ASSESSING THE IMPACT OF BICYCLE INFRASTRUCTURE AND MODAL SHIFT ON TRAFFIC OPERATIONS AND SAFETY USING MICROSIMULATION

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Katherine E. Lee

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COMMITTEE MEMBERSHIP

TITLE:	Assessing the Impact of Bicycle Infrastructure and Modal Shift on Traffic Operations and Safety Using Microsimulation
AUTHOR:	Katherine E. Lee
DATE SUBMITTED:	March 2022
COMMITTEE CHAIR:	Anurag Pande, Ph.D Professor Cal Poly Department of Civil and Environmental Engineering
COMMITTEE MEMBER:	Shams Tanvir, Ph.D Associate Professor Cal Poly Department of Civil and Environmental Engineering
COMMITTEE MEMBER:	Amirarsalan Molan, Ph.D Assistant Professor University of Mississippi Department of Civil Engineering

ABSTRACT

Assessing the Impact of Bicycle Infrastructure and Modal Shift on Traffic Operations and Safety Using Microsimulation

Katherine E. Lee

A transportation system designed to prioritize the mobility of automobiles cannot accommodate the growing number of road users. The Complete Streets policy plays a crucial part in transforming streets to accommodate multiple modes of transportation, especially active modes like biking and walking. Complete streets are referred to as streets designed for everyone and enable safety and mobility to all users. A strategy of complete streets transformation is to connect isolated complete street segments to form a complete network that improves active mobility and public transit ridership.

This research assessed the impact of efficiently and equitably connecting and expanding the biking network using dedicated lanes on the safety and operation of the network in Atlanta, Georgia. These connections are aimed at increasing the multimodal use of the streets in midtown and downtown Atlanta and achieving the mobility and public health goals through the integration of various modes of travel. The evaluation was done by modeling a well-calibrated and validated network of Midtown and Downtown Atlanta in VISSIM using existing travel demand and traffic design conditions (i.e., the baseline or Scenario 0). A total of three different conditions: existing, proposed, and alternative conditions, were modeled to see the effectiveness of bike infrastructure design improvement and expansion. Three scenarios were then modeled as variations of modal demand of the different condition models. Scenarios modeled are based on input from the City and Community stakeholders. Using the trajectory data from microsimulation, the surrogate safety assessment model (SSAM) from FHWA was used to analyze the safety effect on the bike infrastructure improvement and expansion. Results of this study showed a positive impact of complete streets transformation on the streets of Midtown and Downtown Atlanta. These impacts are quantified in this thesis.

Keywords: Complete streets, VISSIM, microsimulation, traffic simulation, large simulation network, measures of effectiveness, street transformation, bike networks, surrogate safety assessment model, SSAM

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1. INTRODUCTION

The transportation system in the United States has primarily prioritized the mobility of motored vehicles. The focus on motored vehicles has resulted in many issues such as pollution, congestion, socioeconomic disparities, and inefficiency in the use of scarce resources such as land and energy, to state a few. Not only that, automobile-centric designs have posed barriers to pedestrians, bicyclists, and public transportation users, limiting active transportation opportunities (U.S. Department of Transportation, 2015). In addition to the automobile focus, economies and populations of major cities continue to increase, leading city streets that focus on single-occupancy vehicles to not be able to support the needs of businesses, tourists, and residents. Streets will need to be made safe and convenient for all people, including children, the elderly, and the disabled. The implementation of the “complete streets” policy will deemphasize the dominance of automobiles and transform streets to accommodate multimodal travel like biking and walking.

According to a survey recently done, 66% of Americans want more transportation options so they have the freedom to choose how to get from one place to another. Currently, 73% feel like they do not have a choice but to drive as their main mode of transportation, and 53% would like to spend less time in the car (Transportation for America, 2010). For the implementation of complete streets, public involvement is key in the planning and decision-making process. The process would involve communication between the citizens and the government to allow agencies to acknowledge, inform, and include the public while using feedback to develop relationships within the community and build better transportation projects. Minimal participation from the public will lead to a lack of support from the community, resistance from stakeholders, and outcries from the public that could end up in costly project delays. The Safe, Accountable, Flexible, Efficient, Transportation Equity Act: A Legacy for Users (SAFETEA-LU) mandated the usage of visualization techniques for describing plans to the public within the transportation planning process to encourage interactive transportation decision making (United States Congress, 2005). In the case of this research, three-dimensional visuals will be used to display project scenarios, quantitative analysis, and results.

