Final Report

EQUITABLE COMPLETE STREETS
Data and Methods for Optimal Design Implementation

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16. Abstract

The Complete Streets concept references roads designed to accommodate: (1) diverse modes, including walking, cycling, public transit, and automobile; (2) different users, e.g. affluent and low-income individuals, people with disabilities, and senior citizens; (3) and a mix of land uses such as office, retail, businesses, and residential to ensure streets are safe, balanced and inclusively support diverse economic, cultural and environmental uses. Today most of our streets are poorly designed and do not offer safe places to walk, bike, or take public transportation. Such streets are particularly dangerous for disadvantaged segments of the population, including people of color, older adults, children, and those living in low-income communities. Successful Complete Streets projects prioritize multi-modal transport systems and have been demonstrated to be effective in fostering more livable communities, increasing equity and improving public health. This project analyzes different components of Complete Streets design and use with the goal of creating fast, low-cost, and high impact (transportation) changes in our communities. In recent years, "complete streets" has been an emerging concept in North American transportation planning and design. To be considered a "complete street", a road should be designed to be safe for users of all traffic modes. This report presents three studies: safety evaluation on the complete streets by simulating different modes, quantify the benefits of complete streets in terms of equity and improved access across different segments of the population (especially low income) and road space allocation on the complete streets.

17. Key Words: Complete Streets; Safety; Non-Motorized Modes; Mode Choice; Road Space Allocation	**18. Distribution Statement**

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EXECUTIVE SUMMARY

The concept of a CS is introduced to ensure access, safety, equity, and a healthy community. In the U.S., the regular transportation trend has been increased vehicle ownership, more parking spaces, reduced travel options, automobile-oriented transport, and, most importantly, fewer options for alternative modes. However, most communities face traffic congestion, environmental pollution, a high rate of traffic accidents, and unfair services for non-drivers. Statistics based on the 2017 National Household Travel Survey (NHTS) show that around 50 percent of all trips made in the U.S. are less than three miles long and that 28 percent of all trips are one mile or less. These distances could be easily covered by walking, biking, or taking a local bus. Yet, the non-motorized modal shares remain very low even for short trips. The reason is mainly that the majority of the roads in northern America are *Incomplete Streets,* i.e. unpleasant, even dangerous roads, which are often impossible to travel by non-motorized means of transportation. In recent years, "complete streets" has been an emerging concept in North American transportation planning and design. To be considered a "complete street", a road should be designed to be safe for users of all traffic modes. CS does not mean simply adding a bicycle lane or a crosswalk where they don't exist. CS related policies seek to provide meaningful transportation choices for all people. Considering this problem, the main goal of this study is to design an efficient CS based on the interactions among different modes of transportation and the benefits of an improved CS across different segments of the population. To achieve this goal, this study has been performed focused on three objectives.

First objective of this study was Evaluating the safety of a CS by simulating the interactions among bikes, cars, and transit using full-size driving and bike simulators. For the first objective of this project a study has been done with 33 participants from Morgan State University and Baltimore metro area where participants should have valid license and fulfil other criteria for the study. The simulation also randomly generated other vehicles with varying speeds and volumes. Performance data collected through driving simulators included the vehicle's instant speed, throttle, brake, lateral movement, offset from road center, and lane changing. In addition, lateral movement and lane change frequency were used as an indicator of driving behavior and defined as the number of times the driver changed lanes while a bike was visible. The study network consisted of an 8,530-foot one-way road with three inner segments. Four research scenarios have been developed for the simulation purposes; S1: Three-lane mixed traffic, each lane 11 feet wide, S2: Two-lane mixed

traffic lanes, plus one transit lane, each lane 11 feet wide, S4: Three-lane mixed traffic, each lane 11 feet wide and one bike lane, six feet wide, S6: Three-lane mixed traffic, 11 feet wide and one bike lane six feet wide. The bike lane is separated from the traffic lane by a 2-foot buffer divider.

The data analysis assumed that driving was mainly affected by the road design and surrounding bicyclists, with speed being the dependent variable. The study area was divided into three segments where an integrated bike appeared in segment 2 and simulator generated bikes were present in segments one and three. Statistical analyses were performed on speed data for each scenario in each segment. The ANOVA results revealed a significant speed difference between the scenarios. Overall, S6, the divided bike lane with a buffer zone and flex posts, showed the highest average speed among the four scenarios, in segments one and three. The increases in speed compared to the base scenario were lowest in the transit scenarios (S2), revealing that people do not speed up significantly in the presence of transit lanes. The highest speed increase was reached in scenario S6 in comparison with the base and other scenarios. Lateral distance analysis also revealed that most drivers increased their lateral distances with the integrated bikes when passing through them in S4 and S6.

Second objective of this study was quantifying the benefits of a complete street in terms of equity and improved access across different segments of the population (especially low income). This study offered a guideline to transportation planners and modelers that intend to improve their existing modeling tools to support plans that seek to transform highway-like corridors into CS. The approach that has been developed comprises several steps. First, behavioral data on CS have been collected using Stated Preference methods; a careful analysis of existing data from National and Regional Travel surveys for the State of Maryland revealed that the exact location for walk trips was not available and that not many CS infrastructure projects have been completed in Maryland. Second, a model was estimated for travelers' preferences for non-motorized transportation alternatives in a CS context. Third, integration of the outcome of model estimation into the Maryland Statewide Transportation Model (MSTM). In MSTM, the mode choice model does not account for walk and bike modes, which is the case for many strategic transportation models in the USA. This study proposed to adjust non-motorized trips on CS in the trip generation phase as a percentage of the total number of trips. Fourth, an illustrative example is proposed for an urban region (Baltimore County); where authors visualize the effects of CS on trips for different purposes and for different income segments. For this work, a specific Stated Choice Experiment was designed with the aim of filling the existing gap in behavioral data relative to the use of CS and to the effects that infrastructure improvements may have on the number of trips made by walking and biking. Specifically, information on the actual behavior of individuals was gathered when they perform short trips, eliciting their preferences towards motorized and non-motorized transportation modes. In this study, four key attributes were retained to define the choice experiment scenarios: *travel time, travel cost (*present only in the *Car* alternative*), parking cost (*present only in the *Car* alternative*), and Level of Traffic Stress* (present only in the *Bike* and W*alk* alternatives).

From the model results, it was observed travel times and costs negatively impact the demand of the alternatives (increases in these LOS reduce the probabilities of the alternatives to be chosen), although the effect is stronger for Bike and Walk. However, more important for analysis, is the second factor with the strongest impact on demand, the LTS, which is actually very similar for both the alternatives in which it is present. According to the results, a 1% reduction in the level of stress for bikers and walkers would encourage them, decreasing motorized trips by an average of 0.087%. From the study authors found that going from a LTS level of 3.5, to a LTS level of 2, which is a 42.9% change, would reduce the use of motorized means by 3.7%. The demand for car would drop from 88.7% to 85.6% and, correspondingly, the demand for non-motorized means would rise from 11.3% up to 14.4%. An application of this methodology depicts shares of non-motorized trips for Baltimore City by both income levels and trip purposes. A first remarkable result is that the low-income population tends to use more non-motorized modes, although the shares do not seem to significantly increase when LTS improve. It can be said that the more favorable the biking and walking conditions are, the more people would bike or walk those segments, except in the case of the poorer population segment. These might be due to its low car ownership rate, which would also explain the existing high rate of fatalities for pedestrians among disadvantaged segments of the population. With respect to the travel purposes, authors conclude that people hardly walk or bike to work in Baltimore City. Additionally, a large share of trips with educational purposes is made by non-motorized modes, even for high values of LTS.

Third objective of this study was to design an efficient complete street. This objective is focused on the road space allocation for minimum travel times. In this study, a bi-level model was proposed that optimizes roadway width allocation to multiple modes, so that total travel time under a given demand matrix is minimized. Traffic characteristics of all lanes are given by Greenshield’s model, whose parameters may be affected by lane widths. Each traveler of an origin-destination (OD) pair faces a mode-specific travel impedance that is affected by traffic condition and other mode-specific items. Given demand, mode and traffic parameters in the system, the lower level iteratively uses a logit mode choice model to obtain equilibrium mode shares for all OD pairs, and thereby computes hourly total travel time for a certain candidate combination of lane widths. With a fixed total width of roadways and limited possible values of lane widths, the upper-level model searches for the combination of lane widths that minimizes total travel time. The model is demonstrated in two numerical cases: one in a simple eight-link intersection, and the other in a single two-directional road. In the first numerical case where three modes: bus, car, and bicycle are considered, the minimal total travel time is obtained when widths of bus lanes and bicycle lanes reach their upper bounds. The effects of switching dedicated lanes to mixed lanes on optimized results are examined. Sensitivities of minimized total travel time and equilibrium mode shares to various parameters are compared. A higher value of user’s time strongly discourages travelers from slow modes such as bicycle. Mode substitution effects between bus and car can be observed with changes in bus fare, average parking fee, and unit car fuel cost. In the second numerical case, car, bicycle, and walking are considered with a different version of impedance function. The total travel time is minimized at the upper-bound bicycle lane width and the lower-bound pedestrian lane width.

This report includes the details of the studies for the three objectives of the project. The results presented in this report are relative to the State of Maryland, but the methods proposed are general and can be easily adopted by any agency or local transport authority, as well as transferred to other geographical areas.

1 Safety Evaluation of Complete Streets

1.1 Introduction

A Complete Street (CS) is an emerging paradigm in transportation engineering and planning that tries to accommodate automobile users, pedestrians, bicyclists, and other transportation users. According to the U.S. Department of Transportation (USDOT), "Complete Streets are streets designed and operated to enable safe use and support mobility for all users. Those include people of all ages and abilities, regardless of whether they are traveling as drivers, pedestrians, bicyclists, or public transportation riders" [1]. According to the definition, a CS can offer a transportation system that gives any road user an easy street crossing and walking system, a safe bicycle riding facility, and a scheduled public transit system. CS design typically offers traffic calming measures, spacious sidewalks, separate bus and bike lanes, extended intersections for pedestrians, and turning lanes for automobiles [2]. The benefit of a CS is a livable community for all users through urban rejuvenation, pedestrian safety through new infrastructure and traffic calming, better public health due to increased walking and cycling, and easy access to services for older adults and people with disabilities [3, 4].

Most traditional roadways are poorly designed and do not offer safe places to walk, bike, or take public transportation. The developed public streets in the U.S. mostly prioritized automobile movement [5]. CS policies impose an emerging response by addressing the inequities in transportation planning to the benefit of the population's disadvantaged segments, including older adults, children, and those living in low-income communities. Successful CS projects prioritize multimodal transportation systems and effectively foster more livable cities, increase equity, and improve public health. In the U.S., almost 900 jurisdictions have adopted CS policies in the last two decades to support all users of public streets [6].

Along with other jurisdictions, Baltimore City passed a Complete Streets Ordinance in 2018 [7]. CS does not mean merely adding a bicycle lane or a crosswalk where they do not exist; CS-related policies seek to provide meaningful transportation choices for all people. This study's findings and recommendations will help change road design practices by integrating all users' needs into everyday transportation planning and design practices. The output provides transportation engineers and planners the technical support for designing more effective roads. The solutions embrace diverse population groups, including low-income, elderly, African American, and

Latinos. The project outcomes address systematic inequities in the accessibility to opportunities and services by disadvantaged segments of the population. Finally, this research provides training to students and professionals in sustainable transportation infrastructure design.

1.1.1 Problem Statement

In the U.S., driving a motor vehicle is a widespread phenomenon, and almost 64% of U.S. adults drive daily [8]. According to the National Household Travel Survey 2017, about 50% of all trips in metropolitan areas are less than three miles, and 28% are less than one mile, easily accomplished by walking, biking, or hopping a bus or train. However, 65% of the shortest trips are now made by automobile, partly because regular streets do not provide good walking or bicycling facilities [9]. The habit of driving for everything dominated as significant resources were invested in U.S. transportation infrastructure between 1920 and 2000 to accommodate more travel demand [10].

In the past, transportation focused mainly on mobility rather than accessibility. Even today, cheap and fast travel is emphasized to give transportation mobility. However, the focus should be on transportation accessibility, where people from all groups can safely access desired goods, services, and facilities. Expanding roads and other facilities near the highway does not ensure accessibility for all. Many people from different races, age groups, and those with disabilities do not drive and depend on walking, cycling, and public transport. Thousands of pedestrians in the U.S. are killed every year, and people of color more so than whites [11]. People of color and different races are disproportionately affected by pedestrian crashes. The pedestrian fatality rates among Black and Hispanic men were found to be more than twice that of white men [12]. The number of pedestrian crashes in low-income and high-minority neighborhoods, termed environmental justice areas, was found to be higher than the non-environmental justice areas [13]. People with different disabilities are more vulnerable to being struck by automobiles as the poor pedestrian infrastructure forces them to use the streets. According to the National Traffic Highway Safety Administration, in the U.S. each year 5,000 pedestrians, including those in wheelchairs, are killed, and 76,000 are injured due to crashes on public roads [14].

These findings demonstrate that our present road structures need to be improved so that our streets are safer for everyone regardless of age, race, or income group. A CS can ensure a multimodal transportation system that allows the best mode for anyone through walking and cycling, public transit access for non-drivers, and automobile travel for dispersed destinations. A CS offers improved transportation services and the accompanying safety, comfort, and performance for all people.

1.1.2 Goal of the Study

The main goal of this study is to design an efficient CS based on the interactions among different modes of transportation and the benefits of an improved CS across different segments of the population. To achieve this goal, the main three objectives of this study are as follows:

1) Evaluating the safety of a CS by simulating the interactions among bikes, cars, and transit using full-size driving and bike simulators. Participants from the different socio-demographic groups were recruited to drive the car (automobile or bus) and ride the bicycle. The study investigated driving behavior and the interactions between the bicyclist, bus driver, and auto driver and tested different CS layouts, using the simulator to find the safest and most acceptable CS configurations.

2) Quantifying the benefits of a CS in terms of equity and improved access across different segments of the population (especially low income), and

3) Designing an efficient CS.

1.2 Literature Review

1.2.1 Complete Street

The concept of a CS is introduced to ensure access, safety, equity, and a healthy community. In the U.S., the regular transportation trend has been increased vehicle ownership, more parking spaces, reduced travel options, automobile-oriented transport, and, most importantly, fewer options for alternative modes. However, most communities face traffic congestion, environmental pollution, a high rate of traffic accidents, and unfair services for non-drivers. Introducing CSs moves many cities to active transportation and demand management programs, more transit options, increased quality of time, alternative solutions to automobiles, a healthy lifestyle, and less traffic congestion. CSs represent a paradigm shift in traditional road construction philosophy. Instead of a reactive attempt to accommodate bicycle- and pedestrian-friendly practices in projects, CS policies require all road construction and improvement projects to begin by evaluating how the right-of-way serves all users. Though all CSs have similar goals, there are no required features. In general, a CS provides safe sidewalks, a protective and low-stress bicycle network, comfortable and accessible transit stops, median islands, and curb extensions that allow people from all walks of life to commute and/or exercise safely [15, 16].

1.2.2 Benefits of CS

The motor vehicle fatality rate of the U.S. is a concerning issue, with some 43,000 fatal accidents annually over the last two decades [10]. This loss of life is one of the significant issues driving communities to convert to CS policies intended to design safe access to roadways for all users. Communities design and operate the CS to ensure all users' rights for various transportation modes. CS design allocates separate spaces for different methods, reducing traffic collisions [17]. The designated area for pedestrians, bicyclists, motorists, and transit users helps the users understand the safety measures and benefits. Smart Growth America and the National Complete Streets Coalition (2015) reviewed 37 CS projects across the U.S. They found that CS decreases road collisions, increases biking and public transit use, and positively impacts road safety [15]. Sanders (2016) did a study to understand perceived comfort while driving and bicycling. The study's result showed that all kinds of road users prefer barrier separated bike lanes or indicated other measures to protect bicyclists. Crosswalks, sidewalks, or raised medians are essential parts of any CS project to improve pedestrian safety [18]. Another study also found that the presence of crosswalks decreases the traffic speed and increases pedestrian usage while streets without sidewalks increase the pedestrian accident rate [19]. Hanson et al. (2013) studied pedestrian crashes in New Jersey between 2007 and 2009 and found that most crashes occur in an area without a crosswalk. The presence of sidewalks was helpful for the survival rate of the pedestrian [20]. The New York Department of Transportation (NYDOT) reviewed their 38 CS projects to analyze the crashes before and after the CS. The review showed that crashes with injuries were reduced by between 12% to 88% after the CS [17, 21]. The Seattle Department of Transportation (SDOT, 2010) repaved a 1.2-mile segment of Sone Road, converted four lanes to two, added a center turn lane and a bike lane, upgraded crosswalks, and did some other initiatives to meet new safety standards. After 28 months, they found that total traffic collisions decreased by 14% while pedestrian collisions decreased by almost 80% [17].

Equity is another vital issue behind CSs. Statistics showed that nearly one-third of the U.S. population are transportation-deprived and cannot easily access daily necessities like medical care, healthy foods, educational institutions, and jobs. Some 3.6 million Americans who are 65 years old or older and non-drivers stay at home on any given day due to a lack of transportation. Additionally, owning a motor vehicle is expensive for a low-income family, which needs to spend 30% to 42% of their income on it [10]. Smart Growth America describes CS policies as "formalizing a community's intent to plan, design, operate, and maintain streets, so they are safe for all users of all ages and abilities" [22]. Additionally, studies show that women are less active than men due to feeling uneasy in the street [23]. Ensuring that women have access to their surroundings in a way that supports their physical activity helps promote gender equity. CSs increase users more than regular urban streets do, and studies show female pedestrians were much less common on low-walkable streets, indicating that street improvements might enhance gender equity [24]. Communities like the city of New Haven introduced the concept of CS beyond safety; they also ensure equity. Their aim and vision are to use the public space with democratic ideas of equality, individual rights and responsibilities, protection of minorities, transparency, accountability, and the rule of law. New Haven’s CS provides the design to ensure meeting users' needs and safety, including people with disabilities, the elderly, children, and people who cannot afford a private vehicle [25]. The potential to achieve equity outcomes will depend upon policy implementation [26].

CSs can help build a healthy lifestyle among the communities. According to the American Public Health Association, obesity is one of the rising health problems. The Centers for Disease Control and Prevention estimated that 12 million people are overweight, and 16% are children. In the early 19th century, many students cycled to school, which dropped from 41% to 13% from 1969 to 2001 and was replaced by a motor vehicle ride [10]. The National Institute of Medicine recommends establishing ordinances to encourage sidewalks, bikeways, and other spaces for physical activity to fight childhood obesity. Studies show that 43% of people meet recommended activity levels if there is a safe place to walk within 10 minutes of their residences [25]. Another study found that walking is beneficial for many health outcomes, such as body mass and diabetes risk [24]. Obesity rate and percentage of people who bike or walk to work found to be significant predictors of CS policy adoption [27]. Furthermore, several studies documented the benefits of CSs on a healthy lifestyle through walkable sidewalks and active living-oriented zoning [28]. In San Francisco, California, the introduction of CS in one community increased the bike and pedestrian activity during peak hours. In Long Beach, California, the cycling activity almost doubled [29]. Another study showed that CS helped with weight loss for new riders [30].

A CS can also improve health by limiting air pollution. The health costs of poor air quality due to the transportation sector are between $40 billion to $64 billion per year. Different diseases such as asthma, respiratory illness, cancer, and heart diseases are directly or indirectly associated with air pollution. Asthma is another major health problem in the U.S., estimated to affect almost 22 million people. Introducing CSs can decrease motor vehicles' use, reducing air pollution and helping build a healthy community. Shu et al. (2014) conducted a study to see the effect of CS in terms of different transportation use and corresponding ultrafine particle (UFP) and fine particle (PM2.5) concentrations. They found that after CS, UFP decreases by 4200 particles cm^3; there is no change for PM 2.5 [31].

Most of the previous studies investigated a different aspect of CS, including health issues, policy, and design. However, no study investigated the socio-economic or socio-demographic importance behind designing a CS. In this study, the research team focused on a different design of CS accompanied by safety, socio-economic, and gender equity. Table 1 shows a summary of the literature review of this study.

Table 1: Summary of Literature Review

Author Name	Objective	Methodology	Outcome
Ingram, M. et al. (2020).	Examining the potential for an equity-focused policy process to address systemic barriers	Descriptive analysis	The potential to achieve equity outcomes will depend upon policy implementation.
Jensen, W. A. et al. (2017).	Audit two mixed-walkability CSs, one low- and one high-walkable street at pre-renovation and twice post-renovation	User counts, site walkability audit, negative binomial model	Complete street users increased, especially for the less urban complete street. Typically, a high-walkable street attracted the most people, both males and females, and the low-walkable street attracted the fewest; CSs were in between.
Gregg, K., & Hess, P. (2019).	Reviewed 113 municipal level CS policies to inventory their qualitative content	Descriptive analysis of CS policies	The study concluded that most CS policies do not guide tradeoff negotiations among users within the right of way.
Brown, B. B., Werner et al. (2015).	Assessed effects of CS on physical activity and weight among participants in a CS intervention that extended a light rail line in Salt Lake City, Utah	Global Positioning System and regression analyses	New riders showed more accelerometer-measured counts per minute than never-riders, and former riders had substantially fewer. New riders lost, and former riders gained weight. Previous riders lost 6.4 minutes of moderate-to-vigorous PA (MVPA) per 10 hours of accelerometer wear and obtained 16.4 minutes of

Author Name	Objective	Methodology	Outcome
			sedentary time. New riders gained 4.2 MVPA minutes and lost 12.8 sedentary minutes per 10 hours of accelerometer wear.
Moreland-Russell, S. et al. (2013).	Identify potential patterns and correlate CS policies	Qualitative analysis and Binary Logistic Regression.	The main outcome of this study is policy adaptation. Three variables were significant predictors of CSs policy adoption: state obesity rate, percentage who bike or walk to work, and the presence of a bordering community with a CS policy.
Handy, S., & McCann, B. (2010).	Funding opportunity for CS	Discussion	Accumulate funding opportunities for bike projects.
Lenker, J. A. et al. (2016).	This report describes a field study that sought to assess the impact of CS projects in Buffalo, New York	A questionnaire survey, standard non-parametric approaches	The analysis indicated that CS corridors absorb higher volumes of vehicles, pedestrians, and bicyclists and become safer in terms of total crashes and injuries.
Smart Growth America	A summary of best CS policies in different states in 2015	Descriptive analysis of different CS parameters	Summary of best CS policies.
Zhu et al. (2016).	Compare CSs with respect to travel behavior and air pollution	Natural experimental design using before-after comparisons and a quasi-experimental design using DID approach	The before-after study showed that the emission-weighted traffic volume decreased by 26% at one study site. This change may explain the observed significant decrease in UFP concentrations after the street retrofit. The total traffic volume decreased 16% after the retrofit at the other site, but no significant difference was observed in the background-subtracted UFP and PM2.5 concentrations.
Carlson, S. A. et al. (2017).	Estimate the prevalence of CS policies	Questionnaire survey	Prevalence of local policies decreased with decreasing population size and was lower among those with the median education level.
Hanson, M. A. (2017)	This paper aims to quantify the impact of CSs projects on pedestrian and bicyclist safety.	Geographic Information System and general statistics	The majority of the CSs projects (six out of nine) did not experience any crashes within the study timeframe. The absence of crashes in the six projects appears to be because they only cover short roadway segments. The three projects that experienced crashes (Franklin Boulevard,

Author Name	Objective	Methodology	Outcome
			El Camino Avenue, and Auburn Boulevard) are the longest, ranging from 1.96 to 3.5 miles.
Sanders, R. L. (2016).	This paper aims to examine perceived comfort while driving and bicycling.	Internet questionnaire survey and focus group	Analysis of variance tests revealed that both drivers and bicyclists are more comfortable on roadways with separate bicycling facilities than on those with shared space. Roads with barrier-separated bicycle lanes were the most popular among all groups, regardless of bicycling frequency. Striped bicycle lanes benefit cyclists and drivers through predictability and legitimacy on the roadway, but the lanes were rated significantly less comfortable than barrier-separated treatments—particularly among potential bicyclists.
Hanson, C. S., Noland, R. B., & Brown, C. (2013).	The analysis focuses on how different road features affect the severity of a pedestrian casualty.	A case-control methodology, geo-coding, regression analysis	Results suggest that the intensity of pedestrian casualties is related to the lack of sidewalks, traffic lighting, high-speed roads, roads with more lanes and a median. Speed is critical and casualties are more severe when it is dark. Older pedestrians face more severe casualties.
NYDOT (2013).	The study developed a robust set of metrics to evaluate its projects' outcomes concerning the agency's policy goals.	Case study analysis	These results suggested that improved accessibility and a more welcoming street environment generate increases in retail sales in the project areas.
Keippel, A. E. et al. (2017).	This case study focuses on the development and adoption of a CS policy.	An incremental and nonlinear policymaking process	The city council unanimously adopted a CS resolution, informed by a gender lens. They used gender information to successfully mobilize the community in response to threats of the policy's repeal and then influenced the adoption of a revised policy.
Van Dyck, D. et al. (2015)	Examine age, gender, and education as potential moderators of the associations of perceived neighborhood environment variables.	The community survey, regression analysis	Overall, adults' perceptions of environmental attributes with MVPA were mostly independent of the socio-demographic factors examined.

