daily commute or travels around Baltimore, how accessible do you find bike lanes from your residence or workplace?
    - Very Accessible
    - Somewhat Accessible
    - Not Accessible

34. If you could choose, would you prefer to see separated bike lanes (physically divided from traffic) or shared lanes with vehicles for cyclists?
    - Separated Lanes
    - Shared Lanes
    - No Preference

35. Overall, how would you rate the quality of Baltimore City's bike lanes?
    - Excellent
    - Good
    - Fair
    - Poor

36. Would you be more likely to consider cycling if you felt safer using bike lanes?
    - Yes
    - No

37. What improvements to Baltimore's bike infrastructure would most encourage you to cycle? (Select all that apply.)
    - ☐ More separated bike lanes
    - ☐ Improved signage and markings for bike lanes
    - ☐ Educational programs on cycling safety for both cyclists and motorists
    - ☐ Improved lighting
    - ☐ Increased enforcement of traffic laws related to cyclists
    - ☐ Other (Please Specify)

38. How often do you feel unsafe due to the lack of signals and vehicle drivers not anticipating cyclists in bi-directional bike lanes on one-way streets?
    - Always
    - Often
    - Sometimes
    - Rarely
    - Never

39. Are there specific areas in Baltimore where you feel bike lanes could be expanded or improved?
    - No
    - Yes (Please specify the location)
    - Don't know/not sure

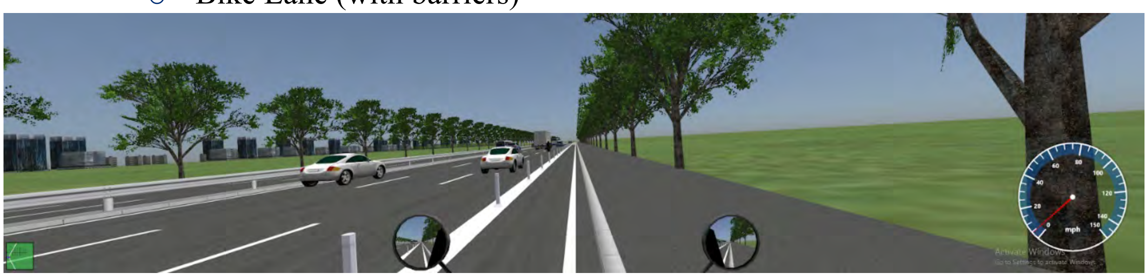
40. 23. Do you have any additional comments or suggestions for improving bike lane safety in Baltimore City? (If no, Please type N/A)

8. APPENDIX B. BIKE SIMULATOR PRE-SURVEY QUESTIONS

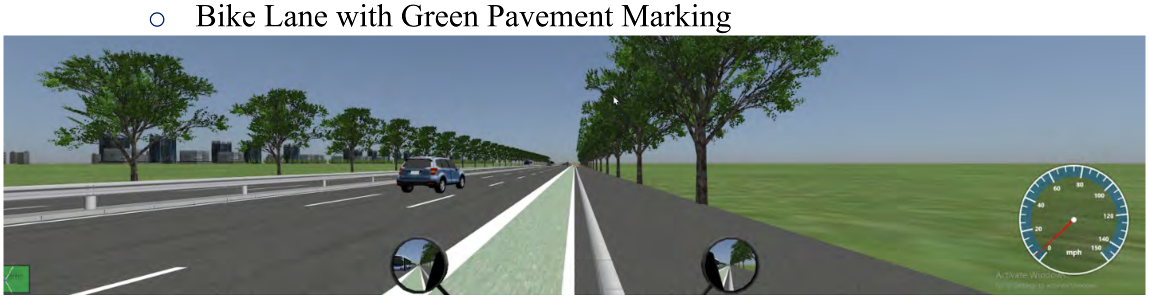
1. Before taking part in this simulation study, which type of bike lane do you prefer to use in Baltimore?
   - Shared Lane