1.1 STUDY AREA: ATLANTA, GEORGIA

Home to Coca-Cola, Home Depot, and The Weather Channel, Atlanta, Georgia, has a population of 506,811 according to the 2019 United States Census Bureau (U.S. Census Bureau, n.d.). With the city being named the "next Hollywood" and being ranked third in the nation for U.S. film production, Atlanta attracts many new residents, businesses, and tourists which results in tremendous growth. In addition to being a film attraction, the local airport is also located just three hours by flight from most major American cities, making it a frequent stop or layover to plane riders which increases Atlanta's population every day. Within the heart of downtown Atlanta resides the main campuses of Georgia State University and Georgia Institute of Technology. With a total of more than 81,000 students enrolled in both universities, safe transportation facilities are needed to enhance comfort and safety for all road users. For a city the size of Atlanta to be efficient and livable, urban transport systems should be able to accommodate all modes of travel such as walking, biking, and transit more effectively. One such method is to implement the "complete streets" policy to transform streets right-of-way to accommodate the multiple modes of travel, including especially the active modes, such as walking and biking.

The study area, shown in Figure 1, consists of the entirety of downtown Atlanta (4.015 square miles). Within the study area, freeways like Interstate 85 (I-85), Interstate 75 (I-75), Route 10, and Route 154 serve as important routes of entry and exit into the downtown area. The study focuses on the bike network in Atlanta metropolitan region due to multiple factors. The first being as such that biking and shared micromobility are rapidly growing as modes of travel in Atlanta and both modes of travel benefit from dedicated bike lanes. The second is that having dedicated bike lanes will ensure safety and comfort for all road users, not just the bicyclists. Third, cycling infrastructure is typically the least well developed amongst other facilities and services dedicated to various modes of transportation. The last factor would be behaving improved cycling infrastructure to encourage people to ride a bike, which promotes clean energy, better public health, and a cleaner environment.