Author Name	Objective	Methodology	Outcome
John DeStefano, Jr., (2010)	Describe areas' CS policies and design	Descriptive analysis	Description of CS policies and design
Schlossberg, M. et al. (2015).	This book documents the redesign of 25 streets across the U.S.	Descriptive analysis	The collection of finished projects provides evidence and inspiration for more communities to rethink and retrofit their streets for the next generation.
Shu, S. et al. (2014).	This work evaluates the effect of a CS retrofit on Ocean Park Boulevard in Santa Monica, California	Statistical analysis	UFP decreased, while PM2.5 had no statistically significant change. The emission-weighted traffic volume decreased by 26% which decreases UFP. Compared to pre-retrofit conditions, the number of pedestrians increased by 37% while the number of cyclists stayed approximately the same.

1.2.3 Different CS Layouts

A well-connected and complete network is essential to achieve safe, prosperous, and vibrant communities, and different jurisdictions adopt the CS approach to ensure safe and robust pedestrian, bicycle, transit, and motorways facilities. As there is no specific CS design, different communities are coming up with policies and toolbox practices that help them plan and make investment decisions for CS. The Maine Department of Transportation (MDOT) offers guidance and design protocols customized for the Twin Cities Lewiston and Auburn. Because their land use has various context zones – such as rural, urban, suburban, special district, etc. – their CS design protocol is customized, and they made a CS toolbox that describes essential CS elements. The different zones can use those elements as required. Some walkability elements are sidewalk width, raised crosswalk, curb extension, in-pavement crossing beacon, pedestrian refuge island, HAWK signals, Rectangular Rapid Flashing Beacon (RRFB), and Leading Pedestrian Interval (LPI).

For cycling, they propose a shared use path; conventional, buffered, and protected bicycle lanes; bicycle priority “super sharrows”; shared-use lane markings; bicycle box; two-stage turn queue box; bicycle refuge island; bike crossing marking; combined bike lane/turn lane; colored pavement; and bicycle signals. Figure 1 illustrates some proposed CS designs for bike lanes, and a curbside extension, crosswalk, and bus bulb.

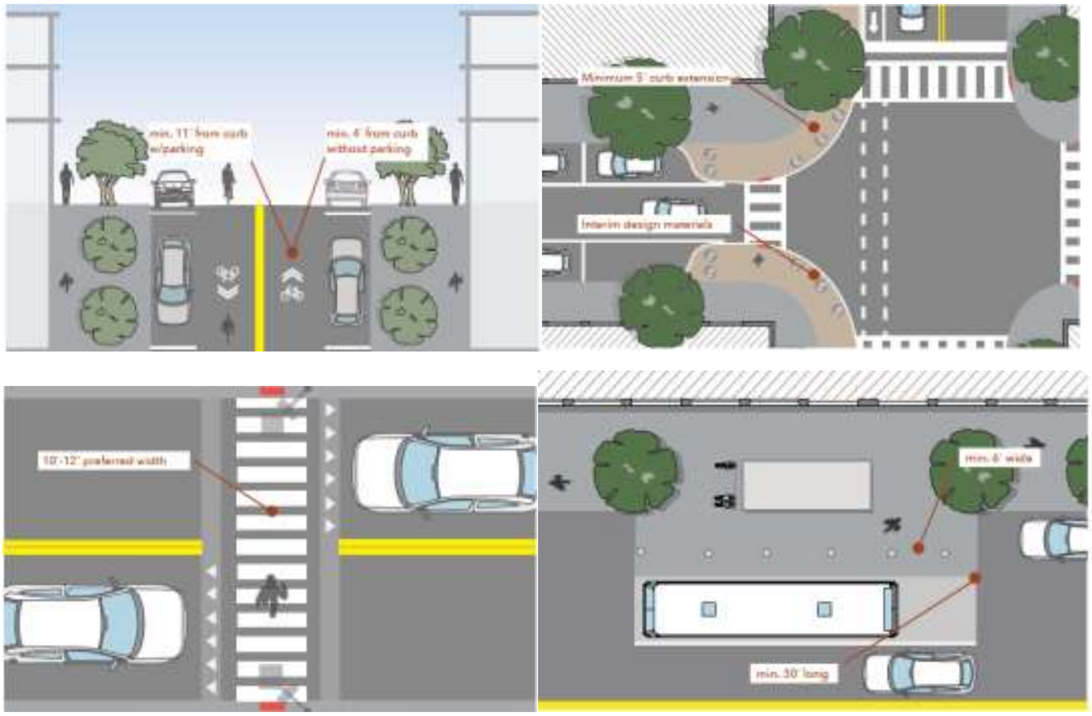


Figure 1: Sample CS designs for bike lanes, curbside extension, crosswalk, and bus bulb.

For public spaces, they propose interim design pedestrian plazas, pocket parks, bioswales, and parklets. They suggest bus shelters, bus lanes, bus lanes without desiccated bikeways, and bus bulbs for public transit.

They propose speed table/raised intersections for motor vehicles, on-street parking, safe-sized travel lanes, corners, effective turn radii, turn apron/mountable curbs, roundabouts, a road diet, daylighting intersection, diverters, and flush medians. They also offered some strategies for signals, design vehicles, iterative design, and maintenance [32].

Some communities took a smaller approach, like changing one or two road sections to CS. Some roadways in the Orlando metropolitan region in Florida were dangerous for pedestrians. Orlando initiated their small CS project on Curry Ford Road in Orange County, which was notorious for pedestrian and bike crashes. The city of Orlando, Orange County staff, and local elected officials came forward and transformed the five-lane speedway to a three-lane CS with a painted pedestrian crossing and protected bike lanes, as shown in Figure 2 [33].

Figure 2: The CS practice in Curry Ford Road in Orlando, Florida.

South Bend, Indiana, started its CS initiatives through traffic calming in a small neighborhood. The city council worked closely with the local community to address the speeding issue there. As shown in Figure 3, they improved the street design by installing traffic circles, chicanes, and bump-outs. They also established educational signs to encourage drivers to slow down; this project demonstrated that tactic and led to a vibrant community [33].

Figure 3: Different traffic calming practices in South Bend, Indiana

In Lexington, Kentucky, two dangerous intersections were considered for implementation of CS strategies. The intersections on Bryan Avenue confused all road users, including pedestrians, bicyclists, and motorists. One of them had an unusual turning pattern and unclear crosswalk that made it dangerous and ambiguous about the right of way. The Lexington-Fayette Urban County government team came forward to solve the issues and work with the local community. They redesigned the intersection to redirect the cars; they also installed a pedestrian crosswalk and refuges to ensure a safer street for all, as shown in Figure 4 [33].

Figure 4: Different CS strategies in Lexington, Kentucky.

1.3 Methodology

This study recruited 33 participants from Morgan State University and the Baltimore metro area via flyers distributed manually, online, and on social media. Flyer content included contact information, a summary of the study's requirements, information regarding COVID-19 restrictions, and an explanation of the monetary compensation for participating in the driving simulator study. The participants were required to have a valid U.S. driving license or learner's permit and were compensated at $15/ hour for their study participation.

The experiments were observed by the Principal Investigator and a team of graduate and undergraduate students. The research assistants observed the IRB-approved driving tasks and collected the pre- and post-survey questionnaire forms. Each driving session started with filling out the consent form and pre-survey questionnaire, which consisted of participants' socio-demographic status and complete street introductory questions.

Participants' average drive time was 1.5 hours in the simulated environment, where they were instructed to drive as they typically would do on a real road, complying with the speed limit. The simulated scenarios were displayed on three 40-inch LCD screens for the car simulator and another LCD screen for the bike simulator. The simulator's driver compartment provided a view of the roadway and dashboard instruments, including a speedometer (Figure 5). The simulated vehicle also consisted of engine sounds, road noise, and sounds of passing traffic for a more realistic feel. The simulation also randomly generated other vehicles with varying speeds and volumes.

Figure 5: Car and Bike simulator

Performance data collected through driving simulators included the vehicle's instant speed, throttle, brake, lateral movement, offset from road center, and lane changing. In addition, lateral movement and lane change frequency were used as an indicator of driving behavior and defined as the number of times the driver changed lanes while a bike was visible. A Tobii Pro glasses 2 head-mounted Mobile eye-tracking system [34] collected the gaze frequency and duration. The eye movement was captured using two sensors for each eye and one central camera that records the main event. The gaze analysis resulting from the Tobii analyzer data is helpful to understand the interaction between the participants and bicyclists.

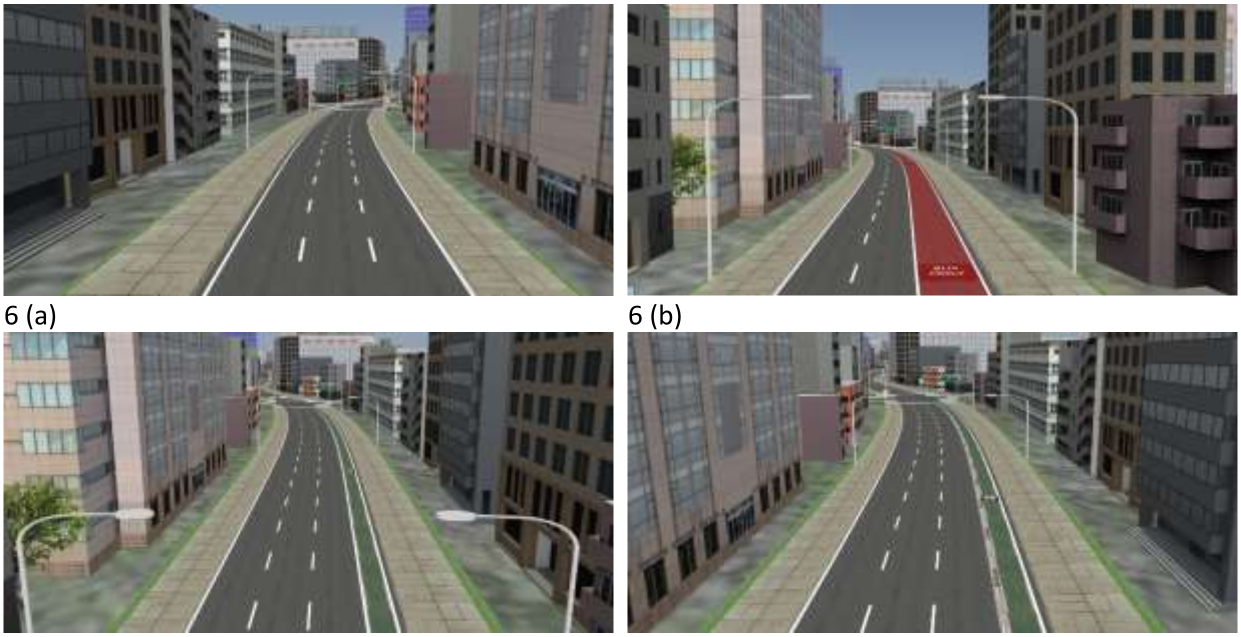
The last step was to fill out a post-survey questionnaire after driving. Participants were asked about their experience with the study, and questions related to complete streets were reiterated post-driving. This information was used during the analysis to investigate the possibility of a correlation between driving behavior in different CS layouts.

1.3.1 Research Scenarios

The study network consisted of an 8,530-foot one-way road with three inner segments. This study had four scenarios named S1, S2, S4, and S6. The scenarios' surroundings and the road lengths are all the same, but the lane designs change to evaluate participants’ driving behavior (Figure 5).

Table 2: Scenario Description

Scenario	Cross segment details
S1	Three-lane mixed traffic, each lane 11 feet wide
S2	Two-lane mixed traffic lanes, plus one transit lane, each lane 11 feet wide.
S4	Three-lane mixed traffic, each lane 11 feet wide and one bike lane, six feet wide
S6	Three-lane mixed traffic, 11 feet wide and one bike lane six feet wide. The bike lane is separated from the traffic lane by a 2-foot buffer divider.



6 (a) 6 (b)

6 (c) 6 (d)

Figure 6: Different Road Layouts (a-S1, b-S2, c-S4, and d-S6)

The base scenario or S1 is designed for a three-lane mix traffic where each lane is 11 feet wide. It was a one-way road with two 6-foot wide pedestrian walkways on each side. The participants were asked to drive the scenario from beginning to end at the posted speed limit of thirty-five km/hr. The participants faced mixed traffic consisting of regular vehicles, buses, small trucks, delivery trucks, etc. Figure 6 (a) shows a typical layout of scenario one. Scenario S2 is also a one-way road consisting of three lanes (11 feet each). It also had six foot-walkways on both sides of the road. However, the rightmost lane is a transit lane (Figure 6b). The other two lanes are mixed lanes of regular vehicles and small trucks. The participants drove the scenario alongside transit vehicles traveling on the dedicated transit lane. Scenarios S4 (Figure 6c) and S6 (Figure 6d) had the same lane numbers and design. Both scenarios had three mixed traffic lanes and one dedicated bike lane.

However, in S4, the bike lane is separated by a pavement marking; a solid white line distinguishes it from the adjacent mixed traffic lane. On the other hand, in S6, the bike lane was separated by fixed flex poles installed in a buffer zone between the bike lane and mixed traffic lane. Both scenarios featured three lanes with mixed traffic that were 11 feet wide and one four-foot wide bike lane on the rightmost lane of the road.

While driving, participants faced integrated and non-integrated bicyclists in different parts of the road. This research attempted to evaluate the drivers' behavior when presented with bicyclists – who are graphic models only, defined as non-integrated bikes, and generated from a virtual reality studio platform to run along a fixed flight path defined by the researcher alongside the road in a loop. At some points, the integration allowed subjects to drive in a bike simulator with a local traffic situation managed by a traffic model while providing a natural flow and density. In this study, the participants were driving the car, and one of the observers was riding the bicycle. Due to the integration of car and bike simulator, the same scenario was simultaneously visible in the two simulators. The car driver and bike rider were sharing the same road segments and interacting without knowing this was a live interaction. On the other hand, in the non-integrated part we used the flight path option of the driving simulator to design bike riders who appeared as machine-generated bikes with different speed patterns.

The road network was divided into three segments for the data analysis (Figure 7). The raw speed data showed that participants used the primary portion of the road (i.e., from 0-150m before segment 1 and 850-950m before traffic signal 1) as an acceleration period and decelerated to stop near the traffic signal.

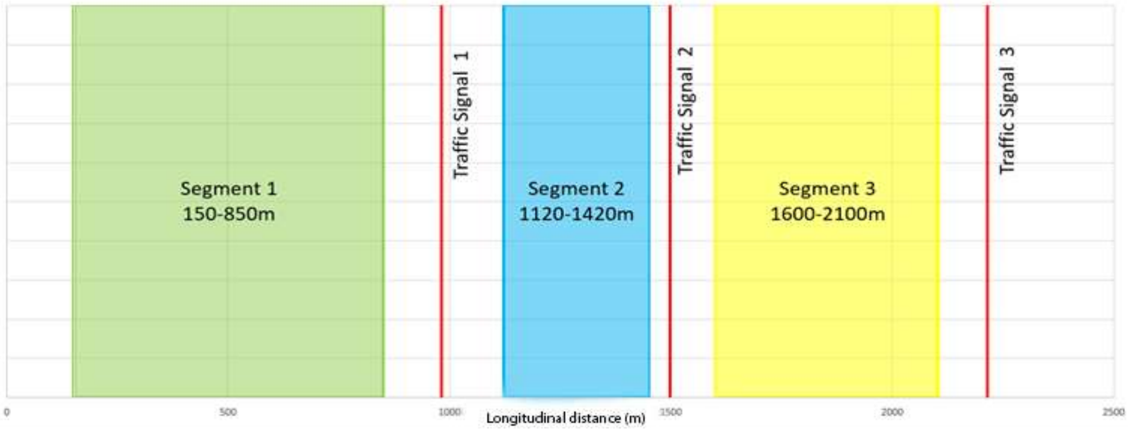


Figure 7: Visual Presentation of Three Road Segments.

Segment one was a 660-meter stretch of road from points at 150m to 810m to avoid the acceleration and deceleration areas between the start point at speed zero and the first traffic signal located at 982m.

Similar to Segment one, Segment three ran from 1600 to 2100m and was chosen because after the second traffic signal at 1497m, drivers reach their optimum running speed at 1600 meters. Again, they start decelerating at 2100 meters as the third traffic signal is 2215m. In the case of Segment two, the location stretches varied as the bicyclist data came from an integrated bicycle simulator.

1.4 Analysis and Discussion

1.4.1 Data

The software logged participants’ driving records, and data screening was performed for each datasheet to check for any missing or outlier data. Finally, 31 participants' data were considered for this study after the screening process. The researchers analyzed the data to evaluate driving behavior and driver-bike interactions under various road layouts and scenarios.

Within the 660m stretch in Segment one and the 500m stretch in segment three, each scenario's average speed per participant was calculated for further analysis. In segments 1 and 3, the 660m and 500m were divided into 20m clusters. One of the primary purposes of clustering was to record the speed in different longitudinal positions along the road for different participants. The data preparation required the speed in the same longitudinal distance for all the participants to compare them. Then the average speed of participants was calculated in each cluster.

Segment two differed from segments one and three due to the presence of the integrated bike. The interaction area between the bicyclist and the driver was defined from the point that the car was 100m upstream of the bike as a point of visibility down to the point along the road where the car was 50m downstream of the bike. Some drivers arrived at a traffic signal before segment two on red light based on their speed and randomly generated traffic conditions. The bicyclists from the integrated bike simulator traveled from the origin point, at the same time, along the road using the bike lane. Consequently, the varying duration that participants stopped at the signal resulted in different starting and ending longitudinal distances for each participant in the interaction area. Speeds were recorded at four specific points for further analysis. The first point was where the bicycle from the integrated bicycle simulator was within the user’s vehicle's vicinity (100m). The second point was the last point when the user's vehicle was behind the bicycle. The third point was the first point that the user's vehicle passed the bicycle. Finally, the fourth point was 50m after the user's vehicle passed the bicycle.

1.4.2 Descriptive Analysis

Descriptive statistics were obtained from pre-survey questionnaire data regarding participants' socio-demographic characteristics (Table 3). The participants were also asked some additional questions to determine their complete street knowledge and understand their past walking and bicycling experience. The response showed that only 10% of participants used bicycles. In Figure 8, we can see from the 10% of bicycle users that most use it for exercise (29.0%) or recreation (25.8%).

Table 3: Participants Socio-demographic Data

Variable		Percent (%)
Gender	Male	51.5
	Female	48.5
Age	18-25	42.4
	26-35	21.2
	36-45	18.2
	46-55	9.1
	56-65	6.1
	65+	3
Ethnicity	White	21.9
	Black/African American	71.2
	Asian	3.1
	Other	3.1
Education	High School or less	0
	Associate	6.1
	Undergraduate	33.3
	Graduate	42.4
	Postgraduate	18.2
Household Size	Only me	34.4
	2 persons	21.9
	3 persons	18.8
	4 or more	25
Employment Status	Full time	31.3
	Part-time	56.3
	Unemployed	12.5
Income (Annual)	≤ $20,000	21.9
	$20,000-$29,000	18.8
	$30,000-$49,999	18.8

Variable		Percent (%)
	$50,000-$74,999	25
	$75,000-$99,999	9.4
	More than $100,000	6.3
Vehicle Ownership	Car owner	90.9
	No Car	9.1
Household Car Number	None	6.3
	One	37.5
	Two	34.4
	Three and more	21.9

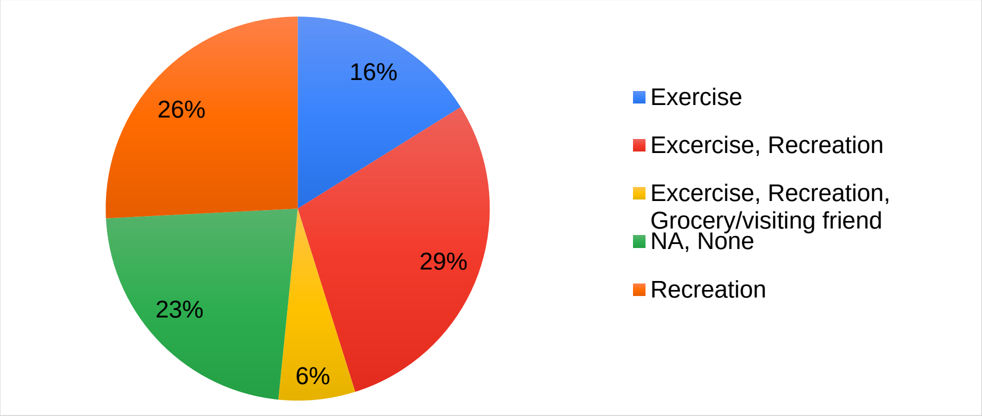


Figure 8: Participants' Primary Purpose of Using Bicycles.

After finishing the driving sessions, participants were questioned regarding their experience driving complete street layouts and future driving, biking, and walking perceptions. Among the 31 participants, 15 of them (48%) found scenario S4 distracting while driving as there was a bike lane beside the car lane (Figure 9). Twenty-four participants (77%) perceived scenario S6 (Figure 10), which featured a divider between bike and car lanes, as the safest layout for driving.