   - Separated Bike Lane

   - Bike Lane (with barriers)



   - Bike Lane with Green Pavement Marking

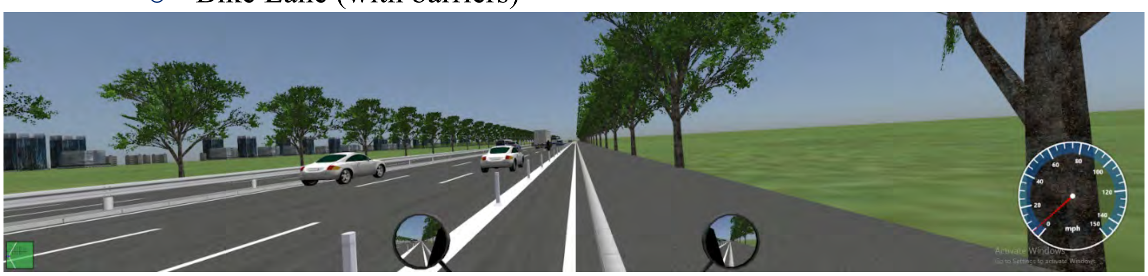


   - Shared Bus-Bike Lane

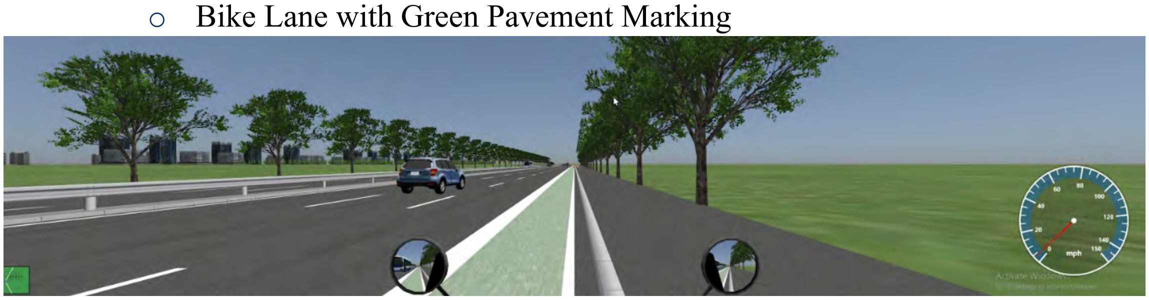
2. Before taking part in this simulation study, which type of bike lane do you prefer the least to use in Baltimore?
   - ○ Shared Lane

   - ○ Separated Bike Lane

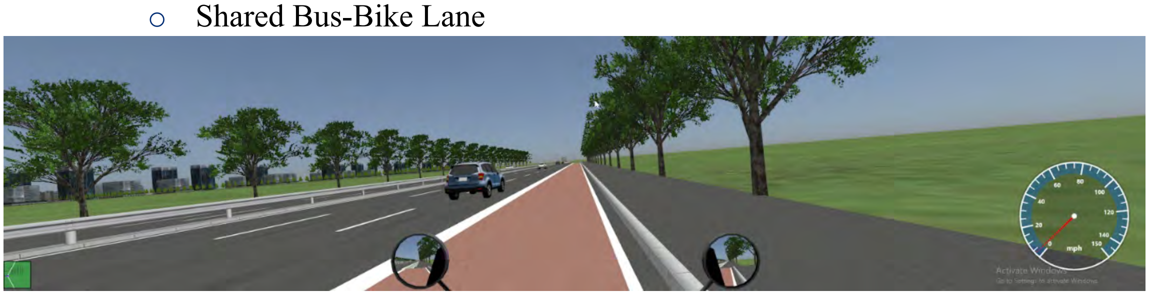
   - ○ Bike Lane (with barriers)