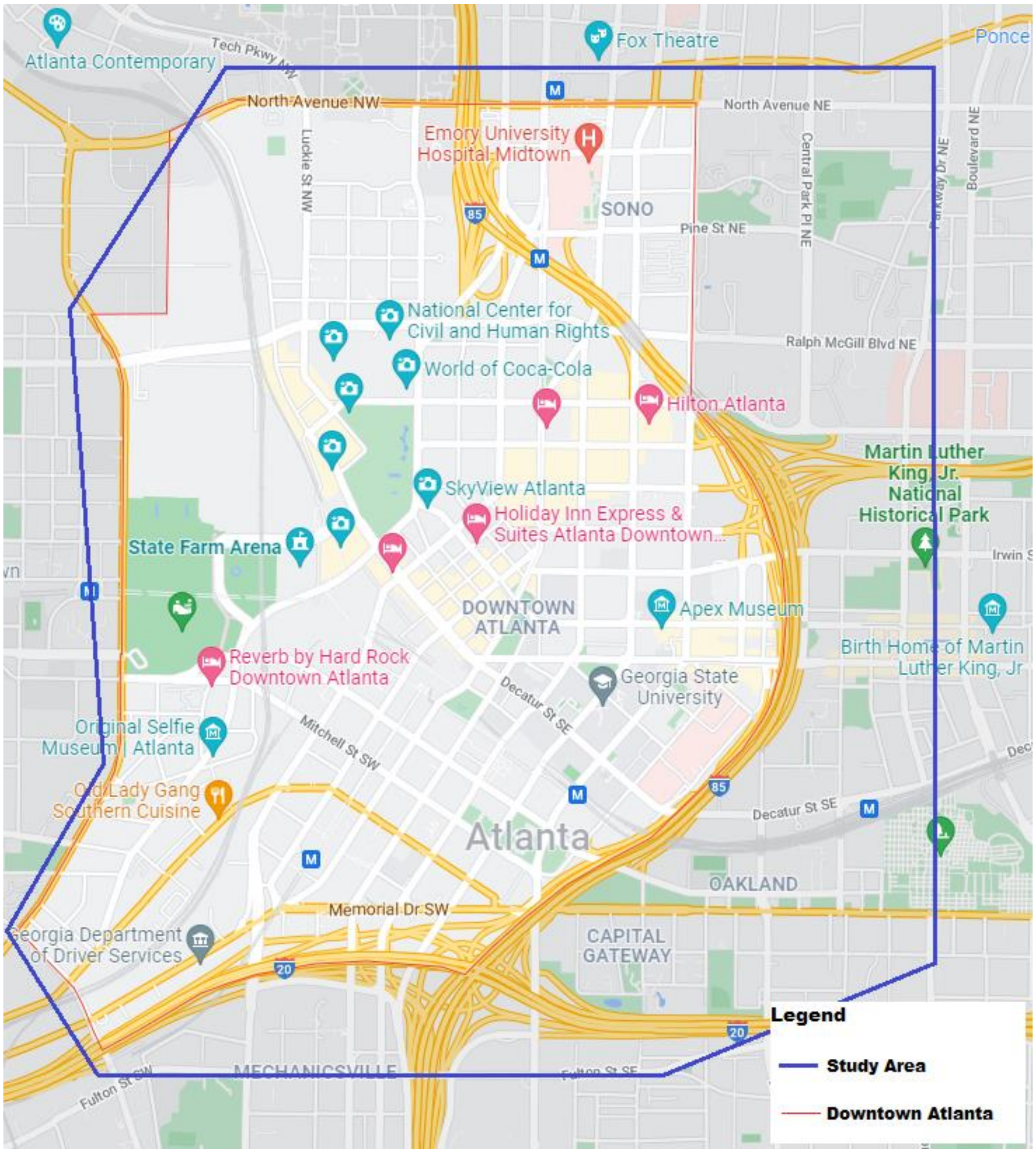

Figure 1. Study Area Map[1]

1.2 STUDY OBJECTIVES

Microsimulation models aid transportation engineers, designers, and planners to assess the impact of different alternatives on existing systems or networks. Using microsimulations can help visualize and evaluate the patterns of the behavior of bicyclists and vehicular traffic in the network. Overall, the model will support the evaluation of the effectiveness of street design changes at varying

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- [1] Google Maps

demand scenarios and for visualizing the movements of individual vehicles, bicyclists, and pedestrians.

The objectives of this study are:

a) Utilize a microsimulation model to visualize and evaluate patterns of behavior of bicyclists and vehicular traffic in the network for existing conditions.
b) Model the efficiently and equitably connected proposed bicycle network using a microsimulation model to assess the operational impacts.
c) Assess potential safety impacts of the changes to the network and possible modal shift scenario.

1.3 REPORT ORGANIZATION

The rest of this document presents a literature review of relevant works done in the past, a detailed description of the network's modeling procedure, an analysis of bicyclist and vehicular traffic behavior, and conclusions. In Chapter 2, the literature review will provide an introduction on traffic simulation, using PTV VISSIM as the microsimulation model, information on complete streets, and information about how bike users are affected by complete streets transformations. Chapter 3 outlines the development of the model, detailing the data collection process, calibration, and validation for the base conditions. Chapter 4 describes the evaluation of the effectiveness of streets design changes at varying demand scenarios. Chapter 5 summarizes the conflicts and safety effects of bike infrastructure improvements along with potential shifts in mode choices. Chapter 6 summarizes the conclusions and provides recommendations for future work.

2. LITERATURE REVIEW

This section of the document reviews the simulations applications and potential advantages and disadvantages of microsimulation. It also discusses complete streets and its policy, tactical urbanism within downtown, and the development of large-scale microscopic traffic simulation models.

2.1 TRAFFIC SIMULATION

The constant increase in the number of cars within cities causes transportation problems that make it necessary to optimize the road network to satisfy the transportation demands of the city (Dorokhin, Artemov, Dmitry, Alexey, & Starkov, 2020). Simulation modeling is an increasingly popular and effective tool used to analyze the behavior and interactions of traffic systems. Traffic simulation is the dynamic representation of a traffic system achieved by building a computer model and moving it through time. The purpose of these models is to optimize the use of resources to organize the effective functioning of the transportation system and to accurately recreate traffic as observed and measured on street and can be applied to plan and manage the traffic within a certain read network (Azlan & Rohani, 2017). They can provide an understanding of cause-and-effect relationships and satisfy a wide range of applications, including evaluation of alternative treatments, testing new designs, safety analysis, training personnel, and as an element of the design process. Modern simulation models are based on random vehicular movements that aim to mimic driver behaviors. Therefore, simulation models can provide an answer to “what-if” questions to aid system designers in assessing the impact of various changes on existing systems in a cost-effective way (Ben-Akiva, Koutsopoulos, Mishalani, & Yang, 2000).