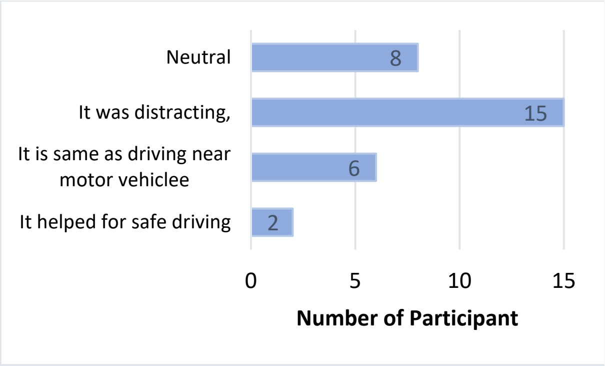


Figure 9: Participant's Post-experiment Perception Regarding Undivided Bike Lanes

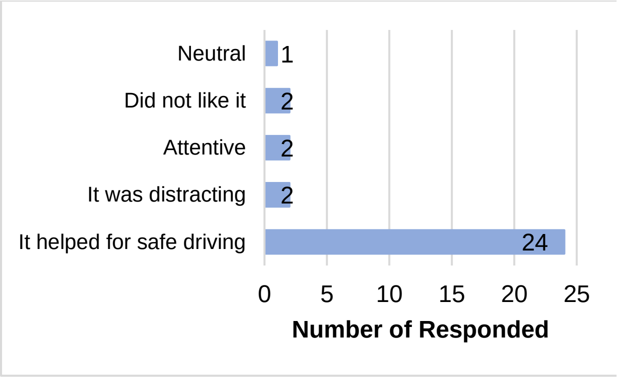
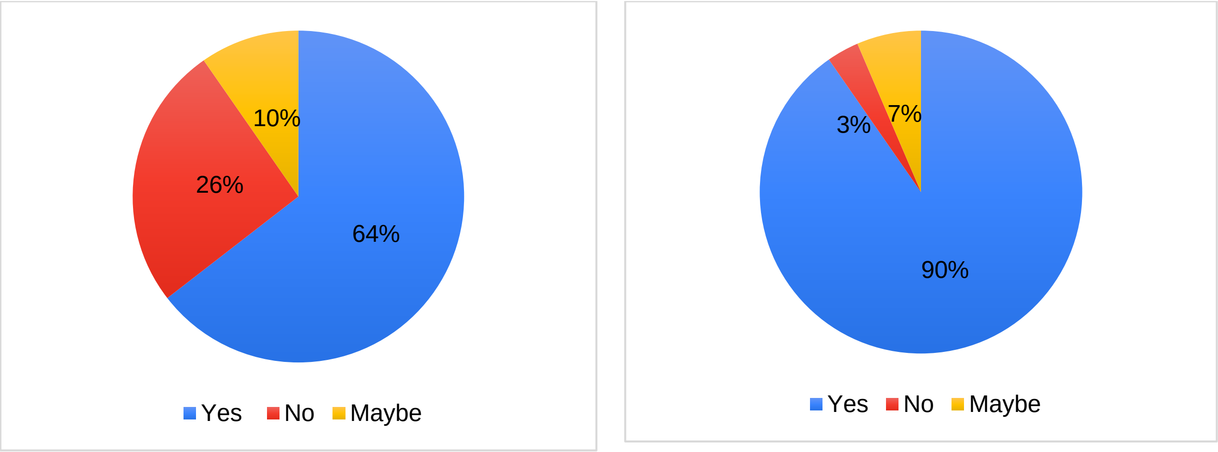


Figure 10: Participants' Post-experiment Perception Regarding Divided Bike Lanes

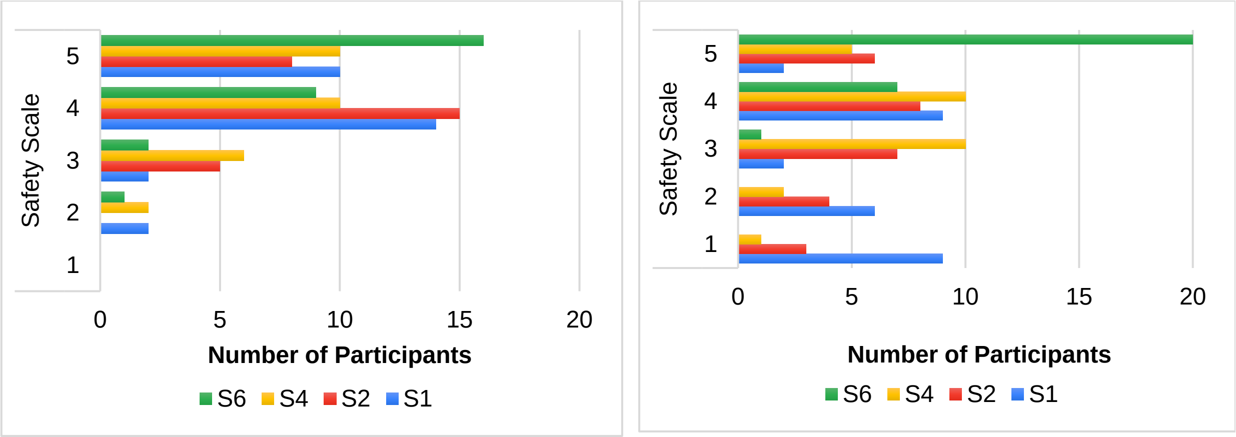
Figure 11 presents participants' future biking and walking activity depending upon CS layout availability. In this case, 64% responded positively to biking (Figure 11 a), and 90% responded positively to walking (Figure 11 b).



(a) Participants' plan for biking (b) Participants' plan for a walk

Figure 11: Participants plan for biking and walking upon CS layout availability

After driving each scenario, the participants were asked to rank each design on a 1 to 5 safety scale, with 1 being the least safe, and 5 the safest. The participants scored each scenario, assuming themselves as both a car driver and a bike rider. Figures 12 (a) and (b) both present scenario S6 as the safest CS layout from the participant's viewpoint. It is noticeable that the S6 scenario always receives safety ranking of 3 to 5 from both car drivers and bike riders (Figure 12).



(a) As a car driver (b) As a bike rider

Figure 12: Participants Safety Ranking of CS layouts after Driving/riding

1.4.3 Data Analysis

1.4.3.1 Non-Integrated Bike Data Analysis (Segments one and three)

Graphical Speed Analysis

The driving course was broadly divided into three segments where Segments one and three were non-integrated conditions, and Segment two was integrated. Figure 13 shows the average speed profile of the participants in each scenario considering the 660m interaction zone of Segment one starting at 150m and ending at 810m. Throughout this interaction, drivers faced multiple bicyclists generated from the VR studio software as a traffic model. The top speed in scenario 1 (S1) was 64 km/h at 330 longitudinal distances, which dropped between 400 and 450m and then rose again. Finally, the speed began to slow from 510m and went down to 54km/h at 810m. In the case of scenario two (S2), where the transit lane was running adjacent to the mixed traffic lane, the average speed was significantly reduced between 150m to 810m. The top speed was 60km/h at 390m and went down to the same as S1 – 54km/h at 810m. Speed reduction to ensure safety for all users is a primary goal of a complete street. Looking at the average speed plot in scenario four (S4), where the bicyclist was introduced in a dedicated bike lane separated by pavement markings, the speed reduction is noticeable. The maximum speed in this scenario was 58km/h at 460m and dropped to 51km/h at 810m.

In contrast, the situation was utterly different in S6, where the average speed of the participants was highest. The top speed was 66km/h at 350m, and the trend line showed a similar pattern to S1 but in the higher speed category. The lowest speed in S6 was 56km/h at 810m.

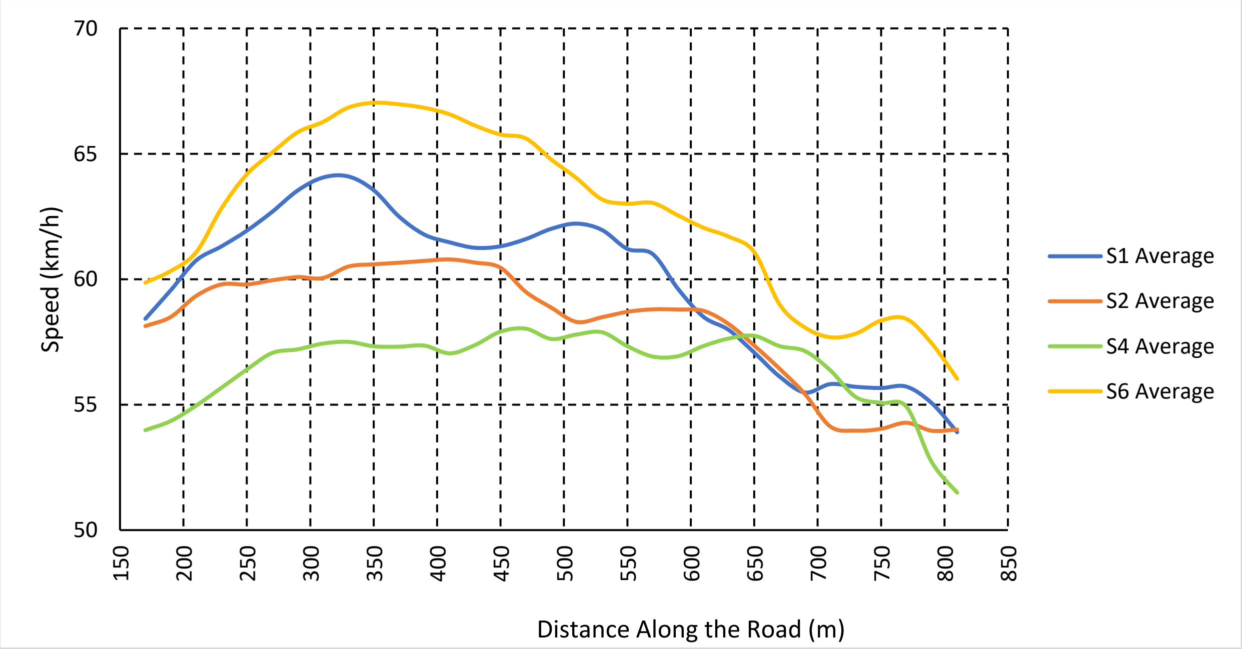


Figure 13: Average Speed 20m Interval in Segment One (150-810m)

Similar to Segment one, in Segment three, S1 had a higher speed of 54km/h between 1950m to 2000m. In S2, the average speed significantly dropped by 0.05km/h. But in S4 the average speed was almost the same as S1. In Figure 14 the green line shows deviations in S4. Finally, in S6, the average speed is highest, like Segment one's overall condition.

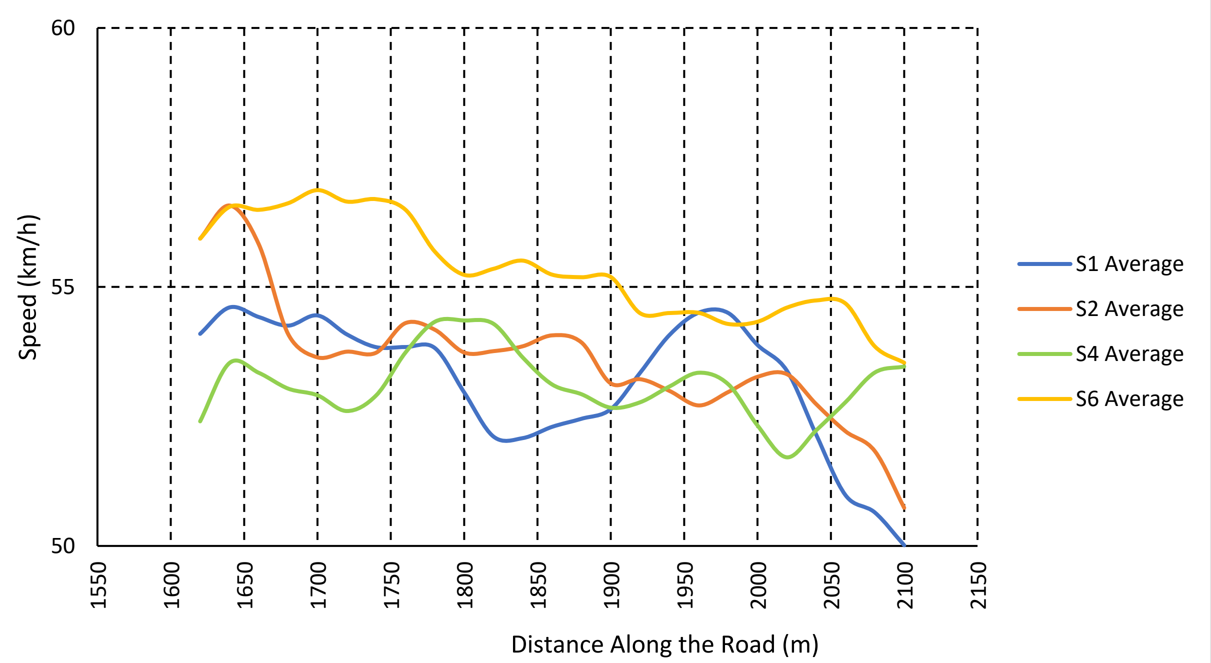


Figure 14: Average Speed 20m Interval in Segment Three (1600-2100m)

Statistical Tests

ANOVA (S1 vs. S2 vs. S4 vs. S6)

A statistical analysis of speed data from the simulation was performed employing ANOVA for the different scenarios (baseline scenarios S1, and S2, S4, and S6 have different road designs) and in the two non-integrated segments (Segments one and three). The objective of ANOVA was to evaluate the differences in driving speeds among the four scenarios that are characterized by different road designs (including the baseline condition with no speed-reducing measure). The descriptive statistics and the resulting ANOVA significance are shown in Table (4)

Table 4: ANOVA test result of driving speed for all Scenarios in Segments One and Three

Segment one					**Segment three**			
Groups	*S1*	*S2*	*S4*	*S6*	*S1*	*S2*	*S4*	*S6*
Average	57.97	57.16	54.35	61.09	52.79	53.16	52.26	55.18
Variance	40.30	55.99	71.43	43.44	21.59	9.07	22.58	24.88
F	4.5				2.57			
F critical	2.68				2.68			
P-value	0				0.06			

The ANOVA test revealed a significant interaction between the type of road design and a demonstrated change in speed, and, more generally, the effectiveness of the segments where the speed was measured. Moreover, the descriptive statistics and speed profile observations also demonstrate that the speed profile changes in different segments. The first segment of the road was statistically significant. The p-value of one-way ANOVA is less than 0.05, suggesting that one or more road designs are significantly different.

According to ANOVA results, this study tried to determine which scenarios with different lane markings showed speed differences compared to the base scenario. The F-test was run to determine the equality of two variances. The t-test was run to determine the mean speed differences in different lane layouts (i.e., various scenarios). (Table 5 and Table 6)

Table 5: Results of the Hypothesis Testing in Segment One

Hypothesis	Compared Scenarios	Scenario	Mean Speed	Variance	[a]F-test (p-value)	[b]t-test (p-value)	Decision on Null hypothesis (H_0)
There is no significant difference in mean speeds due to lane design change	S1 vs S2	*S1*	57.97	40.3	0.19	0.65	fail to reject
		S2	57.16	55.99			
There is no significant difference in mean speeds due to lane design change	S1 vs S4	*S1*	57.97	40.3	0.06	0.06	Fail to reject
		S4	54.37	71.43			
There is no significant difference in mean speeds due to lane design change	S1 vs S6	*S1*	57.97	40,30	0.42	0.06	Fail to reject
		S6	61.09	43.44			
There is no significant difference in mean speeds due to lane design change	S4 Vs S6	*S4*	54.37	71.43	0.08	0.00	Rejected
		S6	61.09	44.46			

a One-tail test with α=0.05.
b Two tail test at α = 0.05.

Table 6: Results of the Hypothesis Testing in Segment Three

Hypothesis	Compared Scenarios	Scenario	Mean Speed	Variance	[a]F-test (P-value)	[b]t-test (P-value)	Decision on Null hypothesis (H_0)
There is no significant difference in mean speeds due to lane design change	S1 vs S2	S1	52.79	21.59	0.01	0.71	Fail to reject
		S2	53.16	9.07			
There is no significant difference in mean	S1 vs S4	S1	52.79	21.59	0.45	0.66	Fail to reject
		S4	52.26	22.58			

Hypothesis	Compared Scenarios	Scenario	Mean Speed	Variance	[a]F-test (P-value)	[b]t-test (P-value)	Decision on Null hypothesis (H_0)
speeds due to lane design change							
There is no significant difference in mean speeds due to lane design change	S1 vs S6	S1	52.79	21.59	0.34	0.06	Fail to reject
		S6	55.18	24.88			
There is no significant difference in mean speeds due to lane design change	S4 Vs S6	S4	52.26	22.58	0.39	0.02	Rejected
		S6	55.18	24.88			

a One-tail test with α=0.05.
b Two tail test at α = 0.05.

The hypothesis for scenario S1 vs. S2 in the first and third segments determines whether the mean speed decreased due to adding a transit lane in S2. The statistical analysis of the t-test for equal variances showed the null hypothesis (H0) was not rejected, and the result concluded that the mean speed due to lane design did not significantly change. However, the S4 and S6 showed no significant difference in speed compared to the base scenario S1.

In the case of Scenario S4 and S6, a separate t-test was run as they had a special treatment (the physical barrier between car and bike lanes). Hypothesis IV for comparing scenarios S4 and S6 shows significance in both segments where mean speed changes due to bike lane design changes.

1.4.3.2 Integrated Data Analysis

As mentioned earlier, Segment two had an integrated bike operated by a rider in a bike simulator. However, these integrated bikes were available only in scenarios S4 and S6 in the bike lane. Therefore, the integrated data was observed separately only for scenarios S4 and S6.

Graphical Speed Analysis

In the case of Segment two, for all scenarios where the driver interacted with a real bicyclist on the bike simulator in the virtual environment, we looked into the spot speed of the participants in four longitudinal points as mentioned earlier. We can observe from Figures 15 and 16 where the speed profile is represented in S4 and S6, respectively. The S4 scenario where the bike lane is separated by a pavement marking only showed that drivers are at a usual or higher speed at the 100m upstream point when the bike first appeared in the vicinity of the car. But at the point right before crossing the bicyclist their speed reduces. The thick red line represents average speed. It can be seen in Figure 15 (S4) that the average speed is lower, and it drops from 49km/h to 48km/h at the position right before passing the bike. Right after the passing point, it rises back to 49km/h. Finally, at the fourth point it's reduced to 45km/h.

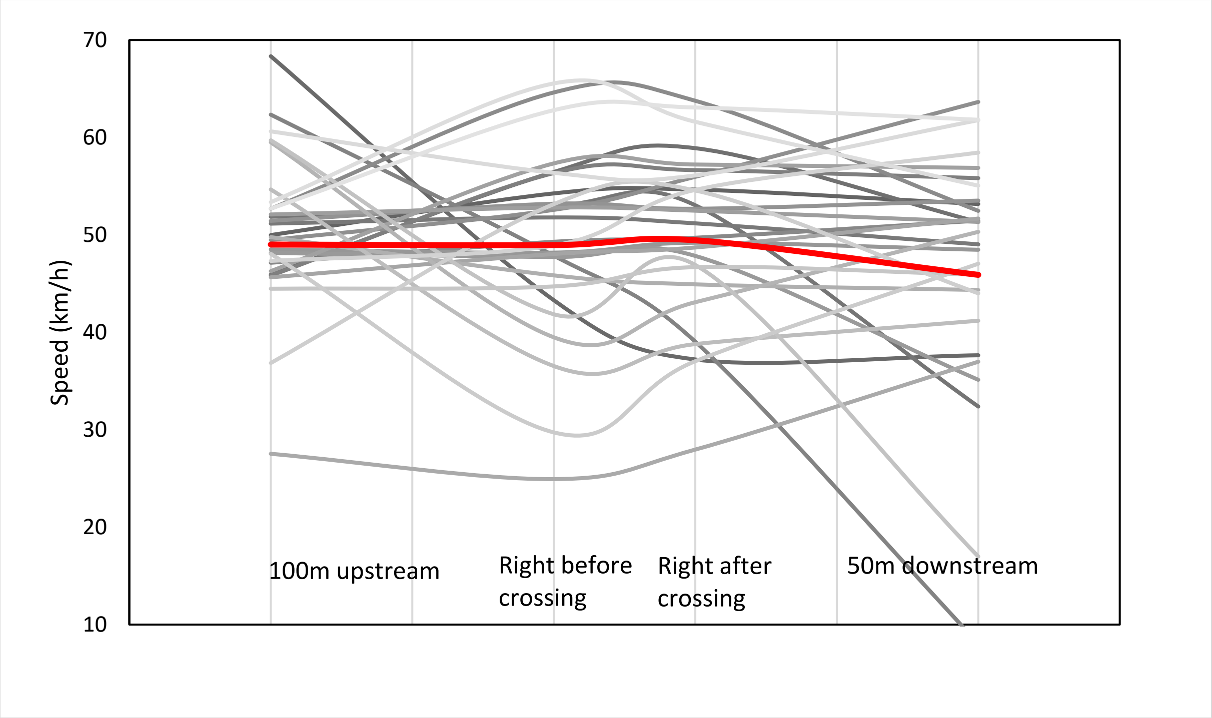


Figure 15: S4 Speed Profile in Segment Two (Car)

On the other hand, in S6 (Figure 16), where the bike lane is separated using a buffer zone and flex posts, the average speed reduction is uniform. But the average speed of the participants is 5-7km/h higher than S4. At the 100m upstream positions, the average speed shown in the thick red line is 55km/h. This gradually reduces to 54km/h right before the passing position. With a similar reduction rate at right after the passing position the average speed is 53km/h. Instead of reducing, it increases when they reach the 50m downstream position.

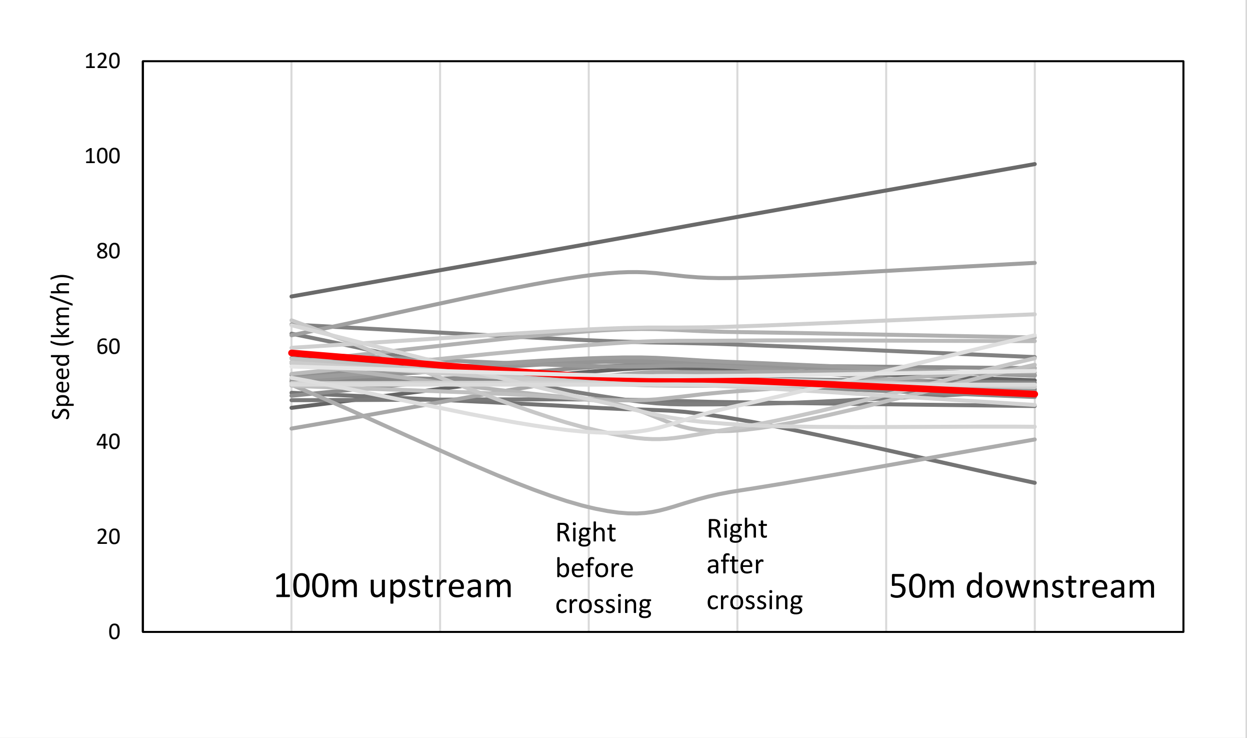


Figure 16: S6 Speed Profile in Segment Two (Car)

A separate ANOVA and t-test were run for Segment 2 speed data. The test result presents a significant difference in speed level between the two scenarios in Segment two.

Table 7: ANOVA test result for all Four Scenarios in Segments Two.

ANOVA	**Segment two**	
Groups	*S4*	*S6*
Average	46.41	55.24
Variance	103.62	57.59
F	14.81	
F critical	4	
P-value	0	

Table 8: Detailed Results of the Hypothesis Test in Segment Two

Hypothesis Segment	**Compared Scenarios**	**Scenario**	**Mean Speed**	**Variance**	**^{a}F-test(P-value)**	**^{b}t-test (P-value)**	**Decision on Null hypothesis (H0)**
There is no significant difference in mean	S4vsS6	S4	46.41	103.62	0.05	0.00	Rejected
		S6	55.24	57.59			

Hypothesis Segment	Compared Scenarios	Scenario	Mean Speed	Variance	[a]F-test(P-value)	[b]t-test (P-value)	Decision on Null hypothesis (H0)
speeds due to lane design change							

a One-tail test with α=0.05; b Two tail test at α = 0.05.

The graphical representation shows participants' speed reductions near the bike. However, a t-test for two paired samples of variance was run in both scenarios (S4 and S6) for Segment two to verify the result. The car's speed 100m upstream was compared with pre-crossing the bike, post-crossing the bike, and 50 m downstream. The analysis was run at a 90% confidence level.

Table 9: Detailed Results of the Hypothesis Test in Segment Two Scenario S4.