   - ○ Bike Lane with Green Pavement Marking



   - ○ Shared Bus-Bike Lane

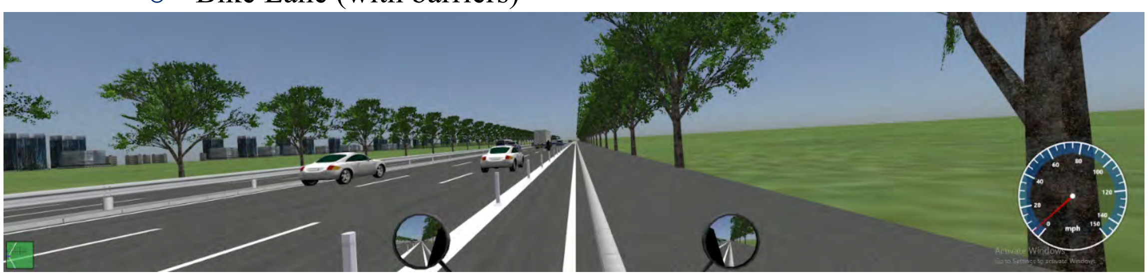


3. Before taking part in this simulation study, which type of bike lane do you feel is safest to use in Baltimore?

- Shared Lane

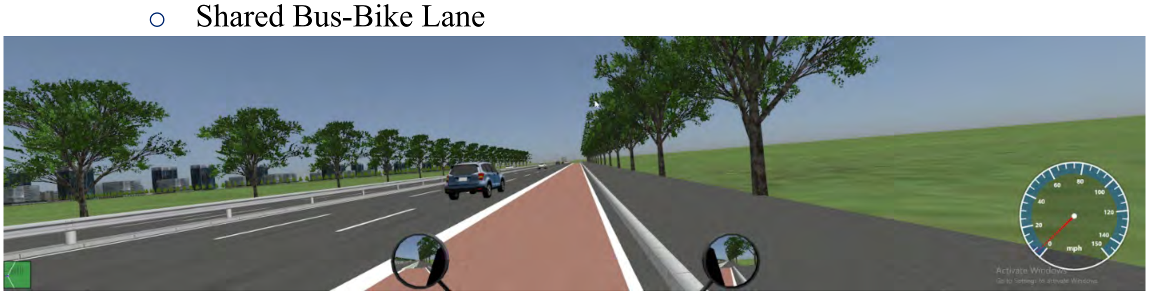
- Separated Bike Lane

- Bike Lane (with barriers)



- Bike Lane with Green Pavement Marking

- Shared Bus-Bike Lane



4. Before taking part in this simulation study, which type of bike lane do you feel is the least safest to use in Baltimore?

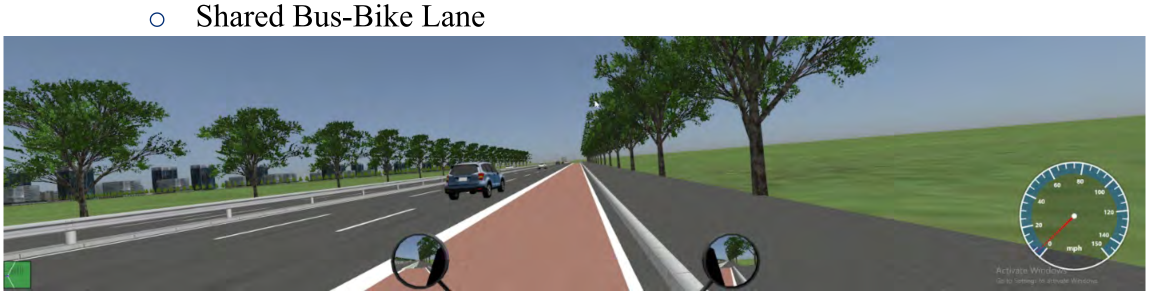
- Shared Lane

- Separated Bike Lane

- Bike Lane (with barriers)