Principally, simulation models focus on three output values to solve traffic problems (Friedrich, 2015). The first output is the traffic flow where the alternative routes can be identified based on the number of vehicles. The second output is the network element. Network elements in traffic simulations consist of a link, merge, roadway geometric design, and other elements of the road

(Barcello, 2010). The last output is the skim category. This is when simulation models are used to estimate the time and cost of travel. This is typically used when the assessment of traffic improvement is needed to be measured (Azlan & Rohani, 2017).

2.2 SIMULATION MODEL CHOICES

There are three classifications of traffic simulation models: microscopic (high fidelity) modeling, macroscopic (low fidelity) modeling, and mesoscopic (mixed fidelity) modeling. Microscopic modeling is based on characteristics of various vehicle movements such as cars, buses, motorcycles, and so on in the traffic flow and describes how traffic states evolve (Transportation Research Board, 2015). These models are typically used for short-term and congestion-related issues (Rousseau, Scherr, Yuan, & Xiong, 2009). Microscopic modeling aims to collect data parameters, such as flow, density, speed, travel, and fuel consumption, just to name a few. This type of modeling is typically based on the car-following model, lane-changing models, and gaps of the individual drivers (Azlan & Rohani, 2017). Microsimulation offers benefits in accuracy, clarity, and flexibility. It can provide a thorough real-time visual display to illustrate traffic operations in a readily understandable manner. These models are effective in evaluating heavily congested conditions, complex geometric configurations, and system-level impacts of proposed transportation improvements that are beyond the limitations of other tool types (Federal Highway Administration, 2020). Compared to macroscopic models, microscopic models must be kept at a reasonable network size and modeling period due to the high number of data inputs, calibration and validation efforts, and computing power for modeling and analysis (Rousseau, Scherr, Yuan, & Xiong, 2009).

Macroscopic modeling describes the intersections at a low level of detail (Rathi & Nemeth, 1996) and is based on the deterministic relationships of the flow, speed, and density of the traffic stream. The simulation in a macroscopic model takes place on a section-by-section basis rather than by tracking individual vehicles. Macroscopic simulation models were originally developed to model traffic in distinct transportation subnetworks, such as freeways, corridors (including freeways and parallel arterials), surface-street grid networks, and rural highways (Federal Highway

Administration, 2020). In this type of model, the traffic stream is represented in an aggregate measured in terms of characteristics like speed, flow, and density.

Mesoscopic modeling describes the analyzed transportation elements in small groups and is a combination of microscopic and macroscopic modeling. As such, mesoscopic models provide less fidelity than microsimulation tools but are superior to the typical planning analysis techniques (Federal Highway Administration, 2020). The hybrid model includes a routable network similar to macroscopic modeling (with a supplementary origin-destination matrix), while also incorporating more detailed operational elements of the transportation network to better estimate travel time based on traffic operations similar to a microscopic model. In other words, they generally represent most entities at a high level of detail but describe their activities and interactions at a much lower level of detail than would a microscopic model (Lieberman & Rathi, 1975).

Simulation models are also classified as deterministic or stochastic by the process represented by the model. Models that have no random variables and perform the same way for a given set of initial conditions are called deterministic models. Models that have processes that include probability functions and introduce randomness are called the stochastic model. The selection of a model mainly depends on the purpose of the analysis and the complexity involved. Microscopic models are useful for preliminary engineering and evaluating alternatives at the local or corridor level. A mesoscopic model can be used to analyze homogenous transportation elements in smaller groups, such as vehicle platoon dynamics and household-level travel behavior. For travel demand modeling, the macroscopic planning model would be the best option. Macroscopic planning models are also suited for conceptual network planning and design and performing analysis at a regional or state level (Lieberman & Rathi, 1975).