Hypothesis Segment	Compared Scenarios	Scenario	Mean Speed	Variance	[a]t-test (P-value)	Decision on Null hypothesis (H0)
The car speed Pre crossing the bike is less or equal to the speed of 100m upstream	100m upstream Vs Pre crossing the Bike	100m Upstream	49.01	130.47	0.49	Fail to reject
		Pre-crossing the bike	48.95	87.54		
The car speed post-crossing is less or equal to the speed of 100m upstream	100m upstream Vs Post Crossing the Bike	100m Upstream	49.01	130.47	0.43	Fail to reject
		Post-crossing the bike	49.45	81.73		
The car speed 50 m downstream is less or equal to the speed of 100m upstream	100m upstream Vs 50 m downstream	100m Upstream	49.01	130.47	0.21	Fail to reject
		50m downstream	45.9	224.25		

a One-tail test with α=0.1.

Table 10: Detailed Results of the Hypothesis Test in Segment Two Scenario S6.

Hypothesis Segment	Compared Scenarios	Scenario	Mean Speed	Variance	^{a}t-test (P-value)	Decision on Null hypothesis (H0)
The car speed pre crossing the bike is less or equal to the speed of 100m upstream	100m upstream Vs Pre crossing the Bike	100m Upstream	55.3	28.69	0.09	Rejected
		Pre-crossing the bike	53.09	67.05		
The car speed post-crossing is less or equal to the speed of 100m upstream	100m upstream Vs Post Crossing Bike	100m Upstream	55.3	28.69	0.06	Rejected
		Post-crossing the bike	52.74	64.54		
The car speed 50 m downstream is less or equal to the speed of 100m upstream	100m upstream Vs 50 m downstream	100m Upstream	55.3	28.69	0.12	Fail to reject
		50m downstream	53.42	66.2		

a One-tail test with α=0.1.

The t-test result in different sections of Segment two in scenario 4 shows that participants decreased their speed right before and after crossing the bike (Table 9). In scenario S6 (Table 10), the t-test result comparing the speed 100m upstream with the pre-crossing and also with the post-crossing points does show significant difference.

Lateral Distance Analysis

For lateral movement analysis of the participants in Segment two, each participants' data was evaluated individually by developing graphs such as Figure 17, which illustrates both the bike's and car's lateral trajectories in the same chart. As in Figure 17 the black lines are showing how the passing zone is observed.

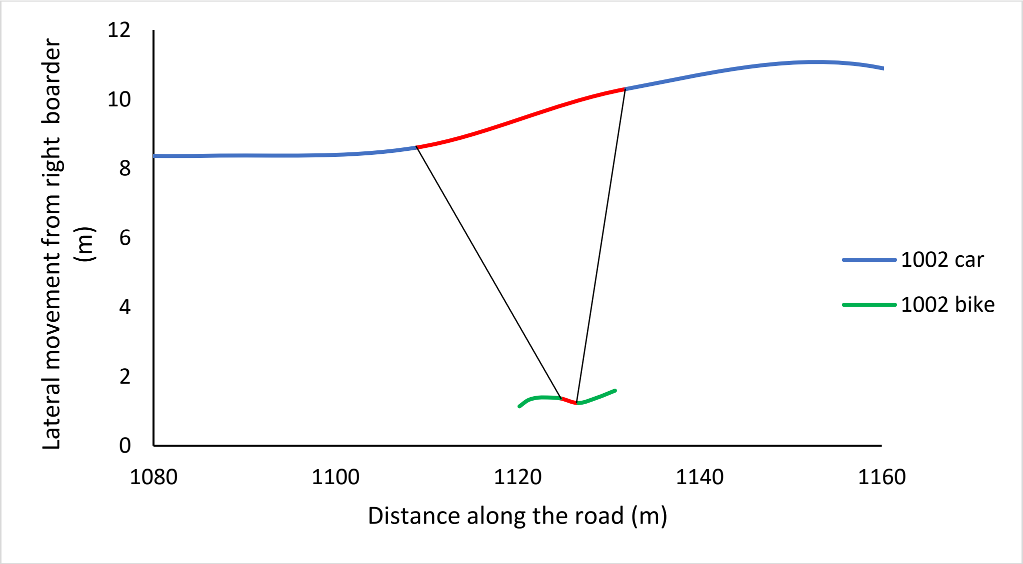
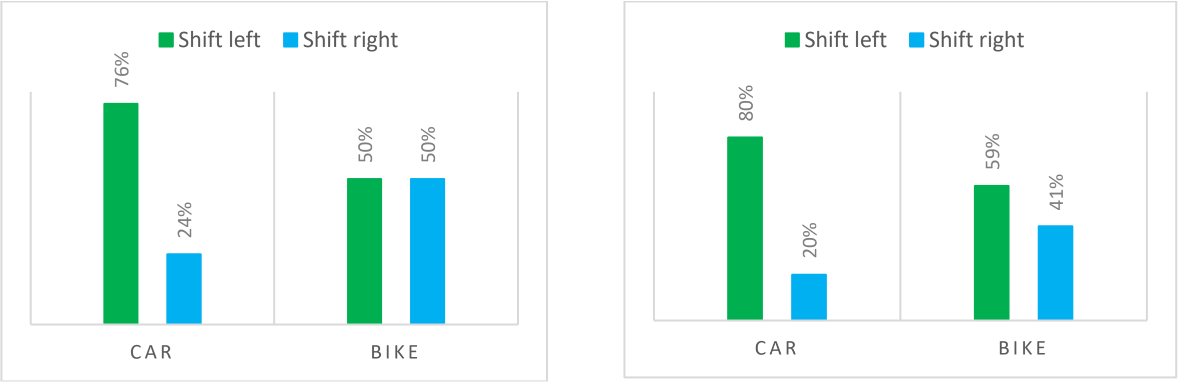


Figure 17: S6 Lateral Movement Analysis Sample (Car & Bike) for One Experiment

Figures 18a & 18b show what percentage of drivers and riders shifted right or left when the car was passing the bike, in S4 and S6, respectively. Results showed that the majority of cars in both scenarios drifted away from the bike when crossing it, to maintain safe side distance. However, bike rider's behavior analysis revealed that an even distribution between those shifted away and toward the car lane.



(a) S4 lateral movement (b) S6 lateral movement

Figure 18: Lateral movement analysis results

The study also drew and investigated gap curves of individual experiments, defined as the difference in longitudinal distance between the car and bike. Figure 19 shows that the overall slope of gap curves in S4 is smoother than the curves in Figure 20 for S6. This indicates that drivers in S4, where there was no physical barrier existed, used more caution when passing the bike.

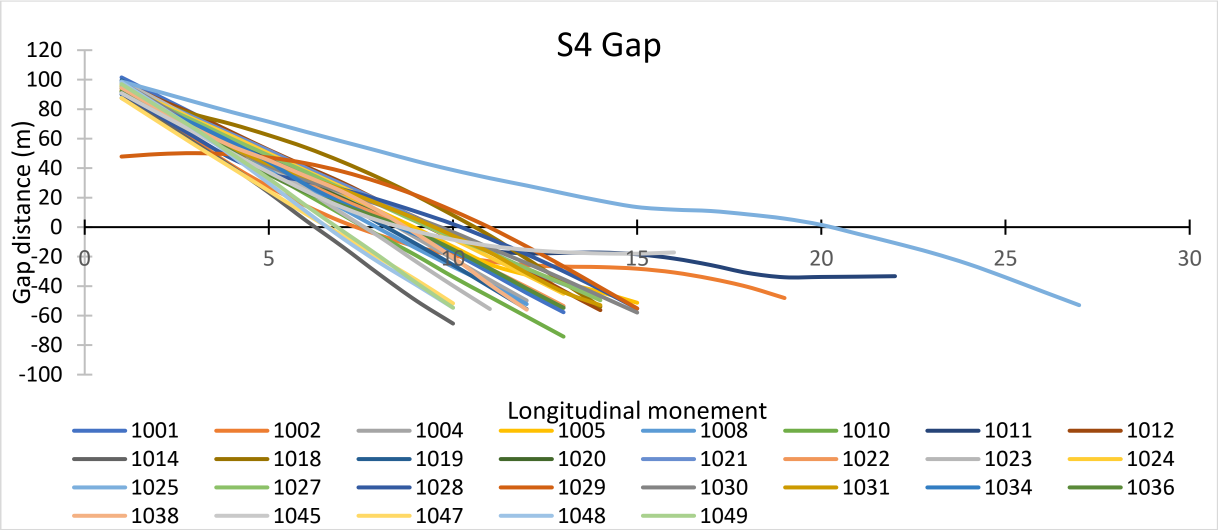


Figure 19: Longitudinal Gap Curves in S4

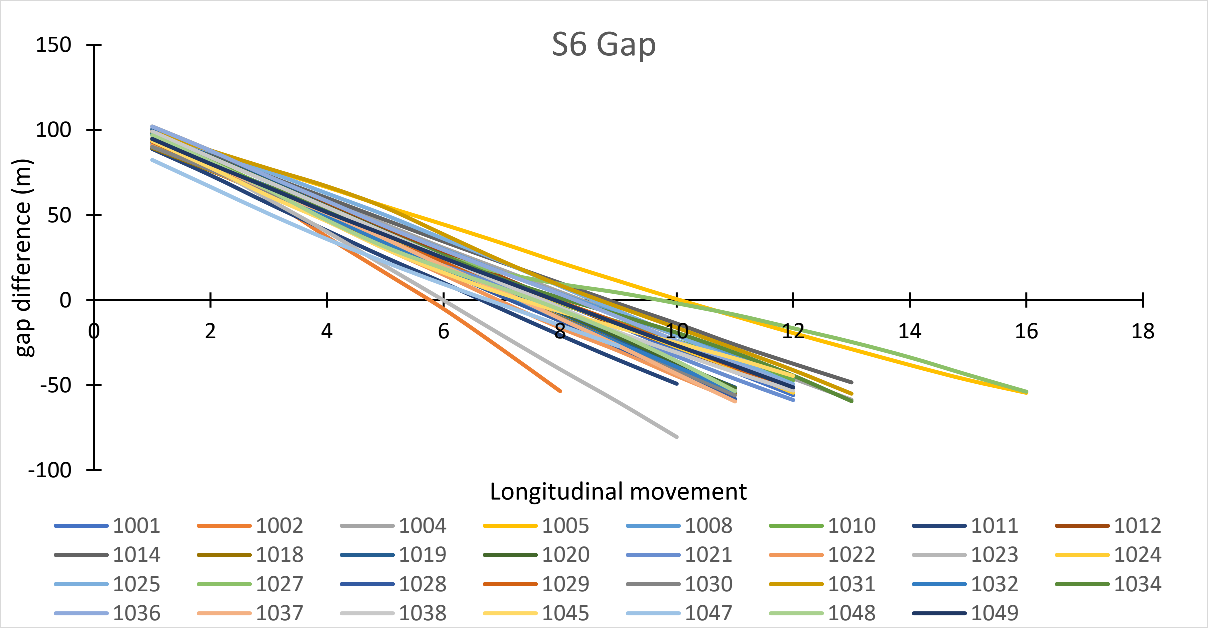


Figure 20: Longitudinal Gap Curves in S6

1.5 Conclusion

This study used a driving and a bike simulator to evaluate driving behavior under four different CS layouts (S1, S2, S4, S6). The data analysis assumed that driving was mainly affected by the road design and surrounding bicyclists, with speed being the dependent variable. The study area was divided into three segments where an integrated bike appeared in segment 2 and simulator generated bikes were present in segments one and three. Statistical analyses were performed on speed data for each scenario in each segment. The ANOVA results revealed a significant speed difference between the scenarios. Overall, S6, the divided bike lane with a buffer zone and flex posts, showed the highest average speed among the four scenarios, in segments one and three. Specifically, average speed was significantly higher in all three segments of the 6-foot divided bike lane than the 6-foot undivided bike lane. However, the increases in speed compared to the base scenario were lowest in the transit scenarios (S2), revealing that people do not speed up significantly in the presence of transit lanes.

It is evident that the effectiveness of the different road layouts strongly depends on the type of barrier applied to the road pavement to separate the car lane from the bike lane. The highest speed increase was reached in scenario S6 in comparison with the base and other scenarios.

Lateral distance analysis also revealed that most drivers increased their lateral distances with the integrated bikes when passing through them in S4 and S6.

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2 A methodological framework for Complete Streets planning and implementation

2.1 Introduction

The *Complete Streets* (CS) concept refers to the implementation of specific urbanistic layouts, as well as the adoption and operation of traffic measures that accommodate all modes of travel and incentivize non-motorized transportation (Litman, 2015). These infrastructure improvements are expected to ameliorate the quality of life of local communities, enhance the safety of pedestrians and bikers, attract economic investments, promote mixed land use development, reduce emissions, and improve the health of individuals and their well-being (National Complete Streets Coalition, 2021).

Statistics based on the 2017 National Household Travel Survey (NHTS) show that around 50 percent of all trips made in the U.S. are less than three miles long and that 28 percent of all trips are one mile or less (NHTS, 2017). These distances could be easily covered by walking, biking, or taking a local bus. Yet, the non-motorized modal shares remain very low even for short trips. The reason is mainly that the majority of the roads in northern America are *Incomplete Streets*, i.e. unpleasant, even dangerous roads, which are often impossible to travel by non-motorized means of transportation. In contrast, CS are well-designed, friendlier, and attractive roadways. They have the potential to create opportunities for neighborhood revitalization and attract businesses, jobs, and individuals interested in a less car-dependent lifestyle. These roads can be traveled by various means of transportation, not only by car, inviting people of different socio-demographic characteristics (even elderly or children) to shop locally, commute by transit with improved access, play in green areas surrounding the CS corridor, or eat-out in nearby restaurants and coffee shops (Litman 2015). Additionally, the implementation of CS elements, such as sidewalks, bike lanes separated from the flow of cars, adequate traffic calming measures (speedbumps, roundabouts, median islands, etc.), and smart crosswalk technologies, might reduce fatalities and increase the safety of pedestrians and bikers especially in disadvantaged neighborhoods, where accidents involving pedestrians are much more likely to occur (Ernst and Shoup, 2009).

In light of the benefits offered by the CS paradigm, cities and local jurisdictions across the U.S. are implementing CS transportation plans to guide local transportation agencies on the construction and on the formulation of design principles that prioritize pedestrians, cyclists, and transit users (McCann, 2011). The purpose of these plans is to assess the needs of their communities and the variety of travelers that constitutes them. To this end, they support legislation that prioritizes alternative travel options to the automobile, providing interconnectivity to all modes. However, these efforts are not always accompanied by quantitative studies on the effects of CS on travel patterns, especially those related to the potential modal shift that their implementation may entail. Therefore, in this context of increasing implementations of these plans, formal methodologies are needed to adequately address a subject as challenging as this one.

This study aims at filling this gap, offering a guideline to transportation planners and modelers that intend to improve their existing modeling tools to support plans that seek to transform highway-like corridors into CS. The results that we present are relative to the State of Maryland, but the methods proposed are general and can be easily adopted by any agency or local transport authority, as well as transferred to other geographical areas. The approach that we have developed comprises several steps. First, we collected behavioral data on CS using Stated Preference methods; a careful analysis of existing data from National and Regional Travel surveys for the State of Maryland revealed that the exact location for walk trips was not available and that not many CS infrastructure projects have been completed in Maryland. Second, we model travelers' preferences for non-motorized transportation alternatives in a CS context. In addition to assessing the drivers of the users’ behavior in this regard, we derive how changes in the characteristics of the CS affect the probabilities of choice of all transportation alternatives considered, (i.e., *direct elasticity* and *cross elasticity*). In this way, we can accurately evaluate how improvements in CS characteristics lead to changes in the demand for all alternatives. Third, we integrate the outcome of model estimation into the Maryland Statewide Transportation Model (MSTM) (Donnelly et al., 2013). In MSTM, the mode choice model does not account for walk and bike modes, which is the case for many strategic transportation models in the USA. Therefore, we propose to adjust non-motorized trips on CS in the trip generation phase as a percentage of the total number of trips. Fourth, an illustrative example is proposed for an urban region (Baltimore County); where we visualize the effects of CS on trips for different purposes and for different income segments.

The remaining of this paper is organized as follows. Section 2.2 reviews CS case studies and implementations and the effects on modal shift to non-motorized modes. The data collection effort and the survey design are covered in Section 2.3. Section 2.4 shows an analysis of the trips reported by the National Household Travel Survey (NHTS), which we used as a baseline for comparison of our results. We discuss in Sections 2.5 and 2.6 model results and elasticities. Section 2.7 describes our effort to update the Maryland Statewide Transportation Model. Conclusions, lessons learned, and avenues for future studies in Section 2.8 close the paper.

2.2 Literature Review

The existing literature on Complete Streets comprises three main aspects: 1) CS policies and projects implementations, as well as their outcomes in mobility and land use (Perk et al., 2015; Moreland-Russell, 2013; Burden and Litman, 2011), 2) changes in expected non-motorized trips or modal shifts measured after a CS implementation from available studies or direct observations (Jensen et al., 2017; Yu et al., 2018; Schlossberg et al, 2015) 3) modeling and planning tools proposed and adopted by agencies to evaluate the effects of CS (Rynne, 2010; Carter et al., 2013). We review these three aspects focusing on U.S. cases, where the problem of incomplete streets is more compelling and where only recently the attention of legislators and planners has been directed to this issue.

Regarding the first of these aspects, the implementation of policies and projects, as early as 1973, the city of Portland passed a landmark law regulating "U*rban Growth Boundaries (UGB)*," which started several innovative planning projects, including the design of Complete Streets around the city. However, the UGB policies was not very successful in controlling urban sprawl or in reducing car use (Jun, 2004). Until recently, Portland's streets were not different from those of any other city in the USA (Goldberg, 2018). Another of the early examples of CS in the U.S. is San Francisco's Embarcadero Freeway. This road was demolished after the 1989 earthquake and rebuilt adding a CS boulevard to a six-lane roadway. It has been reported that after the reconstruction traffic volumes reduced by 50% and that the number of pedestrians, bicycles, and transit users increased, affecting positively the economy of the nearby neighborhoods (Litman, 2015). In more recent times, New York City Department of Transportation updated the *Street Design Manual* in 2009, retrofitting since then several roadways by adding sidewalks, bike lanes, and bus lanes (New York City, 2020). The 9th Avenue became a CS model under this program, with bicycle lanes separated from traffic by a row of parked cars, signaling for pedestrians and bicycles, and dedicated islands for pedestrians to cross safely. Several benefits have been observed, including reduced congestion, increased transit ridership, higher cycling, and pedestrian activities. Adjacent areas have also been reported to attract more businesses and customers (Litman, 2015).

In subsequent years, this plan has been further developed; by 2010 the focus shifted to arterials and their safety; the *Vision Zero* initiative was launched in 2015 to further improve safety; it was followed in 2016 by an action plan to improve public health, expand travel choices, and fight climate change (New York City, 2022). As a result of these efforts, car-dominated arterials had started to be transformed into green boulevards accessible to pedestrians and bikers, that also accommodate bus waiting areas, and where cars travel at a low speed. Another example in this direction is the Arlington County Board (State of Virginia), which established in 2016 the *Neighborhood Complete Streets* (NCS) program to improve safety and access to local roads; albeit limited in scope since arterials were not part of the plan (Arlington (VA), 2016). On the other hand, the current Kansas City Region Metropolitan Transportation Plan has developed a CS policy that includes the development of design concepts (Kansas City, 2017). For now, the plan is limited to one major Street and a Boulevard, but the plan also includes training and communication activities together with new guidelines to design bicycle facilities. In 2020, as part of their CS activities, the City and County of Honolulu reported improvements in pedestrian safety, transit-related enhancement, traffic calming projects, and bike facility installation. In this case, educational efforts were an important part of the effort, too (City of Honolulu, 2014). The Maryland State Highway Administration (MDOT SHA), encouraged by *PlanMD* legislation enacted in 2012, issued a CS policy that same year. The policy aimed to strengthen the balance between safety and mobility of all roadway users by developing context-sensitive solutions that support the mobility and transit accessibility of pedestrians, bicycles, and individuals with disabilities (Maryland SHA, 2012). Similarly, in November 2018, Baltimore City Council passed a Complete Streets bill that targeted the improvement of existing legislation and establishing accountability measures for Baltimore City's Department of Transportation (BDOT), to support the city becoming a Complete Streets pioneer (Baltimore City, 2018). However, although these policy efforts are fundamental and necessary, ground truth transit realities in the Baltimore-Washington Metropolitan area are still challenging, both for motorists and even more so for those relying on transit, cycling, and walking. In conclusion, between 2008 and 2010 the number of CS policies have significantly increased every year, even doubling in some years. More than half of the states in the country had some form of CS policy at the community or state level (Moreland-Russell et al., 2013). As of January 1, 2021, 1,520 jurisdictions in the United States, including 1.312 cities and towns, had adopted some form of CS policy that is intended to support active travel by pedestrians, cyclists, and transit riders by improving the built environment and policy support for walking, cycling, and using transit (Smart Growth America, 2021).

Regarding the second aspects mention above, the expected changes in the use of transportation modes due to the implementation of CS, although policies aiming at incorporating CS elements into existing networks should be supported by quantitative analyses, the number of studies specifically designed to estimate the effects of CS on modal shares and non-motorized trip rates is rather limited. Local and State planning organizations oftentimes work with four-step transportation models that often do not even include walk and bike alternatives into mode choice model specification (Donnelly et al., 2013). Likewise, studies that delve deeper into the travel behavioral changes before and/or after the construction of CS are scarce. In this regard, several studies have focused on the relation between network design and level of bike ridership or pedestrian flows, both usually modeled at aggregated levels. Concerning bike use, (Dill and Carr, 2003) showed that improved quality, density, and connectivity of the bicycle network favorably affect bike use. Dill et al. (2012) collected Stated Preference data to assess individuals' inclination to bike or walk on different types of facilities (i.e. with or without separate lanes), low or high volumes of cars, slow and fast traffic, the presence of smart technologies that will give priority at traffic signals to pedestrians and bikers. Several researchers have proposed the Level of Traffic Stress indicators to describe road conditions and network design (Buehler and Dill, 2016; Cervero et al., 2019; Wang et al., 2020). LTS is measured on an ordinal scale, usually from 1 to 4, with levels at the bottom of the scale corresponding to lower levels of stress. In this vein, Furth et al. (2016), who were among the first to define the LTS in the Netherlands, adopted in their study the following variables to define LTS categories: speed, street width, cycle lane width, speed limit, number of through lanes, and intersection design. Cervero et al., 2019, form their part, used LTS indicators to assess which factors affect cycling to work in 36 urban areas in Great Britain; the study concludes that there is no single factor that boost cycling to work, but "*low stress paths, mixed land use and natural amenities can make a difference*". Wang et al. (2020) adopted LTS criteria to study the relationships between bicycle network design and commute mode shares in Franklin County, Ohio. Their empirical results from aggregated data attest that road segments with a LTS level of 2 are significantly and positively associated with the share of bicycle commuters, while the very low-stress level (LTS 1) are not.

Finally, the number of modeling and planning tools adopted by agencies to effectively design CS and to support their implementation is limited. (Dehghanmongabadi and Hoşkara, 2020) review a broad selection of these frameworks. They identify that these approaches conduct extensive analyses of the social and physical context of the areas where the project is planned by collecting data relative to the present and future characteristics of the zoning, their land use, and the transportation system implemented. Then the authors suggest a policy procedure whereby planners identify the negative and positive aspects of the current network and then propose and test solutions, which are ultimately transferred to engineers who will assess their technical and financial feasibility. On the other hand, Donais et al. (2019) proposed a multi-criteria decision-making framework integrated with a geographic information system to select the streets that should have a higher priority in the context of Quebec City. Jordan et al. (2022) have proposed a new capability maturity model for the evaluation of CS projects that identifies and prioritizes needs, as well as assists in the practice of local agencies. The approach already used in other transportation contexts aims at developing consensus around specific CS projects, identifying and prioritizing needs, and facilitating actions.

Therefore, according to the work described above, it can be concluded that the number of CS projects is increasing in the USA and that planning agencies could benefit greatly from reliable data and evaluation tools to quantify their benefits and to prioritize interventions. It is true that progress has been made in developing indicators that measure the level of stress for walkers and bikers, especially at the network level. However, there is still much to unveil about how travelers behave in the presence of CS; and the state of practice with regard to modeling tools is currently limited in their ability to account for improvements in walk- and bike-ability. For these reasons, we believe that our methodology can make a significant contribution in this regard.