- Bike Lane with Green Pavement Marking

- Shared Bus-Bike Lane



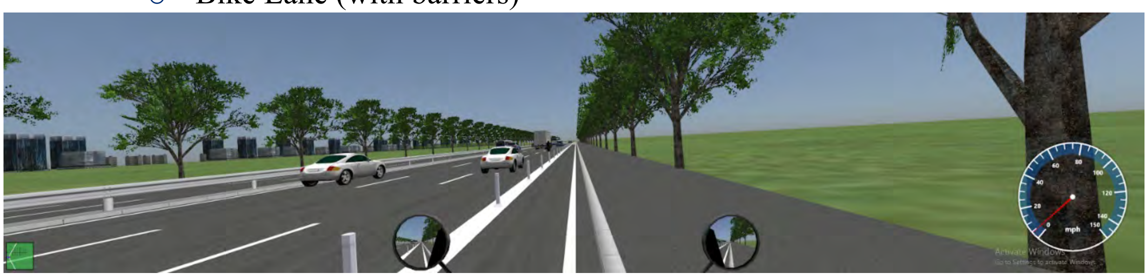
9. APPENDIX C. BIKE SIMULATOR POST-SURVEY QUESTIONS

1. After taking part in this simulation study, which type of bike lane do you prefer to use in Baltimore?

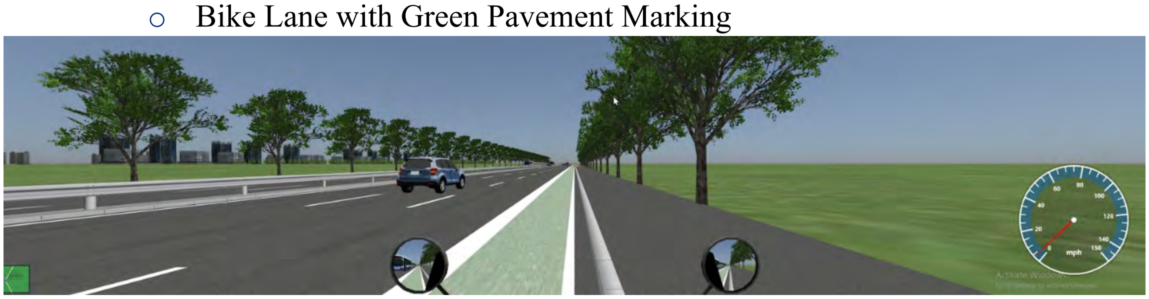
- Shared Lane

- Separated Bike Lane

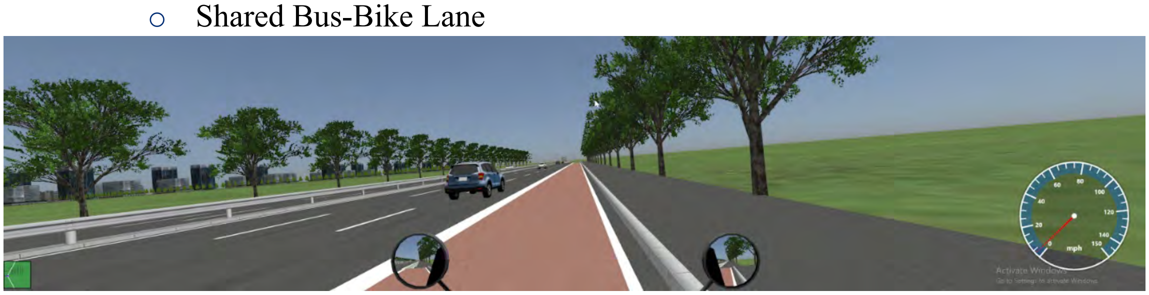
- Bike Lane (with barriers)