2.3 ADVANTAGES AND DISADVANTAGES OF TRAFFIC SIMULATION

Traffic simulation models are powerful tools as they provide relatively fast, inexpensive, and risk-free evaluation environments (Park, Yun, & Choi, 2004). Not only does it account for a variety of different scenarios that cannot be tested in the real world, but it also provides different network performance measures. This has become a widely accepted and useful tool in transportation engineering applications.

Each traffic simulation model has its strengths and weaknesses. An article written by Park, Yun, and Choi provides a summary of the pros and cons of the four traffic simulation models: CORSIM, PARAMICS, SIMTRAFFIC, and VISSIM. CORSIM is a comprehensive microscopic traffic simulation is developed for the Federal Highway Administration (FHWA) and is applicable to surface streets, freeways, and integrated networks with a complete selection of control devices (Corridor Simulation (CORSIM/TSIS), 2020). The Traffic Software Integrated Shell (TSIS) is an integrated development environment for CORSIM simulation. CORSMIN networks use a link-node structure and models yield signs, stop signs, and traffic signals. This simulation model is capable of simulation pretimed and actuated signal controllers allowing one signal plan to be implemented per simulation period. On contrary, CORSIM has very limited capabilities to assess ITS technologies such as variable messages. As CORSIM generated link-based outputs, it is ultimately difficult to obtain certain route-based measures such as travel time (Qi, 2004).

PARAMICS is a 3D traffic simulation developed by Quadstone Ltd. that provides microscopic, time-stepping, and scalable traffic simulation. The networks built in PARAMICS are based on a link-node structure and each route of each vehicle is defined through an assignment. The PARAMICS model also provides a graphical user interface to build networks and to watch the simulation results and animation. One weakness that PARAMICS have is that building actuated control logics are much more difficult since the software does not allow dual-ring concepts or NEMA control concept.

SIMTRAFFIC is developed by Cubic Trafficware Inc. and is a companion product to SYNCHRO, a software package for modeling and optimizing traffic signal timings, for performing microscopic simulation and animation. SIMTRAFFIC is a powerful, easy-to-use software application that performs microsimulation and animation of vehicular and pedestrian-related traffic (Synchro Studio, 2015). This software uses a link-node structure and only models urban networks with signalized and unsignalized intersections. Although SIMTRAFFIC is easy to use, it has many very limited capabilities to access ITS technologies such as variable message signs. This simulation model is also not a multimodal simulation tool and is only able to run SYNCHRO input files.

VISSIM, developed by PTV Group, is the most robust software for microscopic, mesoscopic, and a combination of both in a hybrid simulation. This simulation model is microscopic and is based on time step and behavior. VISSIM is proven to be the world's standard for traffic and transport planning as it gives a realistic and detailed overview about the status quo of the traffic flow and impacts, with the possibilities to define multiple what-if scenarios (Why is PTV Vissim the global leader in simulation?, n.d.). The networks are based on a link-connector structure, instead of the traditional link-node structure. Some weaknesses of VISSIM include not having a built-in actuated controller program, entering conflicting movements are cumbersome and is time-consuming, and does not produce HCM compatible output (Liu, 2019).

In conclusion from the article, VISSIM and PARAMICS showed relatively consistent performance trends to all signal timing plan cases while SIMTRAFFIC and CORSIM produced inconsistent performance trends. For this study, VISSIM was chosen due to the software's ability to analyze multimodal traffic, such as bicycles, automobiles, and pedestrians as well as transit operations under constraints such as lane configuration, traffic composition, traffic signals, transit stops, and other similar criteria (VISSIM 2021 User Manual, 2021). VISSIM also allows the interaction of different modes of transportation, including bicycles, transit, automobiles, and pedestrians. The flexibility of modeling interaction between the different modes of transportation is ideal to evaluate the network changes in our study. However, some weaknesses of utilizing traffic simulation include unrealistic driver behavior, the amount of time needed to develop a good, functioning simulation model, difficulty in analyzing simulation results, and computer limitations.