2.3 Survey design and data collection

For this work, we designed a specific Stated Choice Experiment (SCE) with the aim of filling the existing gap in behavioral data relative to the use of CS and to the effects that infrastructure improvements may have on the number of trips made by walking and biking. Specifically, we gathered information on the actual behavior of individuals when they perform short trips, eliciting their preferences towards motorized and non-motorized transportation modes. We did so in a context in which non-motorized means could be hindered by a certain degree of hazardousness in their use. How we treated this specific aspect is fully described in the next section along with the technical aspects concerning the design of the SCE.

2.3.1 Experimental Design

Stated Choice Experiments can be the right tool to collect information on individuals' preferences towards alternatives that do not exist yet, as is the case of CS segments in areas in which they have not been already implemented. The purpose of a SCE is to determine the influence of the characteristics of a set of alternatives on the probability of choosing them. An experiment consists of several hypothetical scenarios in which different levels of the attributes of the alternatives are shown. By evaluating the information presented, the user makes a choice among the available alternatives. In this case, the alternatives presented were *Car, Bike*, and *Walk*, for which we provided information on the attributes *travel time, travel cost, parking cost*, and *Level of Traffic Stress (LTS)*. LTS is a measure of how difficult —even dangerous— is for bikers and walkers to use the road, and it is described in more detail in the next subsection. It is worth mentioning that, as stated above, we conduct our study on short trips; concretely, shorter than 5 miles. We made this decision for the sake of reality, since we anticipated that only a very reduced number of users would select non-motorized modes for long trips —especially *Walk*, which would have invalidated any trade-off with respect to these modes. Moreover, we defined three different sub-designs based on the length of the trip: *short* (1 mile) trips, *medium* (3 miles) trips and *long* (5 miles) trips. The reason is that although a "short trip" may seem a homogeneous concept, in truth the decision process of a means of transport includes the evaluation of its characteristics, and this evaluation differs when the trip is very short and when it is not so short. For instance, eight minutes of walking may be comparable to four minutes of driving (*ceteris paribus* other aspects of the trip), but 50 minutes of walking compared to 20 of driving, not so much. The same applies, analogously, to the rest of the trip characteristics considered. By making these sub-designs, in which the values of the attributes shown corresponded to a trip of those characteristics (lower travel times and costs), we offered the interviewee more realistic choice scenarios. It is also worth mentioning that since the choice of a mode may differ significantly depending on the purpose of the trip, the scenarios presented in the SCE referred to one of the following trip purposes: *work, school, shop, social or recreational*, and *other*. How we treat these aspects is described in the section dedicated to the questionnaire. Finally, we randomly assigned users to these branches (maintaining even shares among them); each of them contained 24 scenarios divided into four blocks, also randomly assigned. In order to produce these choice tasks, we ran the Modified Federov algorithm with 30,000 iterations using the software *Ngene* (ChoiceMetrics, 2014). We opted for an orthogonal rather than an efficient design because of the difficulty of finding in the literature reliable priors. The design was optimized for the estimation of Multinomial Logit and Nested Logit models. Table A1 in shows as an example the output of the software for a trip of the type *short* (1 mile).

2.3.2 Attributes, levels, and alternatives

The selection of the attributes to be considered in the survey design was based on a comprehensive literature review related to travel behavior on non-motorized alternatives, as well as on previous research experience and knowledge of the field. As indicated above, four key attributes were retained to define the choice experiment scenarios: *travel time, travel cost (*present only in the *Car* alternative*), parking cost (*present only in the *Car* alternative*), and Level of Traffic Stress* (present only in the *Bike* and W*alk* alternatives). It is worth mentioning that other trip or mode characteristics were considered (pollution, landscape, safety, etc.) but finally discarded. They presented difficulties in their definition and could hinder the estimation of the attributes in the choice model, diluting the effect of the main variables of interest, i.e. those related to the CS (LTS).

2.3.2.1 Travel time

Since presenting realistic trips was a priority, and given that this study was geographically framed in the State of Maryland, we chose a segment of the Route 1 in the City of College Park, as the basis for calculating travel times by car. We explored travel times from this origin to destinations 1, 3 and 5 miles away, under normal traffic conditions. With these references, a time range was conformed to be used in the design. Although it follows naturally that travel times by bicycle and walking are proportional to those of car, such a design would generate fully correlated values that would invalidate any further estimates. Therefore, for each car trip time, a range was defined for the cycling and walking trip time. In practical terms, the algorithm performing the statistical design was adjusted to first select a combination of car travel times and then choose the travel times for non-motorized alternatives accordingly, all maximizing the efficiency. In other words, if, for instance, the design had selected a travel time by car of 6 minutes, the biking travel time would have been selected among 6, 8, and 9 minutes; while the walking travel time among 12, 14, and 15 minutes. This avoids a high correlation between the values of these variables. Table 11 depicts the actual travel times and the possible combinations of travel times shown in the survey. It can be seen that bike travel times may be, in the best scenario, equal to car travel times, thanks to CS streets elements such as dedicated lanes or safer conditions that make the cyclists ride faster. In the worst case, they are up to 50% longer. Although a car may be more than 50% faster than a bike, again, this hypothetical trip happens in a CS context, in which vehicle traffic calming measures or other elements of the same nature that slow down automobiles are present. Regarding walking times, they at least double car travel times in all cases, and they might be up to 150% longer.

Table 11: Travel times for 1, 3, 5 miles trips.

Destination	**Length**	**Actual travel time car**	**Survey travel time car**	**Survey travel time bike**	**Survey travel time walk**
Graduate Gardens	1	5	[4,6,8]	4: [4,5,6] 6: [6,8,9] 8: [8,10,12]	4: [8,9,10] 6: [12,14,15] 8: [16,18,20]
Greenbelt	3	9	[10,14,18]	10: [10,13,15] 14: [14,18,21] 18: [18,23,27]	10: [20,23,25] 14: [28,32,35] 18: [36,41,45]
Beltsville	5	12	[13,18,23]	13: [13,17,21] 18: [18,23,27] 23: [23,29,35]	13: [26,30,33] 18: [36,41,45] 23: [45,52,58]

2.3.2.2 Travel cost

Since we considered maintenance costs negligible for short trips, in this study travel cost only includes fuel cost, calculated as cost per mile[1] times trip miles (and slightly adjusted to stress the differences in the perception of the utility among alternatives). Although we considered to differentiate among types of vehicles –bigger vehicles usually consume more implying higher costs per mile– we finally discarded this possibility because the trips considered were so short that we considered in this case too that such difference would have been negligible. Ultimately, the

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[1] Fuel costs are based on average prices for the 12 months ending May 31, 2019, as reported by AAA Gas Prices at www.GasPrices.AAA.com. During this period, regular grade gasoline averaged $2.679 per gallon.
https://exchange.aaa.com/automotive/driving-costs/#.XwRMNudS9hE
https://exchange.aaa.com/automotive/driving-costs/#.Xw2l2edS-Ht
https://exchange.aaa.com/wp-content/uploads/2019/09/AAA-Your-Driving-Costs-2019.pdf

levels defined for this attribute were $0.5, $1.5, and $2 for short, medium and long trips, respectively. On the other hand, bike and walk travel costs were defined as zero.

2.3.2.3 Parking cost

For the sake of simplicity, and without detriment to the results of this exercise, we decided to simply include fixed parking costs on three levels of variation: $0, $1, and $3, for the three trip types.

2.3.2.4 Level of Traffic Stress

Level of Traffic Stress is an indicator, usually expressed on a rating scale that is intended to provide a measure of how safe and comfortable it is to ride a bicycle or walk on a particular road segment (Furth et al., 2016). We decided to use Bike and Walk LTS levels from 1 to 4 according to a project already implemented, the *Carillion Boulevard Complete Street Corridor Study*[2] (City of Galt, Sacramento). In this study, the Bike LTS classification is as follows (Figure 21 depicts each level):

- ***LTS 1****: Represents little traffic stress and requires little attention, so is suitable for all cyclists. This includes children that are trained to safely cross intersections alone and supervising riding parents. Traffic speeds are low and there is no more than one lane in each direction. Intersections are easily crossed by children and adults. Typical locations include residential local streets and separated bike paths/cycle tracks.*
- ***LTS 2****: Represents little traffic stress but requires more attention than young children would be expected to deal with, so is suitable for teen and adult cyclists with adequate bike handling skills. Traffic speeds are slightly higher, but speed differentials are still low and roadways can be up to three lanes wide for both directions. Intersections are not difficult to cross for most teenagers and adults. Typical locations include collector-level streets with bike lanes or a central business district.*
- ***LTS 3****: Represents moderate stress and is suitable for most observant adult cyclists. Traffic speeds are moderate but can be on roadways up to five lanes wide in both directions. Intersections are still perceived to be safe by most adults. Typical locations include low-speed arterials with bike lanes or moderate speed non-multilane roadways.*

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[2] A full report of this study can be accessed at https://www.ci.galt.ca.us/home/showpublisheddocument/33864/637296390164470000, while the detailed classification of the LTS levels can be found in its appendix at https://ceqanet.opr.ca.gov/2020031177/2.

- ***LTS 4**: Represents high stress and suitable for experienced and skilled cyclists. Traffic speeds are moderate to high and can be on roadways from two to over five lanes wide for both directions. Intersections can be complex, wide, and or high volume/speed that can be perceived as unsafe by adults and are difficult to cross. Typical locations include high-speed or multilane roadways with narrow or no bike lanes.*

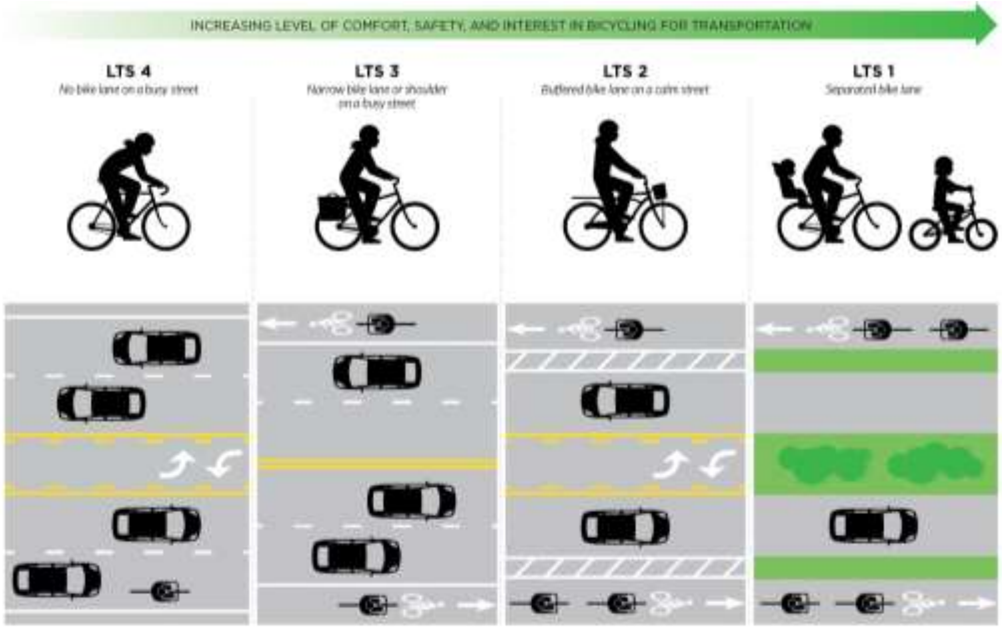

Figure 21: Level of Traffic stress for bicyclists. Source: City of Galt, Carillion Boulevard Corridor Plan.

Similarly, it was necessary to analyze the effect that better infrastructure for pedestrians has on users' choice to walk. In this regard, the project in the City of Galt that we used as a reference to determine the Bike LTS did not include a similar study for pedestrians and, therefore, we had to turn to another source. In this case, we followed the *2019 Low-Stress Walk and Bike Network Plan* developed by the city of Boulder Colorado[3] (CITE) which performs the following LTS classification for pedestrians; similar in concept to that described for Bike (see also Figure 22).

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[3] The complete plan can be found at https://www-static.bouldercolorado.gov/docs/Low-Stress_Walk_and_Bike_Network_Plan_(modified_4.1.20)-1-202004011307.pdf?_ga=2.129065615.2045802425.1594119846-832671723.1594119846

- ***LTS1:*** *Segments and crossings are highly comfortable, pedestrian-friendly, and easily navigable for pedestrians of all ages and abilities, including seniors or school-aged children walking unaccompanied to school.*
- ***LTS2:*** *Generally comfortable for many pedestrians, but parents may not feel comfortable with children walking alone. Seniors may have concerns about the walking environment and take more caution. These streets may be part of an otherwise "pedestrian-friendly" environment, intersecting with a more auto-oriented roadway or other environmental constraints.*
- ***LTS3:*** *Walking is uncomfortable but possible. Minimal crossing facilities may be present, but barriers are present that make the crossing experience uninviting and uncomfortable. Similarly, sidewalk facilities may be present but inadequate for providing comfort.*
- ***LTS4:*** *Walking is a barrier and is very uncomfortable or even impossible. Crossing and segments have limited or no accommodation for pedestrians.*

Segments and crossings are highly comfortable, pedestrian-friendly, and easily navigable for pedestrians of all ages and abilities, including seniors or school-aged children walking unaccompanied to school. LTS 1 indicates an ideal "pedestrian-friendly" environment.

Generally comfortable for many pedestrians, but parents may not feel comfortable with children walking alone. Seniors may have concerns about the walking environment and take more caution. These streets may be part of an otherwise "pedestrian-friendly" environment, intersecting with a more auto-oriented roadway or other environmental constraints.

Walking is uncomfortable but possible. Minimal crossing facilities may be present, but barriers are present that make the crossing experience uninviting and uncomfortable. Similarly, sidewalk facilities may be present but inadequate for providing comfort.

Walking is a barrier and is very uncomfortable or even impossible. Crossings and segments have limited or no accommodation for pedestrians.

Figure 22: Level of Traffic stress for pedestrians. Source: City of Boulder, 2019 Low-Stress Walk and Bike Network Plan.

On the other hand, since users would be choosing among alternatives present in the same road segment, we considered reasonable to assume that cyclists and pedestrians should experience similar LTS. In other words, a road prepared for cyclists (LTS 1) is also likely to be safe, to some extent, for pedestrians, and vice versa. Following this rationale, we only allowed for a variation of one level, up or down, between the Bike LTS and the Walk LTS. For instance, if Bike LTS was defined as 2 in the design of a scenario, the Walk LTS could only be 1, 2, or 3, but never 4. Finally, we followed a color scheme to inform the user of the LTS levels, as shown below in the questionnaire section.

2.3.3 The questionnaire

Although the stated choice experiment was the core of the survey, it was complemented by additional questionnaire modules intended to collect information that could help identify the behavior underlying the choices. Thus, the survey consisted of the following sections:

1. **Last trip.** Information on the last short trip made by the user, including its length, duration, the possibility of having used non-motorized means of transportation to complete the trip, the safety of the road, and the existence of CS elements.
2. **Control questions for experiment logic.** Since mode choice may differ significantly depending on the purpose of the trip, the scenarios presented in the SCE refer to one of the following trip purposes: *work*, *school*, *shop*, *social or recreational*, and *other*. In order to make these scenarios more realistic, we asked the user if she was retired or had any condition that prevented her from working, if she had school-age children, and if she was a student. Depending on the responses, some purposes were discarded from the random assignment made on the SCE –for instance, w*ork* did not appear if the interviewee was retired.
3. **Information about CS.** Information on CS, including external links and real pictures were presented to the respondent (Figure 23). In this section we also asked if the information provided was enough for the respondent to understand what a Complete Street is and its purpose. We also directed respondents to sources where they could obtain more information about CS.

Information about Complete Streets

We now provide you the following public information about *Complete Streets*; what they are and what are their purposes and advantages over regular street designs.

Please take a few minutes to read the materials. If you want to learn more, we invite you to visit the following links and read the information provided by the U.S. Department of Transportation, and the Maryland Department of Transportation

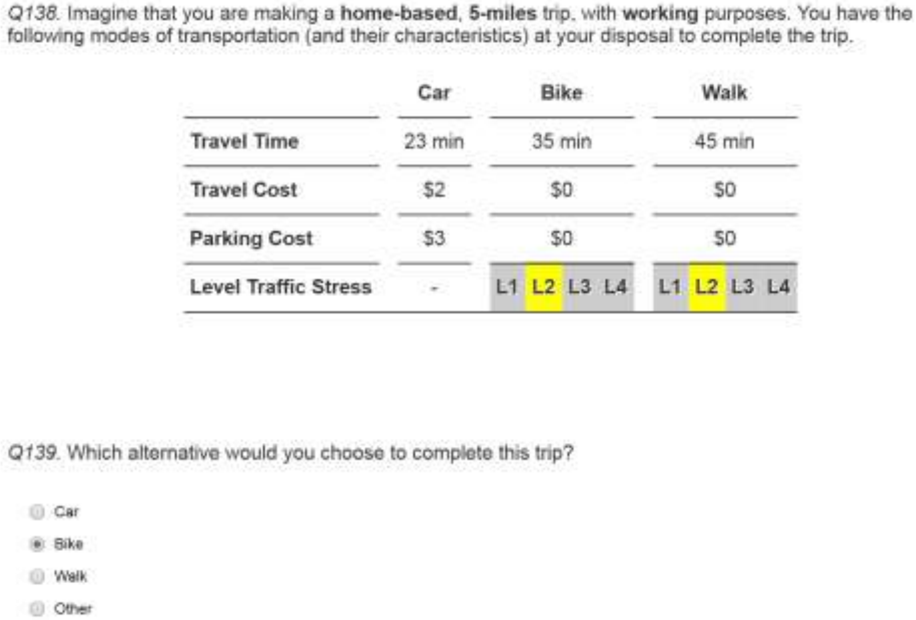
Complete Streets

Complete Streets are streets designed and operated to enable safe use and support mobility for all users, regardless of whether they are travelling as drivers, pedestrians, bicyclists, or public transportation riders. The concept of Complete Streets encompasses many approaches to planning, designing, and operating roadways with all users in mind to make the transportation network safer and more efficient.
These designs may address a wide range of elements, such as sidewalks, bicycle lanes, bus lanes, public transportation stops, crossing opportunities, median islands, accessible pedestrian signals, curb extensions, modified vehicle travel lanes, streetscape, and landscape treatments.

The State of Maryland adopted new legislation in 2018 to promote the adoption of Complete Streets policies at the state and local level. The definition of policy and guidelines for underserved and under invested communities is part of the short-term schedule of the Maryland Department of Transportation.

Figure 23: CS information provided before the SCE.

4. **Pre-scenarios information.** This section introduced the SCE and gives instructions on how to proceed through it.
5. **Stated Choice Experiment.** As indicated above, the SCE was dynamic. Rules were applied to assign users to the branch of the questionnaire that best matched their characteristics, also taking into account randomness and maintaining a balance in the composition of the sample. Thus, in the first place, when the respondent entered the survey, a trip length (1, 3, or 5 miles) was randomly assigned. Then one of the correspondent four blocks of six scenarios created in the statistical design was mapped to the choice tasks that the person would face. Moreover, these choice tasks did not only include the attributes of the alternatives (travel time, costs, and LTS) and the length, but also the purpose of the trip and if it was home-based or non-home-based. These aspects were randomly generated, too, considering the filters set on point 2 of this list, and. Figure 24 shows an example of one of these hypothetical situations.



Q138. Imagine that you are making a **home-based**, **5-miles** trip, with **working** purposes. You have the following modes of transportation (and their characteristics) at your disposal to complete the trip.

	Car	Bike	Walk
Travel Time	23 min	35 min	45 min
Travel Cost	$2	$0	$0
Parking Cost	$3	$0	$0
Level Traffic Stress	-	L1 L2 L3 L4	L1 L2 L3 L4

Q139. Which alternative would you choose to complete this trip?

○ Car
● Bike
○ Walk
○ Other

Figure 24:Example of a home-based, 5-miles trip, with working purposes

6. **Attitudes towards Complete Streets.** The first question in this section presented a list of CS elements (such as paved shoulders, wide sidewalks, dedicated bicycle lanes, etc.). We asked the user to indicate how important each of them was for her. The second question presented a list of statements related to environmental concerns and urban design concepts (such as *Urban*

design should be adapted to non-motorized vehicles) and asked the respondent to state her level of agreement with that statement.

7. **Bicycle ownership.** In this module respondents were asked about their bike ownership status and usage.
8. **Car-sharing usage.** In this module respondents were presented with questions concerning the use of ride hailing services.
9. **Socioeconomic information.** Individual and household socioeconomic information such as age, gender, income, vehicle ownership, etc. were collected.

2.4 Data analysis

2.4.1 The 2017 National Household Travel Survey

To check for consistency with the rationale of our survey, and to set a baseline for comparison of our results, we analyzed non-motorized behavioral patterns using real/experienced data extracted from the 2017 National Household Travel Survey add-on data relative to the State of Maryland. We focused our analyses on modal share, modal share by trip purpose, and modal share by trip length. As expected, most of the trips were made by car/SUV/truck and VAN; walk and bike were the selected mode of travel for, respectively, 8.5% and 0.6% of the overall trips made in the State of Maryland. Most of the trips made by walk were less than one mile long (85.5%), while the Bike trips were more equally distributed across the distance categories considered. On the other hand, Table 2**Error! Reference source not found.** shows that the main mode chosen by travelers is Car (86.46%) followed by Walk (8,61%) and Public Transportation (3,97%). Only 0.68% of the trips were made by Bike. Moreover, most of the trips made by Car were non-home-based trips (27.68%), followed by home-based with the purpose of shopping. The trips made walking were mainly home-based for recreation purposes (2.80%; perhaps, precisely, to go for a walk), home-based with *other* purposes (2.56%), and non-home based (2.08%). The use of bicycle is marginal for all the purposes considered. Although we focus on this study in these three modes of transportation, it is worth mentioning that the use of Public Transportation for working purposes is minimal.

Table 12: Mode shares by trip purpose

Mode	Overall	HBW	HBSHOP	HBSOCREC	HBO	NHB
Car	86.46%	11.49%	20.01%	10.87%	16.41%	27.68%
Walk	8.61%	0.28%	0.89%	2.80%	2.56%	2.08%
Bicycle	0.68%	0.09%	0.08%	0.25%	0.17%	0.10%
Public transportation	3.97%	0.60%	0.26%	0.16%	1.96%	0.99%
Other	0.28%	0.06%	0.05%	0.05%	0.05%	0.07%

Regarding the declared trip length, Table 3 shows it by mode choice. Certain dichotomy can be observed in the length of trips made by travelers. Half of these trips are very short (less than one mile) while 27.23% are longer than 5 miles. This means that only 22.76% of them are between one and five miles. Interestingly enough, around 40% of these very short trips are made by car. In other words, the users do not bike, walk, or use public transportation (just 5.99%) to complete very short trips. In fact, leaving apart the trips of less than one mile, the other means of transportation are practically noy used.

Table 13: Trip length by mode

Mode	<1	1-2	2-3	3-4	4-5	5+
Car	40.08%	6.44%	4.96%	3.95%	2.76%	21.98%
Walk	1.19%	0.04%	0.12%	0.39%	0.35%	0.29%
Bicycle	0.09%	0.01%	0.01%	0.03%	0.02%	0.01%
Public transportation	5.99%	1.03%	0.70%	0.37%	0.39%	3.50%
Other	2.65%	0.66%	0.53%	0.00%	0.00%	1.45%
Total	50.00%	8.18%	6.32%	4.74%	3.52%	27.23%

These findings helped in taking our decision of constraining the study to trips of length 5 miles or shorter. We believed that trips over 5 miles cannot be realistically done by walking, at least in a significant amount. We also restrict bike trips to the same 5-mile threshold, given their very limited modal share in NHTS.