- Bike Lane with Green Pavement Marking



- Shared Bus-Bike Lane

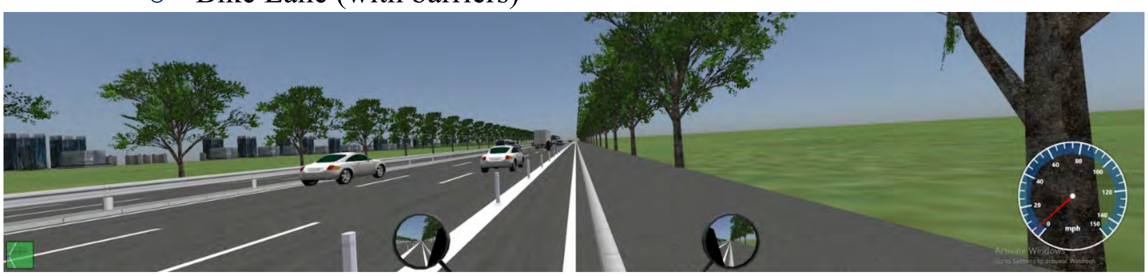


2. After taking part in this simulation study, which type of bike lane do you least prefer to use in Baltimore?

- Shared Lane

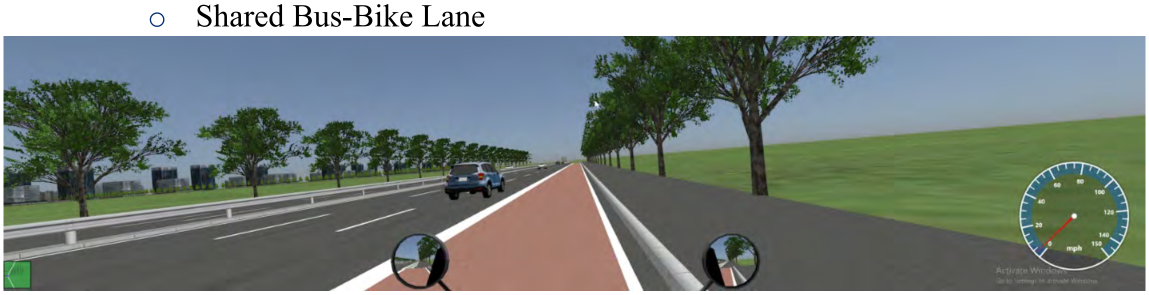
- Separated Bike Lane

- Bike Lane (with barriers)



- Bike Lane with Green Pavement Marking

- Shared Bus-Bike Lane



3. After taking part in this simulation study, which type of bike lane do you feel is safest to use in Baltimore?

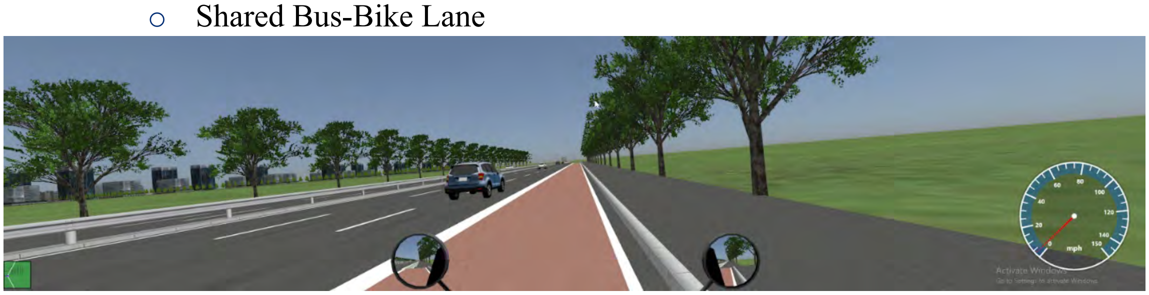
- ○ Shared Lane

- ○ Separated Bike Lane

- ○ Bike Lane (with barriers)