2.4 LARGE-SCALE MICROSCOPIC TRAFFIC SIMULATION MODEL

With the development of new traffic simulation models such as AIMSUN, Paramics, and VISSIM, it is now more convenient to simulate increasingly larger networks with complex scenarios that involve intelligent transportation system (ITS) elements, incident scenarios, and highway construction, to name a few. But as the simulation of large networks is like those of smaller ones on the abstract level, it poses some practical (and sometimes theoretical) difficulties concerning the development and calibration of models (Jha, et al., 2004). Some difficulties include the high level of uncertainty in modeled systems due to the necessity of a large amount of input data either not being available or observable, making the process of calibration and validation a bit challenging.

Bartin et al. presented the process of building a large-scale traffic simulation model on PARAMICS with the use of multi-source data for its calibration and validation process via the real-world case study. The case study was done on the reconstruction of one of the bridges located in Newark Bay Hudson County Extension (NBHCE) of New Jersey Turnpike (NJTPK), a tolled highway. The base model of the study area consists of 3,784 links, 2,393 nodes, 133 zones, and 106 traffic signals. Building the model took many years to complete due to the complexity of the network and had been modified multiple times for specific analysis to include various potential alternative routes. The calibration and validation process was performed through an iterative process where when each component of calibration is performed, it impacts another component that is already calibrated. By doing this process, higher accuracy would be expected when comparing the simulation model outputs with the observed values. Overall, the paper stated that there are inherent difficulties in building, validating, and calibrating large-scale microscopic traffic simulation models such as constructing the network in the correct scale, inputting the details of link geometry and capacity, adding various traffic control signs and devices, and the details of their turning movement priorities, selecting the number and the location of demand zones and their connections to the traffic network, estimating and converting an origin-destination (O-D) demand matrix, acquiring the necessary data for validation and calibration process and the amount of computational time (Bartin, Ozbay, Gao, & Kurkcu, 2018).

Another study done by Jha et al. presented the development and calibration of a microscopic traffic simulation model using MITSIMLab. The model was done on the entire Des Moines Area and is intended to complement the existing regional planning model which consists of approximately 200 square miles of various types of roads including freeway, principal arterials, and other major roads. In total, the Des Moines model consists of 1,479 nodes, 3,756 links, 5,479 segments, 10,657 lanes, 1,979 sensors, and traffic signals at about 250 intersections. With this, 400 traffic analysis zones (TAZs) were identified and translated to approximately 150,000 O-D pairs. Parameters and inputs such as parameters of the driving behavior model, route choice model, O-D flow, and habitual travel times were calibrated in this model. Ideally, all parameters would be calibrated together, but due to the large scale of the model, driving behavior was calibrated separately from the others. The calibration process for the remaining parameters was done using an iterative process (Jha, et al., 2004). Overall, the article stated that calibration method and validation results were promising but see the need for further research to improve computational performance.

2.5 COMPLETE STREETS

Roads that are built for everyone are defined as “complete streets”. They are designed and operated to prioritize safety, comfort, accessibility to various designations for all people who utilize the streets, especially to those with disabilities, older adults, and young children. Complete streets typically include sidewalks, bike lanes, bus lanes, comfortable and accessible public transportation stops, frequent and safe crossing opportunities, median islands, accessible pedestrian signals, curb extensions, narrower travel lanes, roundabouts, and more (What are Complete Streets?, n.d.).

Figure 2 is an example of a complete urban street. This diagram shows the unity of various modes of transportation such as biking, walking, riding the bus, and by car. In addition, crosswalks are paved, pedestrian signals are implemented at the intersection for pedestrian safety, and sidewalks are wide enough to provide space for people to walk and to sit.

Figure 2. Illustration of Complete Streets[2]

2.6.1 Benefits of Complete Streets

Numerous studies have highlighted various benefits of complete streets; however, most depend on the local context. Overall, complete street networks bring a wide variety of direct and indirect benefits such as more livable communities, fewer energy consumptions, improvement in equity, safety, public health, and lower greenhouse gas emissions. In an article by Shu et al., they identified that there was a 37% increase in pedestrian and a decrease of 26% in emission-weighted traffic volume as a result of complete street implementation. In an article published by the U.S. Department of Transportation (USDOT), complete streets conversion reduces motor vehicle-related crashes and pedestrian risk as complete streets promote walking and bicycling by providing safer places to achieve physical activity through transportation. With a well-designed bicycle-specific infrastructure, bicycle risks will also be expected to reduce. One study found that 43% of people reporting a place to walk were significantly more likely to meet current

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[2] *https://www.danielrturner.com/portfolio/new-jersey-complete-streets-design-guide/*

recommendations for regular physical activity than were those reporting no place to walk (Complete Streets, 2015).