2.4.2 Survey data analysis

The data for this study was collected in two phases: a pilot (100 complete surveys collected) and a final launch (766 completes). The pilot was launched with a two-fold aim. First, to check questionnaire consistency. Minor errors were identified during this phase that did not require any significant modification of the structure of the questionnaire or its flow. The second objective of conducting a pilot was the estimation of preliminary models, similar to those that would ultimately be calculated. This is a capital step on studies of this nature since any identification problem, non-significant coefficients or, in general, results that deviate from what is reasonably expected, must be addressed before full data collection. Precisely, in our case, we decided to adjust some of the levels of the alternative's travel times, to stress more the differences among alternatives[4]. It was not necessary to modify the LTS levels as they were highly significant from the outset.

After a thorough analysis of the responses, the pilot and launch data were merged, and some observations removed due to inconsistencies, yielding a total of 862 completes (5,172 pseudo-observations). Table A2 in the appendix show the statistics of the most important variables. The socioeconomic characteristics reasonable match census information for the State of Maryland. The second section of the table refers to trip revealed preferences, i.e., the last trip made by the interviewee. Average travel time was 17.9, while average length was 3.5 miles. Additionally, users felt that those trips were safe since the mean of this variable is 3.9 over a maximum safety of 5. Interestingly, to the question *Would you say that the road infrastructure allowed for this trip to be made by non-motorized means such as walking or biking?* they declared 3.1, on average, expressed in the same Likert scale (*definitely not - definitely yes*).

Of special interest are the results of the information collected on the importance of several CS elements (6th module of the questionnaire). All of them appear to be reasonably important to users. (means higher than 3), being the most relevant one the existence of wide sidewalks, paved shoulders, medians, and traffic calming measures. On the contrary, bicycle parking, landscaping or truck mountable curbs in roundabouts are the features to which users state that they do not attach much importance.

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[4] It is worth mentioning in this regard that Table 2 above presents the final levels appearing in the full launch of the survey, and not those intermediate that are mentioned here.

The variables about attitudes reflect agreement with sentences in favor of both motorized and non-motorized means of transportation, as well as with pro-environmental or pro-ridesharing statements (ATT_EC2 is expressed in negative terms, so disagreement to it means actually environmentally friendly). Finally, the variables about bike ownership show that 50% of the sample own a bike. Among these individuals, many of them use it to get to work (frequency of 3.6 over 5), but only to get to another main mean of transportation (commute to bus or metro), since 1.5 is the mean value to the use of the bicycle as the main mean of transportation to go to work.

We also derived the following information shown in Table 4 and Table 5 about the revealed preferences, which served also to confirm the assumptions made for the design.

Table 14: Average trip length by purpose

Purpose	**Average trip length**
Home-base Other	3.35
Home-based School	3.96
Home-based Shopping	3.31
Home-based Social	3.42
Home-based Work	4
Non-home-based	3.49

Table 15: Share of home-based/non home-based, and purpose trips

Home/Non-home based	**Share**
Home-based	79.95
Other	16.81
Recreational	21.74
School	3.62
Shopping	46.67
Work	11.16
Non-Home-based	20.05

2.5 Models for travel behavior assessment

As for the analysis of individual preferences towards non-motorized means of transportation, we estimated a Multinomial Logit (MNL) Model (Ben-Akiva and Lerman, 1985). It is worth mentioning that other models were considered. Namely, we estimated a Nested Logit (NL) structure that grouped non-motorized alternatives, as they might pertain to the same *slow mode* family. However, the tests performed with both pilot and released data showed that there was not significant improvement in the use of NL. Therefore, all analyses and results presented in the following Sections are based on MNL.

The random utility obtained by an individual n when choosing the alternative *j* pertaining to a set *J* is:

$$\boldsymbol{U_{nj} = \beta'_n x_{nj} + \varepsilon_{nj}} \qquad \text{(a)}$$

where x_{nj} are observed attributes, β'_n is a vector of coefficients representing individuals' tastes, and ε_{nj} is the error term independently and identically Gumbel distributed. Having defined the linear combination of estimated coefficient and alternative attributes as the deterministic part of the utility V_{nj}, the choice probabilities can be expressed as:

$$P_{ni} = \frac{e^{\beta'_n x_{nj}}}{\sum_j e^{\beta'_n x_{nj}}} \qquad \text{(b)}$$

On the other hand, one of the key elements in this project was the calculation of elasticities. Elasticities represent the change in the probabilities of choosing an alternative in response to a change in some observed factors. For instance, to what extent car would be less demanded if car travel times would increase, or how many more people will choose to walk or bike if safer and better roadways would be available. These are the so-called *direct elasticities*. On the contrary, to what extent the probabilities of choosing an alternative are affected by a change in the attribute of another alternative (to what extent bike would be more demanded if car travel times would increase) are called *cross elasticities.* In the case of discrete choice models, such as the MNL, the calculation of elasticities involves the derivatives of the choice probabilities. Ultimately, they can be calculated (direct and crossed, respectively) as shown in equations (c) and (d):

$$\xi_{iz_{ni}} = \frac{\partial V_{ni}}{\partial z_{ni}} x_{ni}(1 - P_{ni}) \tag{c}$$

$$\xi_{iz_{ni}} = -\frac{\partial V_{ni}}{\partial z_{nj}} x_{ni} P_{nj} \tag{d}$$

If utilities are linear in parameters β_n' the derivates become $\beta_z x_{ni}(1 - P_{ni})$, and $\beta_z x_{ni} P_{nj}$, respectively (Train, 2019).

2.6 Model estimation results

Following the specification defined in the previous section, several models were estimated with a two-fold aim. Our first objective was to identify the key variables that influence users' choice of motorized and non-motorized modes of transportation. These variables included the *Level of Service* (the attributes defined in Section 2.3.2), socioeconomic factors, and the purpose of the trips treated as dummy variables. However, for the shake of completeness, and related to the second goal of these estimations, we also estimated a series of models only on the data corresponding to each purpose. This is, one model in the subset of data corresponding to the scenarios in which the purpose was *work*, one model in the subset of data corresponding to the scenarios in which the purpose was *shopping*, and so on. Moreover, since we presumed that income could also play a capital role in the preference for non-motorized means, we ultimately estimated one independent model on the subsample of each combination of purpose and income bracket (5 purposes, 5 income brackets; 25 in total). The income brackets were defined in accordance with the structure of the MSTM, given our interest in updating the non-motorized trip table generation module of this statewide model.

The second aim of these estimations was to calculate elasticities from the coefficients obtained. Namely, the direct and cross elasticities for each attribute, for each alternative, for each of the 25 models. This led to the estimation of 525 elasticity values. In addition to the intrinsic value of these calculations in understanding the changes in the probability of using each alternative when the characteristics of the CS change, we use the elasticities to compute non-motorized modal shares in the MSTM by updating the non-motorized trip table generation module. However, it is important to highlight that, due to data sparsity, some of these sub-models were not completely identified, or provided results contrary to expectations. In those cases, as will be explained below, we opted for using the elasticity from the general model to carry out this update, since they were highly reliable given the larger amount of data used for their estimation, and its coherence.

Thus, Table 6 below presents the results of the general model (whole sample, purposes as dummy variables), and the specific models estimated on each subset of the data (one for each purpose). For the sake of brevity, the results of the other 25 models are not reported, only the elasticities obtained from them.

With reference to the model estimated on the complete dataset, the attributes referring to the alternatives have the expected negative effect (time, cost, level of stress) and in most cases are also highly significant. Some LOS are not, but they do provide interesting insights concerning travel behavior on Complete Streets. Travel time by bike or walk are highly significant variables, while travel time by car is not. This is a natural result in this specific experiment since driving time for short trips is small and, therefore, increments on it do not make users change their minds. In other words, once driving, even a 100% increase in driving time from 2 to 4 minutes, is not perceived as a big loss. Something similar occurs with the travel cost by car, which is not perceived as harmful as the parking cost (which can go up to $3). It is especially significant the effect of LTS for both non-motorized modes, as well as their more negative coefficient, emphasizing how important this aspect is when making the decision to walk or use a bicycle. Finally, not all trip purposes played a relevant role in users' choices. Only shopping was the purpose that had a significant effect. Expressed differently, the purpose of the trips is not that relevant when users are deciding among Car, Bike, or Walk in the context of Complete Streets[5]. On the other hand, the models estimated for the five purposes considered show results that are coherent with respect to those of the general one. Only the models for purposes *school* and *shopping* present a lower number of significant variables. Regarding the socioeconomic factors, gender, age, pertaining to the medium income bracket, bike ownership, and frequency of use of the bicycle were found significant (the last two only present in the utility function of the Bike alternative).

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[5] It is worth clarifying that we do not state that the purpose of a trip does not influence the choice of a non-motorized means of transportation, but that it is not significant when the trip takes place on a road segment that is a CS.

Table 16: Modelling results

	General model		**Purpose Work**		**Purpose School**		**Purpose Shopping**		**Purpose Social**		**Purpose Other**	
	estimate	t-ratio	estimate	t-ratio	estimate	t-ratio	estimate	t-ratio	estimate	t-ratio	estimate	t-ratio
ASC car	-		-		-		-		-		-	
ASC bike	0.1325	0.63	0.6274	1.56	-0.1374	-0.19	0.0852	0.24	-0.3113	-0.92	0.0174	0.05
ASC walk	0.329	1.35	0.8316	1.71	-0.7198	-0.97	0.4265	0.99	-0.0954	-0.27	0.5523	1.44
ASC other	-3.5578	-14.2	-2.79	-7.08	-3.4582	-5.14	-4.0515	-10.7	-3.6166	-7.69	-3.9176	-9.31
Travel time car	-0.0084	-0.73	0.0066	0.24	-0.0123	-0.29	-0.0305	-1.25	-0.0028	-0.11	-0.0166	-0.63
Travel time bike	-0.0319	-4.01	-0.0228	-1.42	-0.0412	-1.47	-0.0585	-3.56	-0.0299	-1.76	-0.0343	-2.03
Travel time walk	-0.0469	-7.16	-0.0428	-3.29	-0.0271	-1.43	-0.0719	-5.77	-0.0524	-4.22	-0.0574	-4.77
Male	0.2495	2.89	0.3792	2.19	0.1084	0.4	0.209	1.67	0.1105	0.88	0.4107	3.27
Age	-0.0133	-4.46	-0.0167	-2.85	-0.0033	-0.29	-0.0154	-3.34	-0.0094	-2.27	-0.0139	-3.26
Income	0.2997	3.07	0.4255	2.36	0.3155	1.11	0.0041	0.03	0.3626	2.49	0.4026	2.84
Bike ownership	1.1971	5.95	1.1871	3.23	0.5555	1.11	1.6109	4.96	1.3723	4.33	0.9705	3.2
Frequency use bike other	-0.2041	-3.68	-0.2634	-2.61	-0.1601	-1.15	-0.2969	-3.45	-0.1931	-2.27	-0.1358	-1.6
Travel cost car	-0.1243	-1.47	-0.0547	-0.23	-0.1747	-0.52	-0.1762	-1.02	-0.1612	-0.9	-0.2089	-1.26
Parking cost car	-0.0696	-3.77	-0.0425	-0.79	-0.1814	-1.89	-0.0447	-0.99	-0.0962	-2.09	-0.1197	-2.71
LTS bike	-0.3096	-8.88	-0.3812	-5.1	-0.3204	-2.46	-0.3379	-4.72	-0.2389	-3.78	-0.3969	-6.18
LTS walk	-0.275	-6.54	-0.3991	-4.32	-0.2746	-1.66	-0.2966	-3.29	-0.1757	-2.17	-0.3956	-4.75
Purpose work	0.0638	0.84										
Purpose school	0.1852	1.58										
Purpose shop	0.3468	4.23										
Purpose social	0.0036	0.06										
Adj.Rho-square (0)	0.2909		0.2388		0.2154		0.3621		0.2757		0.2764	
AIC	10180.69		1872.07		720.08		2345.37		2632.61		2654.33	
BIC	10305.18		1943.89		777.11		2423.22		2710.29		2732.15	

For the sake of brevity, and without detriment to the overall results, the elasticities resulting from the general model are shown in Table 7, while in the Appendix are presented the purpose-based elasticities (Table A3) and the elasticities of each the 25 sub-models that combine purpose and income level (Table A4), and which are used to update the Maryland Statewide Transportation Model. It is worth to recall that, since LOS have an inverse relation with the probabilities of choice (the higher the travel time, cost, LTS; the less demanded the alternative), the direct elasticities should present a negative sign. Correspondingly, the cross elasticities should be positive (the higher the travel time, cost or LTS of an alternative; the more demanded the other alternatives are). Additionally, larger elasticity values mean that a 1% change in the LOS has a more intense impact on the probabilities of these alternatives to be chosen.

Table 17: Direct and cross elasticities resulting from the general model

	Car	**Bike**	**Walk**
Travel time Car	-0.0448	0.0636	0.0504
Travel time Bike	0.1333	-0.3923	0.1259
Travel time Walk	0.1629	0.1931	-0.9901
Travel Cost Car	-0.0712	0.1006	0.0814
Parking Cost Car	-0.0400	0.0537	0.0523
LTS Bike	0.1876	-0.5667	0.2027
LTS Walk	0.0960	0.1072	-0.5696

As expected, travel times and costs negatively impact the demand of the alternatives (increases in these LOS reduce the probabilities of the alternatives to be chosen), although the effect is stronger for Bike and Walk (-0.3923 and -0.9901, respectively). Interestingly, the latter has almost an *elastic* demand (elasticity above one in absolute value). An elastic demand would have meant that increments in walking travel time would have impacted more than proportionally the probability of that alternative being demanded. On the other hand, the magnitude of the elasticity of the travel and park costs is also in line with that of travel time.

However, more importantly for our analysis, is the second factor with the strongest impact on demand, the LTS, which is actually very similar for both the alternatives in which it is present (-0.5667 and -0.5696). A deterioration in the driving conditions for cyclists or pedestrians importantly reduce the willing to use this means of transportation. Of course, the opposite is also true: implementing roadway improvement policies that reduce the level of stress to which cyclists and pedestrians are subjected to when completing their trips (such as the construction or design of more Complete Streets elements) would significantly increase the demand for these modes of transportation.

2.7 Non-Motorized shares calculation

In this section, we describe how the model outcomes obtained in the modeling phase were integrated into the Maryland Statewide Transportation Model (MSTM) to implement the CS design concept with the aim of performing policy analysis. For a brief explanation of the current MSTM, it considers 1588 statewide model zones (SMZs) that include areas in the States of Maryland, Washington DC, and Delaware, as well as some areas in the State of Pennsylvania. Concretely, 1178 of these 1588 SMZ are located in the State of Maryland. The MSTM, estimated on a 2007 regional travel survey, is a classical four-step model, but in which the mode choice model does not include the Bike and Walk modes. On the contrary, these non-motorized trip shares are estimated in the trip generation phase, which is segmented according to five purposes (i.e. Work, School, Shopping, Social, and Other) and five income levels. This estimation is performed using aggregated survey information at the zone level, by means of linear regression with the following predictors: on the one hand, household, employment, and activity densities; on the other hand, measures of transit and car accessibility to residence, employment, and retail. Once the non-motorized trip shares are estimated, they are subtracted from the total trips, and only the motorized trips are carried on into the subsequent phases.

With respect to our objective of evaluating policies for the promotion of the non-motorized means, the most straightforward method would have been to incorporate those alternatives into the choice sub-model to perform policy analysis attending to the attributes incorporated. However, many agencies certainly do not incorporate a discrete choice model in their methodological framework for project assessment. Moreover, in many cases, they do not have an LTS assigned to their zones either. We, therefore, intended to propose a procedure that can be applied by most of the agencies, using the MSTM as a case study. We start by inferring the current LTS of each zone. Then we use the elasticities to LTS obtained in the travel behavior model described in Section 2.5 to update the non-motorized share based on hypothetical LTS reached after completing the CS design.

Following this procedure, we first approximated the baseline LTS for all zones covered in MSTM. We do so by scaling the current non-motorized shares, which take a value between 0 and 1, to the LTS range, which, as previously described, is from 1 to 4. For instance, if in the current MTSM the percentage of non-motorized means for four different zones was 0, 0.33, 0.5, 0.66, and 1, then we assumed LTS values of 4, 3, 2.5, and 1 –it is worth remembering that the lower the LTS, the more favorable. We rely for this reasoning on the idea that higher shares may be due to traffic conditions more conducive to this type of transport. Secondly, since elasticities measure the percent change of shares in response to a one percent change in an attribute, once the current LTS values are inferred, they can be adjusted using the elasticities yielded by the behavioral model[6]. As an example, suppose an area in which motorized share is 88.7% and, therefore, its current LTS is 3.5. How would an improvement in the infrastructure of this area, leading to LTS of 2, impact the use of the available modes of transportation by the lowest income individuals that make trips for working purposes? According to our results, a 1% reduction in the level of stress for bikers and walkers would encourage them, decreasing motorized trips by an average of 0.087% (0.093% and 0.081, first column in Table A4). Thus, following our example, going from a LTS level of 3.5, to a LTS level of 2, which is a 42.9% change, would reduce the use of motorized means by 3.7% (42.9*0.087). The demand for car would drop from 88.7% to 85.6% and, correspondingly, the demand for non-motorized means would rise from 11.3% up to 14.4%.

An application of this methodology can be found in Figure 24, from which valuable conclusions can also be drawn on the policies to be implement for the promotion of non-motorized means. It depicts shares of non-motorized trips for Baltimore City by both income levels (a) and trip purposes (b). A first remarkable result is that the low-income population tends to use more non-motorized modes, although the shares do not seem to significantly increase when LTS improve. This can be seen in the first row on the left side of the figure, where lower LTS levels do not imply a significantly larger green, or even greener, surface on the map. However, this does appear to be the behavior for all other income levels, although very limited in the case of the highest income individuals. In other words, the more favorable the biking and walking conditions are, the more people would bike or walk those segments, except in the case of the poorer population segment. These might be due to its low car ownership rate, which would also explain the existing high rate

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[6] We remind the reader that 25 sub-models were calculated, one for each purpose-income combination, and that they can be consulted in Table A4 in the Appendix.

of fatalities for pedestrians among disadvantaged segments of the population (NHTSA, 2020; MacLeod et al., 2018).

With respect to the travel purposes, we can conclude that people hardly walk or bike to work in Baltimore City. Additionally, a large share of trips with educational purposes is made by non-motorized modes, even for high values of LTS. This may be of great interest to the local public authorities since some students might be going to school in unsafe conditions. These routes may be precisely the ones that could benefit the most from a CS redesign. For all other purposes, there is also a general trend that improvements in LTS lead to increased use of non-motorized means in the area, as well as an intensification of their use where they were already adopted.

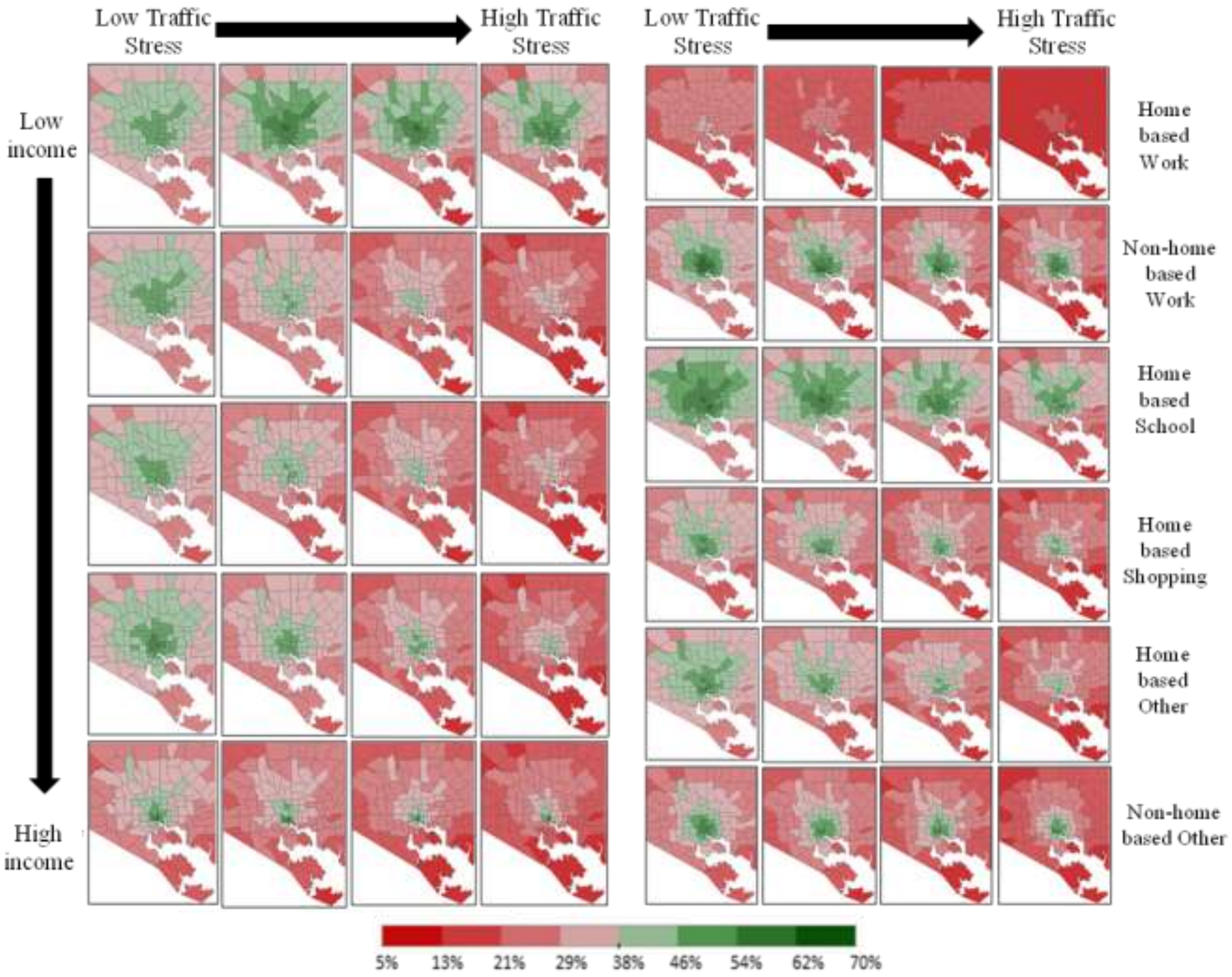

Figure 25: Non-Motorized shares in the Baltimore City by income level (left) and purposes (right)

2.8 Supporting Complete Streets Policies

The case study explored in this work supports Maryland State Highway Administration's Complete Streets vision with reliable data and models that could be integrated into their planning process using existing tools. However, this vision is shared by many other planning agencies across the USA who are seeking to *plan, design, build, maintain, and operate* (https://minneapolis2040.com/policies/complete-streets/) a more sustainable, accessible, and equitable transportation system. Therefore, we consider that the analysis conducted and the results obtained may form the basis for the following action steps, addressed to public agencies and transport authorities.

First, the existing modeling tools (and methodological frameworks, in general) discussed in section 2.2 seem to lack a methodology for analyzing the specific effect that CS plans may have on non-motorized market shares. Therefore, we suggest adopting the easy-to-implement, highly-descriptive methodology presented in this work, which would provide a quantification of the changes in the demand of motorized and non-motorized means of transportation when CS elements are implemented in urban designs. It can be used even when a mode choice (Walk, Bicycle) is not part of an initial transportation model or even when the model does not explicitly account for non-motorized modes at all. Hence, we believe that it can certainly assist planning agencies in their task of assessing this type of projects, as has been the case with the Maryland State Highway Administration.

However, for an evaluation tool to be comprehensive, it must consider elements as well beyond travelers' behavior change, equity being one of the most relevant. In this regard, our results show that low-income population is more likely to use non-motorized modes (especially walking) and that they walk out of necessity even when the level of traffic stress is high. This conclusion is in line with earlier studies that have shown that low-income communities are disproportionately affected by unsafe streets and limited access to jobs and opportunities (Ernst and Shoup, 2009; Ganz, 2003). Therefore, we suggest to transportation authorities the implementation of Complete Streets with adequate traffic calming measures (such as reduced speed limits and smart crosswalk technologies), especially in disadvantaged neighborhoods, to reduce fatalities and increase the safety of pedestrians and bikers. In this vein, our results for Baltimore city have also shown that a relatively high percentage of trips to school are non-motorized and that they happen in unsafe conditions. Therefore, we suggest prioritizing projects around schools, especially in an urban context, by creating pedestrian/biking priority networks and by improving connectivity across neighborhoods.