- ○ Bike Lane with Green Pavement Marking

- ○ Shared Bus-Bike Lane

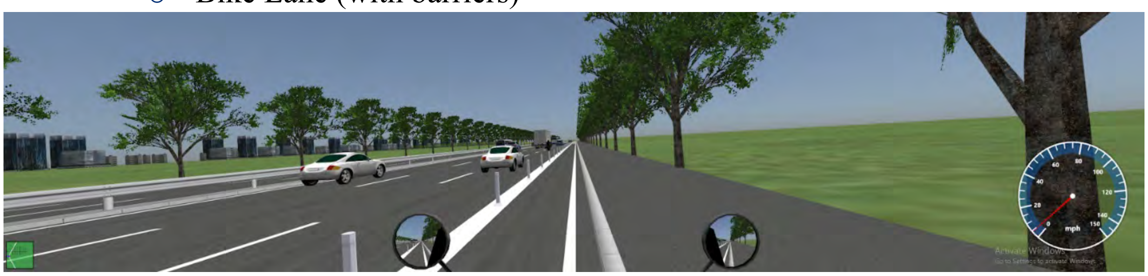


4. After taking part in this simulation study, which type of bike lane do you feel least safest to use in Baltimore?

- Shared Lane

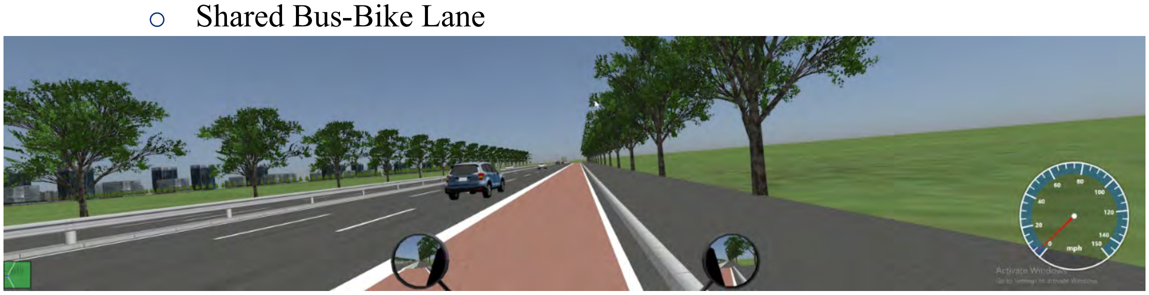
- Separated Bike Lane

- Bike Lane (with barriers)



- Bike Lane with Green Pavement Marking

- Shared Bus-Bike Lane



10. APPENDIX D. IRB APPROVAL

MORGAN STATE UNIVERSITY

GROWING THE FUTURE • LEADING THE WORLD

Institutional Review Board (IRB)

March 20, 2024

Dr. Eazaz Sadeghvaziri
School of Engineering
Morgan State University

RE: IRB #24/03-0076

Dear Dr. Sadeghvaziri,

Following expedited review of the materials submitted to the IRB with respect to the study being conducted in collaboration with Dr. Mansoureh Jeihani, titled "*Investigating the Effect of Different Bike Lane Types on Bicyclists' Safety and Behavior in Baltimore City*", I am pleased to inform you that **IRB Approval** is hereby granted for the project.

Please note that the current **approval** is for a one-year period from the date of this letter. If the research extends beyond the expiration date, it is the responsibility of the principal investigator to obtain continuation of IRB approval prior to the expiration date. Also, note that it is your responsibility to inform the IRB promptly should there be a substantial change in the study methodology.

Do not hesitate to contact me at Benjamin.welsh@morgan.edu, or Dr. Isuk at X3447 if you have any questions.

Sincerely,

MORGAN STATE UNIVERSITY
IRB
APPROVED
Signature: Benjamin H. Welsh
Date: 3/20/2024
Void one year from the above date

Benjamin Welsh, Ph.D.
IRB Chairperson

Cc: Dr. Edet Isuk, IRB Administrator

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