2.6.2 Expansion and Improvement in Bicycle and Pedestrian Infrastructure

Complete Streets Policies are aimed to transform streets to accommodate multiple modes of travel, especially the active modes, such as walking and biking. As this study focuses on the bike network in Atlanta metropolitan area, it is important to understand how biking and pedestrian infrastructures make the streets more “complete”. Focusing on Atlanta, biking and shared micromobility are rapidly growing modes of travel throughout the city and both travel modes will benefit from dedicated bike lanes. In addition, studies have shown that dedicated bike lanes will ensure safety and comfort for all roads and improved cycling infrastructures will encourage more people to ride a bike, which also promotes clean energy, better public health, and a cleaner environment.

According to the USDOT, expanding and improving bicycle and pedestrian infrastructure means ensuring that a network of infrastructure is in place to make bicycling or walking viable modes of travel. This also means making sure that the infrastructure is safe and comfortable to be used. Some examples of bicycling and pedestrian infrastructure include bike lanes, bicycle parking and storage facilities, intersection treatment for bicycles, paved shoulders, pedestrian-and bicyclist-scale lighting, trails, shared-use paths, etc.

Studies have found that bike users are most affected by complete street transformations. For example, bicycle and pedestrian infrastructure location and type can affect health outcomes. Bike riders and pedestrians who use pathways next to heavily congested roadways may experience increased exposure to vehicle emissions. But with the transformation to include bicycle infrastructure that physically separates bicyclists from vehicles can help increase bicycle can increase public health, increase bicycle use, especially by less confident riders, and support safe travel in some applications (Pucher & Buehler, City Cycling, 2012) (Lusk, et al., 2011). Aside from that, Carter et al. compared the level of service (LOS) of each type of road user after complete street interventions and showed that bicycle LOS was improved more than any other mode (Carter, et al., 2013). A similar analysis was done by Elias, it also indicated that designated bike lanes significantly improved bike LOS while LOS of pedestrians who have already had sidewalks were not much affected by complete street elements (Elias, 2011). While bicycle LOS and connectivity were used for the evaluation of bike networks, few studies have considered the aspects of transit access, multimorbidity, and equity.

2.6.3 Bike Lanes

Bicycling is one of the most energy-efficient modes of transportation since it emits no pollution, needs no external energy source, and it effectively moves people from one place to another without adverse environmental impacts (AASHTO, 2012). With complete streets transformation, designated bike lanes are highly encouraged to be implemented as it promotes safety on the road and comfortability to bicyclists. FHWA states that some of the safety benefits of bike lane additions can reduce up to 49% for total crashes on urban 4-lane undivided collectors and local roads, and 30% for total crashes on urban 2-lane undivided collectors and local roads (Bicycle Lanes, 2022).

There are four classifications of bike lanes: Class I, Class II, Class III, and Class IV, each having its characteristics. Class I bike lanes are typically identified as a path. According to Caltrans' Guide to Bikeway Classification, Class I bikeways are facilities with exclusive right of way for bicyclists and pedestrians, away from the roadway and with cross flows by motor traffic minimized (Caltrans, 2017). Typically, this bike classification can be found in recreational areas such as the park, school areas, along canals and rivers, to list a few. The second bikeway classification is Class II. Class II, also known as conventional bikeways, are typically found on streets with more than 3,000 motor vehicle average daily traffic, on streets with a posted speed of more than 25 mph, and streets with high transit vehicle volume (NACTO, 2011). These types of bike lanes are defined by pavement striping and signage to delineate a portion of a roadway for bicycle travel (Caltrans, 2017). Conventional bike lanes also bring in various benefits to bike riders and other road users such as increasing the comfort and confidence level of bicyclists on busy streets, having a separation between bicyclists and automobiles, increasing the predictability of bicyclist and motorist positioning and interaction and visually reminding motorists and bicyclists' right to the street (NACTO, 2011). Class III, also known as bike routes or bicycle boulevards, are identified with bike route signs and optional shared roadway markings (sharrow) along the roadway. These bikeways are preferred routes that are designated for bicyclists on streets shared with motor traffic not served by dedicated bikeways. Class IV bikeways are often referred to as cycle track or protected bike lanes as it is physically separated from motor traffic with vertical features such as flexible posts, inflexible barriers, or on-street parking. The physical separation of motor vehicles and bicycles can reduce the level of streets, improve comfort for all types of bicyclists, and contribute to an increase in bicycle volumes and mode share (Caltrans, 2017).