Finally, it is worth noting, as indicated in the numerical example given in Section 2.7, that improvements in LTS may not lead to substantial impacts on the use of non-motorized modes for certain trips and user characteristics. That is, even in a scenario that is entirely favorable to pedestrians and bicyclists, individuals may simply not want to walk or bike, or may prefer to use a motorized vehicle due to other personal circumstances or preferences. To be fair, this is one of the limitations of our methodology. We lumped all possible CS elements into one only measure of stress/risk. Probably, the explicit inclusion of specific CS elements (such as separated lanes, roundabouts, speed control, etc.) would lead to more accurate elasticities, which ultimately would provide a more comprehensive perspective of the drivers of individuals' preferences towards non-motorize means of transportation. In this sense, it would also be necessary to evaluate different standards along with those proposed in this paper, and to monitor the achievements by comparing them with initial objectives and best practices around the world.

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2.10 Appendix

Table A1: Orthogonal Design

Choice situation	Car travel time	Car travel cost	Car parking cost	Bike travel time	Bike LTS	Walk travel time	Walk LTS	Block
1	4	0.5	1	6	1	9	2	3
2	4	0.5	3	5	2	8	1	1
3	4	0.5	0	4	1	10	1	4
4	4	0.5	1	6	3	10	2	2
5	6	0.5	1	6	4	14	4	2
6	6	0.5	0	6	1	12	1	4
7	8	0.5	0	10	4	20	3	4
8	8	0.5	3	12	3	20	3	2
9	6	0.5	1	9	1	14	2	1
10	8	0.5	1	12	4	18	4	3
11	8	0.5	3	8	1	18	1	2
12	8	0.5	3	10	2	18	1	3
13	6	0.5	0	9	3	12	2	3
14	8	0.5	0	8	2	20	2	1
15	8	0.5	3	12	2	16	2	4
16	4	0.5	3	5	3	10	3	1
17	4	0.5	1	5	4	9	3	3
18	6	0.5	0	9	1	15	2	1
19	4	0.5	3	4	3	8	4	3
20	6	0.5	0	8	4	12	4	1
21	6	0.5	3	6	3	15	4	4
22	4	0.5	1	6	2	8	3	4
23	4	0.5	1	4	4	9	3	2
24	8	0.5	0	10	2	16	3	2

Table A2: Descriptive statistics of the main variables in the dataset.

Variable	Mean	Std. dev.	Min.	25%	Median	75%	Max.
AGE	42.3	17.5	18	27	40	58	87
GENDER	1.6	0.5	1	1	2	2	3
MARRIED	1.5	0.5	1	1	2	2	2
EMPLSTAT	4.0	2.8	1	1	3	7	9
EDUDGR	3.4	1.1	1	3	3	4	5
HHINC	75,202.1	239,441.7			38,000	100,000	1,000,000
ONLYWORKER	1.7	0.5	1	1	2	2	2
INDINC	32,070.3	56,805.3			3,000	50,000	600,000
RETORCOND	1.7	0.4	1	1	2	2	2
SCHOOLCH	1.7	0.4	1	1	2	2	2
STUDENT	1.8	0.4	1	2	2	2	2
TRIPLONG	17.9	50.0	1	5	10	15	1,000
TRIPMILES	3.5	1.5	0	2	4	5	5
TRIPHB	1.2	0.4	1	1	1	1	2
TRIPSAFETY	3.9	1.1	1	3	4	5	5
TRIPPOSOTHERMEAN	3.1	1.3	1	2	3	4	5
TRIPNUMWORKING	2.8	1.4	1	2	2	3	7
TRIPNUMWEEKEND	3.0	1.4	1	2	3	4	7
IMPCSPASHO	3.5	1.1	1	3	4	4	5
IMPCSWSIDE	3.6	1.1	1	3	4	4	5
IMPCSDEDBILA	3.4	1.2	1	3	4	4	5
IMPCSDEDBUSLA	3.1	1.3	1	2	3	4	5
IMPCSPMEDIANS	3.5	1.1	1	3	4	4	5
IMPCSCALM	3.5	1.1	1	3	4	4	5
IMPCSTRUCKCURBS	3.0	1.2	1	2	3	4	5
IMPCSBUSSTOPACC	3.4	1.2	1	3	4	4	5
IMPCSBUSSTOSHEL	3.4	1.3	1	3	4	4	5
IMPCSONSTPARK	3.2	1.2	1	2	3	4	5
IMPCSBIKEPARK	3.1	1.3	1	2	3	4	5
IMPCSLANDSCAPE	3.1	1.2	1	2	3	4	5
ATT_CAR1	3.9	1.1	1	3	4	5	5
ATT_CAR2	3.7	1.1	1	3	4	5	5
ATT_CAR3	3.2	1.2	1	2	3	4	5
ATT_NOMOT1	3.7	1.0	1	3	4	4	5
ATT_NOMOT2	3.9	1.0	1	3	4	5	5
ATT_SHARED	3.4	1.2	1	3	4	4	5
ATT_EC1	3.5	1.1	1	3	4	4	5
ATT_EC2	2.8	1.3	1	2	3	4	5
OWNBIKE	1.5	0.5	1	1	1	2	2
FREQUSEBIKEWORK	3.6	1.4	1	3	4	5	5
FREQUSEBIKEOTHER	3.1	1.1	1	2	3	4	5
USEBIKEWORKMAIN	1.5	0.5	1	1	1	2	2
USEBIKEOTHERMAIN	1.5	0.5	1	1	1	2	2

Table A3: Direct and cross elasticities resulting from the sub-models

	Purpose Work			**Purpose School**			**Purpose Shopping**			**Purpose Social**			**Purpose Other**		
	Car	**Bike**	**Walk**	**Car**	**Bike**	**Walk**	**Car**	**Bike**	**Walk**	**Car**	**Bike**	**Walk**	**Car**	**Bike**	**Walk**
Travel time Car	0.0351	-0.0410	-0.0329	-0.0679	0.0830	0.0812	-0.1190	0.2392	0.1856	-0.0142	0.0190	0.0149	-0.0827	0.1056	0.0826
Travel time Bike	0.0951	-0.2393	0.0891	0.1657	-0.4632	0.1700	0.1759	-0.6925	0.1747	0.1229	-0.3335	0.1139	0.1326	-0.3700	0.1291
Travel time Walk	0.1440	0.1671	-0.8137	0.1077	0.1123	-0.6325	0.1702	0.2158	-1.3965	0.1721	0.2034	-1.0056	0.2005	0.2469	-1.0524
Travel Cost Car	-0.0306	0.0356	0.0290	-0.1042	0.1274	0.1257	-0.0736	0.1475	0.1178	-0.0880	0.1170	0.0941	-0.1122	0.1426	0.1138
Parking Cost Car	-0.0248	0.0276	0.0266	-0.0958	0.1162	0.1205	-0.0189	0.0356	0.0360	-0.0511	0.0644	0.0620	-0.0659	0.0780	0.0773
LTS Bike	0.2391	-0.6201	0.2536	0.1933	-0.5401	0.2004	0.1457	-0.5853	0.1694	0.1400	-0.3939	0.1545	0.2245	-0.6382	0.2376
LTS Walk	0.1317	0.1458	-0.7311	0.0938	0.0933	-0.5406	0.0730	0.0866	-0.5839	0.0591	0.0669	-0.3384	0.1418	0.1555	-0.7112

Table A4: Elasticities resulting from the 25 sub-models that combine purpose and income level.

	Income Bracket 1 Purpose Work			Income Bracket 1 Purpose School			Income Bracket 1 Purpose Shopping			Income Bracket 1 Purpose Social			Income Bracket 1 Purpose Other		
	Car	Bike	Walk	Car	Bike	Walk	Car	Bike	Walk	Car	Bike	Walk	Car	Bike	Walk
Travel time Car	-0.079	0.103	0.078	0.126	-0.152	-0.163	-0.284	0.532	0.367	0.073	-0.109	-0.099	-0.026	0.039	0.037
Travel time Bike	0.201	-0.572	0.186	0.200	-0.651	0.247	0.196	-0.709	0.180	0.117	-0.445	0.116	-0.549	0.160	0.195
Travel time Walk	0.151	0.182	-1.208	0.044	0.051	-0.333	0.179	0.234	-1.702	0.123	0.136	-0.686	-0.841	0.120	0.153
Travel Cost Car	-0.055	0.072	0.055	-0.331	0.402	0.424	0.021	-0.039	-0.028	-0.042	0.062	0.057	-0.135	0.202	0.190
Parking Cost Car	-0.057	0.071	0.072	-0.099	0.127	0.129	0.116	-0.066	0.116	-0.029	0.043	0.041	-0.066	0.097	0.099
LTS Bike	0.093	-0.271	0.103	0.233	-0.731	0.247	0.079	-0.292	0.094	-0.005	0.021	-0.007	0.211	-0.723	0.259
LTS Walk	0.081	0.100	-0.647	0.160	0.177	-1.198	0.034	0.041	-0.309	-0.065	-0.082	0.374	0.105	0.125	-0.717

	Income Bracket 2 Purpose Work			Income Bracket 2 Purpose School			Income Bracket 2 Purpose Shopping			Income Bracket 2 Purpose Social			Income Bracket 2 Purpose Other		
	Car	Bike	Walk	Car	Bike	Walk	Car	Bike	Walk	Car	Bike	Walk	Car	Bike	Walk
Travel time Car	0.266	-0.282	-0.257	-0.363	0.421	0.420	-0.157	0.270	0.251	-0.197	0.263	0.194	-0.135	0.172	0.111
Travel time Bike	0.025	-0.064	0.024	0.222	-0.560	0.254	0.244	-0.944	0.265	0.106	-0.260	0.088	0.147	-0.374	0.110
Travel time Walk	-0.341	0.081	0.086	0.139	0.156	-0.988	0.208	0.240	-1.253	0.217	0.241	-1.227	0.320	0.368	-1.426
Travel Cost Car	-0.025	0.026	0.024	-0.078	0.090	0.092	-0.124	0.212	0.200	-0.079	0.104	0.079	-0.307	0.387	0.257
Parking Cost Car	-0.011	0.011	0.011	-0.152	0.174	0.189	0.024	-0.040	-0.042	-0.046	0.056	0.056	-0.067	0.074	0.071

LTS Bike	0.262	-0.699	0.276	0.139	-0.988	0.156	0.168	-0.657	0.196	0.276	-0.696	0.265	0.320	-1.426	0.368
LTS Walk	0.163	0.173	-0.688	0.108	0.101	-0.712	0.105	0.121	-0.631	0.093	0.085	-0.489	0.179	0.170	-0.743

	Income Bracket 3 Purpose Work			**Income Bracket 3 Purpose School**			**Income Bracket 3 Purpose Shopping**			**Income Bracket 3 Purpose Social**			**Income Bracket 3 Purpose Other**		
	Car	**Bike**	**Walk**	**Car**	**Bike**	**Walk**	**Car**	**Bike**	**Walk**	**Car**	**Bike**	**Walk**	**Car**	**Bike**	**Walk**
Travel time Car	0.390	-0.365	-0.288	-0.056	0.088	0.059	0.120	-0.325	-0.230	-0.200	0.219	0.151	-0.827	0.735	0.627
Travel time Bike	-0.299	0.510	-0.306	0.278	-0.910	0.294	0.096	-0.450	0.128	0.482	-0.946	0.492	0.421	-0.936	0.418
Travel time Walk	0.018	0.023	-0.115	0.307	0.454	-1.803	0.112	0.217	-1.447	0.246	0.358	-1.749	0.354	0.401	-1.486
Travel Cost Car	0.270	-0.251	-0.201	-0.337	0.517	0.377	-0.109	0.293	0.212	-0.065	0.071	0.051	0.523	-0.472	-0.405
Parking Cost Car	0.047	-0.041	-0.041	-0.272	0.402	0.319	0.005	-0.013	-0.013	-0.012	0.012	0.011	-0.014	0.012	0.012
LTS Bike	0.400	-0.724	0.485	0.078	-0.269	0.106	0.228	-1.093	0.343	0.201	-0.407	0.242	0.291	-0.682	0.350
LTS Walk	0.145	0.170	-0.881	0.017	0.023	-0.095	0.110	0.175	-1.341	0.160	0.254	-1.185	0.147	0.176	-0.626

Table A4 (cont.):

	Income Bracket 4 Purpose Work			**Income Bracket 4 Purpose School**			**Income Bracket 4 Purpose Shopping**			**Income Bracket 4 Purpose Social**			**Income Bracket 4 Purpose Other**		
	Car	**Bike**	**Walk**	**Car**	**Bike**	**Walk**	**Car**	**Bike**	**Walk**	**Car**	**Bike**	**Walk**	**Car**	**Bike**	**Walk**
Travel time Car	-0.240	0.379	0.272	-0.848	0.751	0.892	0.653	-2.453	-1.423	0.345	-0.373	-0.287	1.448	-1.537	-1.776
Travel time Bike	0.215	-0.733	0.259	0.411	-0.997	0.499	-0.246	1.435	-0.222	-0.089	0.203	-0.108	-0.706	1.824	-0.914

Travel time Walk	0.272	0.468	-2.178	0.213	0.217	-0.841	0.123	0.199	-1.495	0.099	0.147	-0.570	-0.706	-0.914	1.824
Travel Cost Car	-0.413	0.643	0.497	0.812	-0.740	-0.854	-0.623	2.216	1.407	-0.522	0.553	0.441	-0.100	0.103	0.121
Parking Cost Car	-0.049	0.068	0.073	0.087	-0.082	-0.087	0.069	-0.217	-0.215	-0.124	0.126	0.115	-0.139	0.138	0.160
LTS Bike	0.372	-1.302	0.508	0.213	-0.841	0.217	0.236	-1.470	0.312	0.429	-0.955	0.460	0.364	-0.974	0.475
LTS Walk	0.164	0.212	-1.168	-0.021	-0.026	0.089	-0.035	-0.043	0.400	0.258	0.295	-1.331	0.127	0.117	-0.606

	Income Bracket 5 Purpose Work			**Income Bracket 5 Purpose School**			**Income Bracket 5 Purpose Shopping**			**Income Bracket 5 Purpose Social**			**Income Bracket 5 Purpose Other**		
	Car	**Bike**	**Walk**	**Car**	**Bike**	**Walk**	**Car**	**Bike**	**Walk**	**Car**	**Bike**	**Walk**	**Car**	**Bike**	**Walk**
Travel time Car	-4.754	6.044	2.818	NA	NA	NA	NA	NA	NA	-1.183	1.041	1.037	0.138	-0.205	-0.130
Travel time Bike	-0.143	0.844	-0.464	NA	NA	NA	NA	NA	NA	1.229	-1.936	1.749	0.285	-0.846	0.222
Travel time Walk	0.019	0.122	-0.175	NA	NA	NA	NA	NA	NA	0.361	0.525	-3.344	0.339	0.430	-1.418
Travel Cost Car	4.212	-5.970	-2.897	NA	NA	NA	NA	NA	NA	-0.252	0.227	0.211	-0.535	0.760	0.531
Parking Cost Car	-0.342	0.319	0.300	NA	NA	NA	NA	NA	NA	-0.185	0.162	0.174	-0.086	0.104	0.107
LTS Bike	0.009	-0.071	0.046	NA	NA	NA	NA	NA	NA	0.149	-0.223	0.185	-0.413	1.321	-0.454
LTS Walk	0.045	0.199	-0.329	NA	NA	NA	NA	NA	NA	0.203	0.343	-2.035	-0.075	-0.119	0.339

3 Road Space Allocation for Minimum Travel Times on Complete Streets

3.1 Introduction

In recent years, “complete streets” has been an emerging concept in North American transportation planning and design. To be considered a “complete street”, a road should be designed to be safe for users of all traffic modes. “Complete streets” involves systematic changes in decision making and design process so that all users are “routinely considered” in the lifecycle of all roadways. (LaPlante and McCann, 2008) When applying “complete streets” to arterial roads, mobility should be emphasized, and one aspect of mobility is total travel time of all users (LaPlante and McCann, 2008). To optimize total travel time of all road users with a given limited road space, the allocation of functional zones, lanes and road width to multiple modes plays an important role.

For various types of lanes, decisions on location, tolling policy, and width assignment have non-negligible impacts on resulting traffic flow, thereby affecting system performance measures such as total travel time, throughput, and accident frequency. For managed lanes, including high-occupancy vehicle (HOV) lanes and high-occupancy toll (HOT) lanes, multiple researchers have developed dynamic tolling strategies (i.e., tolling is responsive to real-time demand changes) with different optimization objectives, such as maximizing corridor throughput while maintaining free-flow traffic (Yin and Lou, 2009), maximizing revenue and minimizing total system travel time over a finite duration (Pandey and Boyles, 2018), and minimizing total person delay in the equilibrized system (Tan and Gao, 2018). Kim and Schonfeld (2008) and Song et al. (2015) jointly optimized locations and toll rates of managed lanes to maximize social benefit. Saad et al. (2018) optimized length and location of weaving access zones to managed lanes to maximize system efficiency, with dynamic tolling considered. Wang et al. (2019) optimized capacity allocation for HOV lane in morning commute to minimize system cost. For exclusive (dedicated) lanes, optimization is mostly focused on where to set these bus or bike-dedicated lanes in a network (Bayrak et al., 2021). Typically, a bi-level programming model is used, with the lower level conducting traffic assignment and the upper level serving for various objectives, such as minimizing the sum of users' and operators' cost (Yao et al., 2012), minimizing the weighted sum of car users' travel time and bicyclists' travel distance (Mesbah et al., 2012), and minimizing total travel cost in a network (Si et al., 2017). Some researchers determined minimal widths for exclusive lanes for comfort (Law and Sohadi, 2005) and safety (Lee et al., 2016), but width has not been explicitly optimized for reducing costs or travel time.

Speed-flow-density models have been estimated for managed lanes (e.g., Ardekani et al., 2011) and exclusive lanes (e.g., Hussain et al., 2011). Some studies explored possible effects of lane width on traffic, safety and comfortability characteristics. Hussain et al. (2011) found that motorcycle lane width influences riding behavior patterns. Manuel et al. (2014) found lane width to be negatively related to collisions on collector roads. Fitzpatrick et al. (2017) observed that free-flow speed on a managed lane is positively correlated with envelope width of the lane. Ibrahim et al. (2018) revealed that motorcycle lane width affects riders' lateral position, thereby affecting likelihood of comfortable overtaking.

The existing literature on optimization of roadway width allocation is very limited. Labi et al. (2017) optimized allocation of a given total roadway width to the lane and shoulder for minimizing the lifecycle sum of agency (construction and maintenance) cost and user (crash-related) cost. Chen et al. (2020) developed a policy for optimizing width allocation of traffic lanes and footpaths. The objective is to minimize the weighted sum of construction cost and safety cost, which is based on safety performance functions whose results indicate sensitivity of casualties to lane widths. Both studies are safety-oriented, and there has not been any width allocation optimization for mobility-oriented objectives.

In this paper we propose a bi-level model that optimizes roadway width allocation to multiple modes, so that total travel time under a given demand matrix is minimized. Traffic characteristics of all lanes are given by Greenshield’s model, whose parameters may be affected by lane widths. Each traveler of an origin-destination (OD) pair faces a mode-specific travel impedance that is affected by traffic condition and other mode-specific items. At the lower level, logit mode choice model is used iteratively to determine mode shares based on traffic volumes and relative impedance levels in the previous iterations. Output shares become inputs in the next iteration, and equilibrium shares are reached after multiple iterations, upon which hourly total travel time is computed for the width combination being evaluated. The upper-level model searches for the lane widths combination that results in the shortest total travel time.

In the following sections, formulation of this problem is first described. Then the model is demonstrated through two simple numerical cases, the first of which includes sensitivity analyses. In the conclusion section possible future improvements of this study are suggested.

3.2 Problem Formulation

A certain number of nodes ($n \in N$) are connected in a road network with intersections. Roads in this network are divided into links ($l \in L$), each end of a link being either an intersection or a node. With a length of d_l, each link is one-directional even though two links in opposing directions can be in the same road segment. Four modes are considered for road traffic: bus, car, bicycle, and walking. Lanes in a link may be dedicated to any of these modes or be available for mixed use of cars and buses, while each mode can only use one type of lane in a link. For each link l, a lane for traffic mode $m \in M$ has its free-flow speed U_l^m and its jam density K_l^m. Both values may depend on the lane width, denoted as w_l^m. Since the relation among speed, density and flow (volume) is assumed to be given by Greenshield's model, the capacity of each lane is $F_l^m = U_l^m K_l^m / 4$.

Travel demand in this road network is externally given by a demand matrix, with each element q_{ij} $(i, j \in N)$ denoting the number of travelers moving from i to j per hour. It is assumed that $q_{ij} = 0$ if $i = j$. For the OD pair $(i, j) \in P$, the shares of travelers using buses, cars, bicycles and walking are denoted as s_{ij}^{bus}, s_{ij}^{car}, s_{ij}^{cyc}, and s_{ij}^{ped}, respectively. Travelers are assumed to use the shortest route in their travels. Then, the set of OD pairs whose routes include link l is denoted as P_l. The hourly traffic flow on a lane with mode m in link l is given by:

$$f_l^m = \frac{1}{n_l^m} \sum_{(i,j) \in P_l} q_{ij} \left(\frac{\delta_{bus}^m s_{ij}^{bus}}{a_{bus}} b + \frac{\delta_{car}^m s_{ij}^{car}}{a_{car}} + \delta_{cyc}^m s_{ij}^{cyc} + \delta_{ped}^m s_{ij}^{ped} \right) \tag{1}$$

where δ_{bus}^m, δ_{car}^m, δ_{cyc}^m, δ_{ped}^m are binary indicators for whether bus/car/bicycle/walking is usab1le in the lane that allows mode m (single or hybrid), respectively. a_{bus} and a_{car} are the average numbers of persons in a bus and in a car, respectively. b is a factor that converts the number of buses into equivalent cars. n_l^m is the number of lanes for mode m in link l.

It is required that the hourly traffic flow on each lane must not exceed the lane capacity ($f_l^m \leq F_l^m$). With this constraint, traffic density (in vehicles/bicycles/pedestrians per lane mile) as well as traffic speed (in miles per hour) on a lane can be uniquely determined using Greenshield's model:

$$k_l^m = \frac{K_l^m}{2} - \sqrt{(\frac{K_l^m}{2})^2 - \frac{K_l^m f_l^m}{U_l^m}} \tag{2}$$

$$u_l^m = U_l^m(1 - \frac{k_l^m}{K_l^m}) \tag{3}$$

For a hybrid lane with mixed flow of buses and cars, the traffic speed applies for each bus or car. Denote the set of links used by OD pair (i, j) as L_{ij}. After the traffic speed determined, the travel time (in hours) for a traveler of OD pair (i, j) using a certain mode m can be obtained:

$$t_{ij}^m = \sum_{l \in L_{ij}} \frac{d_l}{u_l^m} \tag{4}$$

The impedance for each traveler can be calculated with value of travel time (v = user's value of time in \$/hr) plus additional prices such as parking fees, bus fares, and fuel costs:

$$I_{ij}^m = v t_{ij}^m + misc. \tag{5}$$

Alternatively, travel impedance can be formulated as a linear combination of values (x) of some selected attributes $c \in C$ (e.g., travel time, travel cost, and parking cost) with coefficients (β) estimated outside the model, plus an estimated constant coefficient term β_{ASC}:

$$I_{ij}^m = \sum_{c \in C} \beta_{c,ij}^m x_{c,ij}^m + \beta_{ASC,ij}^m \tag{6}$$

For travelers of OD pair (i, j), the mode share parameters s_{ij}^{bus}, s_{ij}^{car}, and s_{ij}^{cyc} serve as input parameters. With the logit mode choice model, resulting mode shares are given by:

$$s'^{m'}_{ij} = \frac{e^{-I_{ij}^{m'}}}{\sum_{m \in M_{(i,j)}} e^{-I_{ij}^m}}, m' \in M_{(i,j)} \tag{7}$$

where $M_{(i,j)}$ denotes the set of all available traffic modes for OD pair (i, j). These output mode shares become new input mode shares in the next iteration. As iterations continue, for all OD pairs the output mode shares are expected to converge. When a certain threshold is reached, the iterations are stopped and the equilibrium mode shares are obtained for all OD pairs. At the equilibrium shares, total travel time of all travelers in the examined network within an hour is given by:

$$T = \sum_{(i,j)\in P} (q_{ij} \sum_{m\in M_{(i,j)}} s_{ij}^{m} t_{ij}^{m}) \tag{8}$$

As mentioned above, both free-flow speed (U_l^m) and jam density (K_l^m) of a lane can depend on its width (w_l^m). Consequently, the equilibrium hourly total travel time (T) is also a function of multiple width values of lanes. With fixed total width of each link as well as given upper and lower bounds of lane widths for various modes in different links, the objective is to find the optimal configuration of lane widths in the network that minimizes the hourly total travel time.

In practice, possible width values of lanes are discrete and limited within their upper and lower bounds. If the number of optimizable width values does not exceed 3, and computation time needed for reaching equilibrium mode shares is below 1 second for each combination of widths, then exhaustive enumeration can be used for finding optimal widths. If there are 4 or more width values to be optimized, especially on larger networks with dissimilar links, then considering the discrete nature of possible width values, simulated annealing (SA) or another metaheuristic method can be applied to optimize the lane width combinations.

3.3 Numerical Cases

Case I: A crossroad

To demonstrate the proposed problem formulation and solution method, a numerical case with a simple example road intersection is synthesized. As shown in Figure 26, there are four demand nodes connected by two intersecting roads: the south-north major road and the west-east minor road. Both roads are two-directional. For each link in this network, its total width, length, lane configuration, and Roman number label are shown in Figure 26. Key properties of lanes – upper and lower width limits, free-flow speeds, and jam-densities – are given in Table 18. In the computation of traffic flow and its corresponding speed and density for a bus lane, the number of buses is converted to its equivalent number of cars.

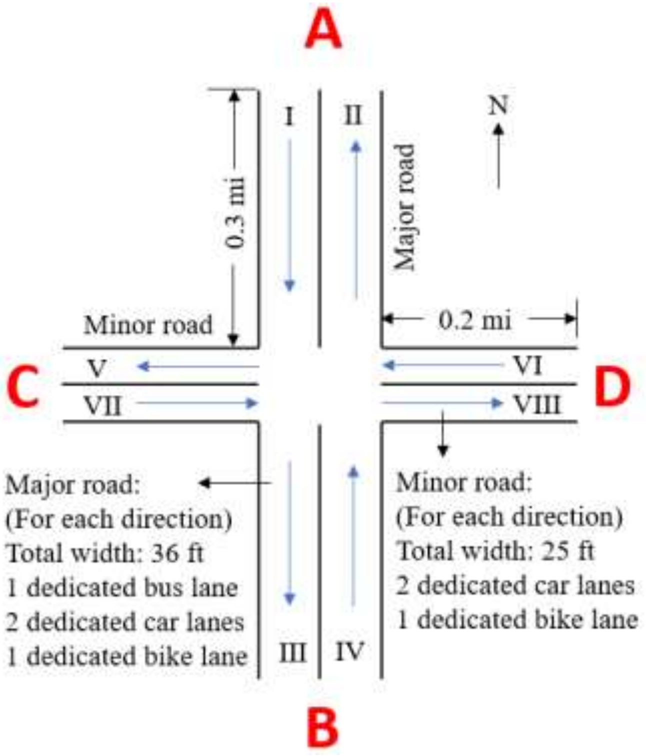

Figure 26 Configuration of example road intersection

Table 18: Traffic parameters of lanes – Case I

Lane types	Width range (ft)	Free flow speed (mph)	Jam density
Bus lanes	$9 \leq w_l^{bus} \leq 11$	$40[1+(w_l^{bus}-10)/5]$	160 (equivalent cars) veh/mi
Car lanes	$9 \leq w_l^{car} \leq 11$(major)	$40[1+(w_l^{car}-10)/5]$	160 veh/mi
	$9 \leq w_l^{car} \leq 10$(minor)		
Bicycle lanes	$5 \leq w_l^{cyc} \leq 7$	$11[1+(w_l^{cyc}-6)/5]$	$800[1+(w_l^{cyc}-6)/5]$ cyc/mi

Hourly travel demand among these four origins/destinations are given by Table 19. The mode option for bus is only available for passengers from A to B or from B to A, while all travelers can choose between car and bicycle. Parameters for computing total travel impedance are in Table 20. For each traveler using a bus, components of travel impedance include value of in-vehicle time, value of waiting time, bus fare, and bus fuel cost. For each bus passenger in a certain direction, the average waiting time (counted as a part of travel time) is half the average headway (in hours), which is the reciprocal of the hourly bus count in this direction. For each traveler using a car, components of travel impedance include value of in-vehicle time, parking fee, and car fuel cost. The fuel cost for each traveler using a certain mode is given by unit fuel cost × travel distance / average load per vehicle. For simplicity, travel impedance of a bicycle rider is given by value of travel time multiplied by a scale factor. (5 is used here.) Travelers' delays at the intersection are neglected in computations of travel impedance and travel time.

Table 19: Hourly demand matrix

Flow q_{ij}	To A	To B	To C	To D
From A	0	2,000	400	600
From B	2,500	0	400	200
From C	500	600	0	800
From D	300	500	700	0

Table 20: Parameters for impedance computation – Case I

Average load per bus	30 person/veh.	Average load per car	1.5 person/veh.
Equivalent cars per bus	2	Bus fare	1.2 $/psgr.
Average parking fee	1 $/psgr.	Value of user's time	15 $/hr/psgr.
Unit bus fuel cost	1 $/veh./mi	Unit car fuel cost	0.4 $/veh./mi

The objective is to find the optimal configuration of lane widths that minimizes hourly total travel time of all travelers over all OD pairs. Widths are optimizable for the bus lane of the major road, the bike lane of the major road, and the bike lane of the minor road. We assume that each road uses the same lane width for a certain mode in all four links the road contains. The search step is 0.5 ft for each lane width increment. All possible combinations of lane widths are enumerated for finding the minimal total travel time. When evaluating each combination of widths, of all travelers moving between A and B the shares of bus users start from 0.15. For all OD pairs the shares of bicycle users start from 0.02. The iteration of mode shares stops when the largest absolute difference between input and output shares does not exceed 0.001.

In the results, when the widths of the bus lane and the bicycle lane reach their upper bounds (11 ft and 7 ft, respectively), the equilibrium hourly total travel time attains its minimum of 220.974 hours. The corresponding width of each car lane is 9 ft in both major and minor roads. In this configuration of lane widths, equilibrium mode shares of bus for OD pairs A-B and B-A are 0.422 and 0.436, respectively. Equilibrium mode shares of bicycles (s_{ij}^{cyc}) are shown in Table 21. For OD pairs A-B and B-A, mode shares of car are therefore 0.510 and 0.497, respectively.

In an alternative situation, buses are allowed to share traffic with cars on the major road. Then there are three lanes for mixed motor vehicles on the major road. With all other parameters unchanged, the optimizable parameters are the bicycle lane widths of the major and the minor roads. Result shows that upper-bound widths (7 ft) for bike lanes of both roads produce the minimal hourly total travel time of 184.230 hours. In this numerical case, switching dedicated bus and car lanes into mixed lanes results in saving minimized total travel time by 16.6%. With car taking up a higher share than bus for OD pairs A-B and B-A, and the average load per vehicle for a car being 1/20 of that for a bus, the number of cars moving on dedicated lanes of major roads is significantly higher than that of buses. When distributing cars from two dedicated lanes to three mixed lanes, there is a noticeable decrease in traffic density for cars. In contrast, the increase in density for buses by sharing traffic with cars in three lanes is relatively small. As a result, the increase in the speed of cars outweighs the slowing down of buses, contributing to an overall decrease in travel time.

The corresponding equilibrium mode shares of bus for OD pairs A-B and B-A are 0.384 and 0.400, respectively. Equilibrium mode shares of bicycles are also shown in Table 21. For OD pairs A-B and B-A, mode shares of car are 0.547 and 0.531, respectively. The decrease in bus share and the increase in car share for travelers between A and B, as compared to the dedicated lane scenario, is consistent with travel speed changes for these two modes, as mentioned above.

Table 21: Equilibrium bicycle shares in two situations

With dedicated bus lane in major road				
s_{ij}^{cyc}	To A	To B	To C	To D
From A		0.068	0.180	0.180
From B	0.067		0.180	0.180
From C	0.179	0.179		0.263
From D	0.180	0.180	0.264	

Mixed bus and car lanes in major road				
s_{ij}^{cyc}	To A	To B	To C	To D
From A		0.069	0.175	0.175
From B	0.067		0.176	0.176
From C	0.175	0.174		0.263
From D	0.175	0.175	0.264	

Based on the numerical case with dedicated lanes, sensitivity analysis is conducted on five selected parameters: demand level (q_{ij}), value of user's time, average parking fee, bus fare, and unit car fuel cost. Here we examine the sensitivity of the optimized solution to these parameters. In each modified numerical case the value of one selected parameter is slightly varied from its original value by no more than 20%, with other parameters unchanged. When demand level is changed, all elements in the demand matrix (q_{ij}) are multiplied by the same factor.

In all the modified numerical cases, the resulting optimal lane widths are the same as those in the original case. Now we compare the sensitivity of total travel time and mode shares to changes in various parameters. Changes in hourly total travel time, bus share for OD pair A-B, and car share for OD pair A-B in response to varied parameters are plotted in figure 27, 28, and 29, respectively. Equilibrium bicycle shares for all OD pairs with the value of user's time (average parking fee) changed by -10% and +10% from its original value are shown in Table 22 and Table 23.

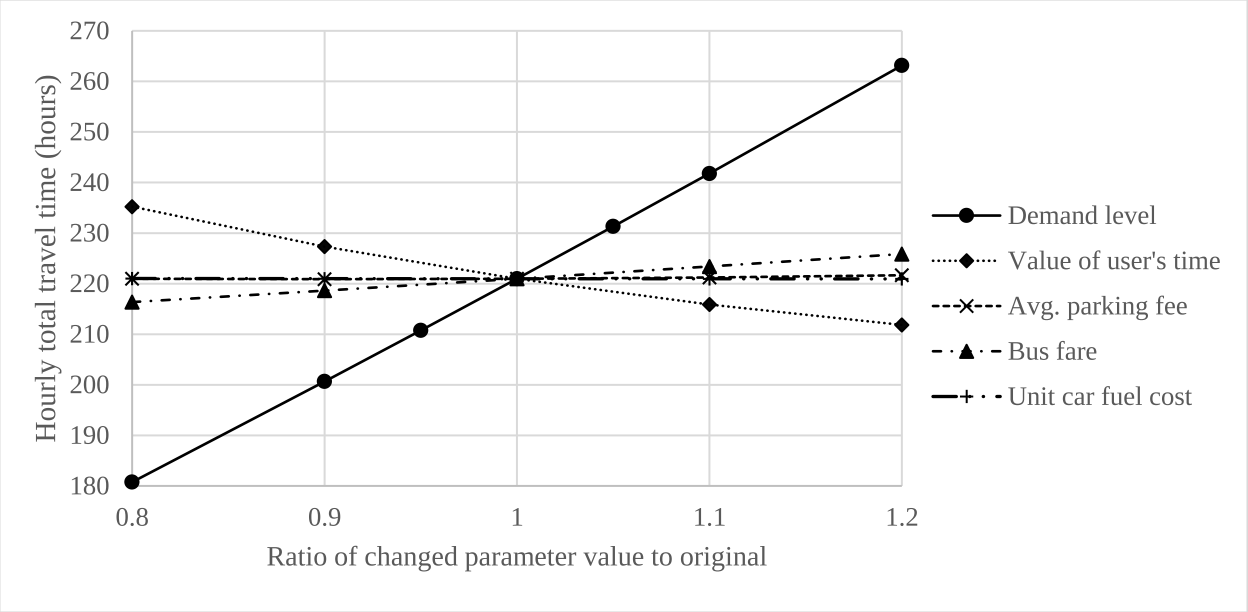

Figure 27: Changes in hourly total travel time in response to various parameter changes

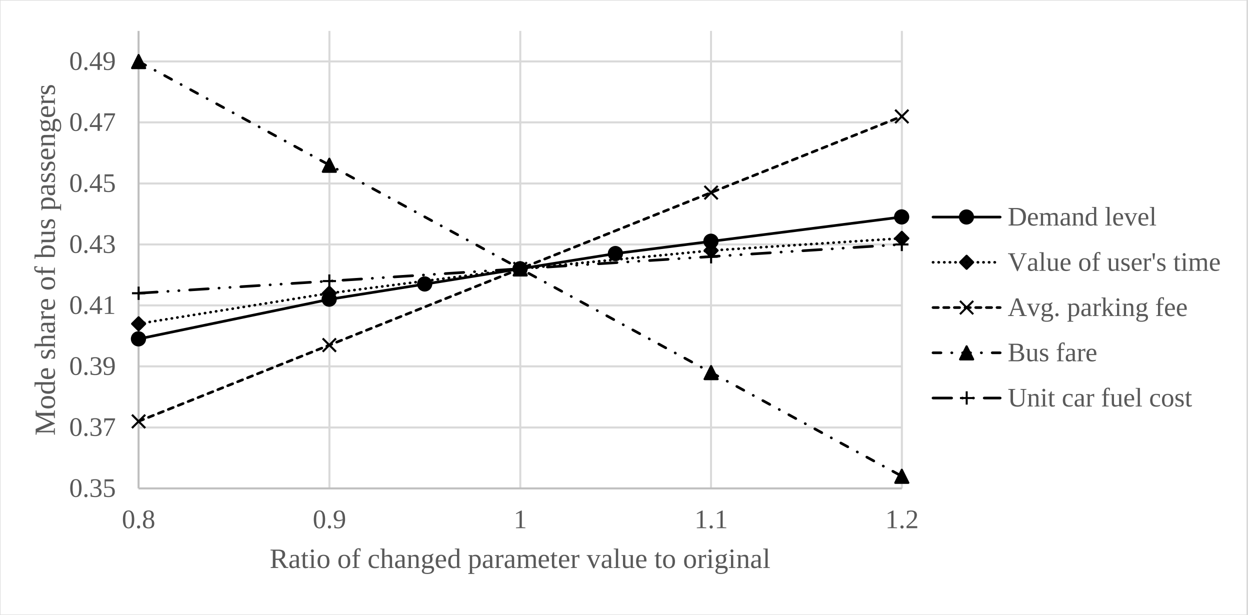

Figure 28: Changes in bus share in A-to-B travelers in response to various parameter changes

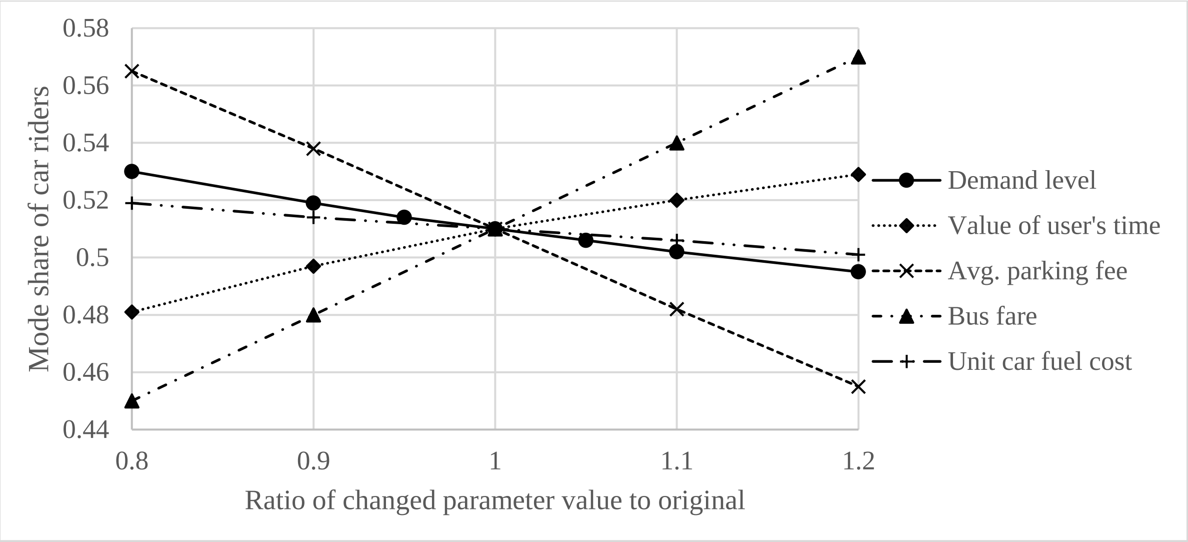

Figure 29: Changes in car share in A-to-B travelers in response to various parameter changes

Table 22: Equilibrium bicycle shares with different changes in value of user's time

With -10% value of user's time				
s_{ij}^{cyc}	To A	To B	To C	To D
From A		0.089	0.219	0.219
From B	0.088		0.220	0.220
From C	0.218	0.218		0.303
From D	0.219	0.219	0.305	

With +10% value of user's time				
s_{ij}^{cyc}	To A	To B	To C	To D
From A		0.052	0.146	0.146
From B	0.051		0.147	0.146
From C	0.146	0.146		0.226
From D	0.146	0.146	0.227	

Table 23: Equilibrium bicycle shares with different changes in average parking fee

With -10% average parking fee				
s_{ij}^{cyc}	To A	To B	To C	To D
From A		0.065	0.166	0.166
From B	0.064		0.167	0.167
From C	0.166	0.166		0.245
From D	0.167	0.166	0.246	

With +10% average parking fee				
s_{ij}^{cyc}	To A	To B	To C	To D
From A		0.071	0.194	0.194
From B	0.069		0.195	0.194
From C	0.193	0.193		0.282
From D	0.194	0.194	0.283	

Figure 27 explicitly shows that hourly total travel time under the optimized width configuration is most sensitive to changes in demand level, which is unsurprising. In fact, when demand level is varied by -20%, -10%, +10%, and +20%, total travel time changes by -18.2%, -9.2%, +9.4%, and +19.1%, respectively. It can be inferred that the average travel time per traveler in the system slightly decreases with the rising demand level, which can be attributed to the highly undersaturated traffic and the decrease in bus waiting time. (Figure 28 shows increase in bus share for OD pair A-B with higher demand level, which means higher bus frequency.) For other parameters, the value of user's time has the largest impact on total travel time. With a higher value of user's time, for bicyclists the disadvantage of being slower than the other two modes becomes more pronounced. This results in sharp reduction in bicycle share for all OD pairs (as shown in Table 23). With total demand unchanged, as more travelers choose cars and buses in the undersaturated traffic, total travel time is reduced. A higher bus fare leads to slight increase in total travel time by encouraging travelers between A and B to shift from buses to cars, whose dedicated lanes are more crowded than bus-exclusive lanes. The remaining two selected parameters have marginal effects on total travel time.

Figure 28 shows that the equilibrium bus share is most sensitive to bus fare changes, which fits the intuition that a higher bus fare discourages travelers from riding a bus. This effect is also reflected in Figure 29 with the equilibrium car share being most sensitive to bus fare changes as well. Bus and car shares are also sensitive to changes in average parking fee for a similar reason that a higher parking fee motivates more travelers to shift from cars to buses. In contrast, a higher unit car fuel cost poses a same-direction yet much weaker substitution effect on car and bus shares. A higher value of user's time increases both bus and car shares due to the sharp decrease in bicycle share. A higher demand level appears to attract more travelers from cars to buses, possibly attributable to higher traffic density in car-dedicated lanes. The marginal effect of the additional demand on increasing travel time by car is larger than that by bus.

Besides, Tables 22 and 23 show that equilibrium bicycle share is highly sensitive to value of user's time and moderately sensitive to average parking fee, respectively. Its sensitivity to other selected parameters is negligible.

Case II: A single two-direction road

In another numerical case, two demand nodes A and B are connected by a 2.5-mile road with two directions. In each direction the link has 3 car lanes, one bicycle lane, and one pedestrian lane, with a total width of 45 feet. Traffic parameters of lanes are given in Table 24.

Table 24: Traffic parameters of lanes – Case II

Lane types	Width range (ft)	Free flow speed (mph)	Jam density
Car lanes	$9 \leq w_l^{car} \leq 11$	$40[1 + (w_l^{car} - 10)/5]$	160 veh/mi
Bicycle lanes	$5 \leq w_l^{cyc} \leq 7$	$11[1 + (w_l^{cyc} - 6)/5]$	$800[1 + (w_l^{cyc} - 6)/5]$ cyc/mi
Pedestrian lanes	$7 \leq w_l^{ped} \leq 11$	$3.4[1 + (w_l^{ped} - 9)/10]$	$18000 w_l^{ped}/9$ ped/mi

Hourly travel demands are 3,600 for both A to B and B to A. Selected attributes and their corresponding parameters for computing total travel impedance are listed in Table 25. The lane configuration has a level of traffic stress (LTS) of 3 for bicyclists, according to Mekiura et al. (2012) For each mode, its travel time through the road is subject to change during iterations for the equilibrium mode shares. The constant coefficient β_{ASC} is 0 for car, 0.74696 for bicycle, and 0.47018 for walking. All listed attribute and coefficient values are unaffected by the direction of travel.

Table 25: Parameters for impedance computation – Case II

Attributes of modes (c)	**Attribute values (x)**	**Coefficient values (β)**
Travel time of a car (minutes)	Changeable in iteration	0.01144
Travel time of a bicycle (minutes)	Changeable in iteration	0.03790
Travel time of a pedestrian (minutes)	Changeable in iteration	0.05325
Parking cost by car ($)	2	0.09908
Other travel cost by car ($)	2.5	0.22579
Level of traffic stress for bicycles	3	0.18724
Level of traffic stress for pedestrians	3	0.13112

In both directions of this road, the objective is to optimize lane widths for all three modes so that hourly total travel time of all travelers is minimized. A given mode has the same lane width in both directions. With a search step of 0.5 ft for widths of bicycle lanes and pedestrian lanes, all feasible combinations of lane widths are enumerated for finding the minimal total travel time. When evaluating each combination of widths, for both OD pairs the shares of cyclists and pedestrians start from 0.15 and 0.02, respectively. The stopping criterion for iterations is the same as in Case I.

In the results, when the bicycle lane is at its upper-bound width (7 ft) and the pedestrian lane is at its lower-bound width (7 ft), the hourly total travel time attains its minimum of 474.614 hours. The corresponding width of each car lane is 31/3 ft. In this configuration of lane widths, equilibrium mode shares of car, bicycle, and walking are 0.700, 0.265, and 0.035 respectively.

3.4 Conclusion

A bi-level model is proposed for optimizing lane width allocation in roadways to minimize total travel time of system users. Given demand, mode and traffic parameters in the system, the lower-level iteratively uses a logit mode choice model to obtain equilibrium mode shares for all OD pairs, and thereby computes hourly total travel time for a certain candidate combination of lane widths. With a fixed total width of roadways and limited possible values of lane widths, the upper-level model searches for the combination of lane widths that minimizes total travel time. The model is demonstrated in two numerical cases: one in a simple eight-link intersection, and the other in a single two-directional road. In the first numerical case where three modes -- bus, car, and bicycle – are considered, the minimal total travel time is obtained when widths of bus lanes and bicycle lanes reach their upper bounds. The effects of switching dedicated lanes to mixed lanes on optimized results are examined. Sensitivities of minimized total travel time and equilibrium mode shares to various parameters are compared. A higher value of user’s time strongly discourages travelers from slow modes such as bicycle. Mode substitution effects between bus and car can be observed with changes in bus fare, average parking fee, and unit car fuel cost. In the second numerical case, car, bicycle, and walking are considered with a different version of impedance function. The total travel time is minimized at the upper-bound bicycle lane width and the lower-bound pedestrian lane width.

This preliminary model could be improved in the following ways:

1) A detailed solution method could be proposed for solving this optimization problem in a large-scale roadway network with a large number of optimizable width parameters. This method could be heuristic, most likely based on simulated annealing.

2) With multiple intersections in a roadway network, effect of traffic signals on traffic flow and travel time could be considered.
3) More complicated relations between lane width and traffic parameters can be explored, with possible help from driving simulator results and field observations.
4) In addition to total travel time, the objective function could consider costs, air quality, safety and energy consumption.

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