2.7 SURROGATE SAFETY ASSESSMENT MODEL (SSAM)

The SSAM is a software application developed to automatically identify, classify, and evaluate traffic conflicts in the vehicle trajectory data output from microscopic traffic simulation models (U.S. Department of Transportation Federal Highway Administration, 2021). A conflict is defined as an observable situation in which two or more road users approach each other in time and space to such an extent that there is a risk of collision if their movement remains unchanged (Gettman & Head, 2002). In a study done by David Lemcke et al., the safety performance can be examined through analysis of surrogate measures of safety, such as conflicts identified using post encroachment (PET) or time-to-collision (TTC). Surrogate safety parameters can be extracted using a vehicle, bicycle, and/or pedestrian trajectories obtained from microsimulation software using SSAM (Lemcke, Riffle, Russo, & Smaglik, 2021). However, in VISSIM, trajectory files are generated for the whole network per selected simulation; there is no option in SSAM to sort conflicts by vehicle type. Overall, SSAM is a promising approach to assessing the safety of new facilities, innovative designs, or traffic regulation schemes (Preston & Pulugurtha, 2021). While the potential conflicts could be reasonably predicted using SSAM (Muley, Ghanim, & Kharbeche, 2018), the accuracy of the safety assessment depends on the microscopic traffic simulation model used to generate vehicle trajectory data (Vasconcelos, Neto, Seco, & Silva, 2014).

2.8 CONCLUSIONS FROM LITERATURE REVIEW

The literature review provides preliminary information on the development of traffic simulation models and complete streets strategies. Complete streets policies play an integral role within the community as it transforms existing streets to be more “complete”. Having complete street networks brings in a wide range of direct and indirect benefits such as more livable communities, less energy consumption, lower greenhouse gas emissions, and enhanced public fitness and health. Bicyclists showed to be positively impacted by bicycle infrastructure expansions and improvements, which are elements of complete street transformation. Microsimulation allows for detailed modeling and visualization of the transportation network. The simulation approach allows large-scale networks to be analyzed and for studying network-wide impacts of complete street strategies. In addition to detailed modeling, SSAM would be used to analyze conflicts and the safety effects of the implementation and expansion of bike infrastructure within the study network. Although SSAM is not the primary focus of this thesis, it still plays a crucial role in evaluating the overall effect of the complete bike networks. Our study aims to connect and expand the biking network using dedicated lanes while also identifying streets that can be designed as complete streets efficiently and equitably.

3. NETWORK MODELING

Georgia Institute of Technology worked with various stakeholders to obtain the base network of Midtown and Downton Atlanta. Shapefiles and other data sets were collected to build a base map on ArcMap. The study area was concluded to cover all Downtown Atlanta and most of Midtown due to signalized intersection locations and was modeled in VISSM. Signal timing and traffic volumes were provided by the City and included in the Synchro network which was provided by a Community stakeholder. To accurately replicate the most congested period within Atlanta, Georgia, the network was modeled with weekday PM peak hour travel demand. This section explains the network modeling procedure, calibration, and validation. Figure 3 is a visualization, provided by Georgia Institute of Technology, of all signalized intersections within the study. Note that the region shown in Figure 3 is larger than the Midtown and Downtown modeled in VISSIM.

Figure 3. Signalized Intersections Within Study Area

3.1 NETWORK CREATION

3.1.1 Road Network

The City of Atlanta worked with Kimley-Horn to provide us with the Synchro base network. Within the network, signal timing, lane geometry, speed limits, and traffic counts were embedded within the base network. The general lane geometrics included both automobiles and bike lanes, but there was no clear differentiation between vehicle and bike counts nor did the Synchro network classify the existing bike lanes within the existing network. The complete network consisted of 214 intersections and 3,700 links resulting in a total length of 757,361 feet (143.5 miles) in the network shown in Figure 4. Out of the 214 intersections in the study area, approximately 207 of the intersections were pretimed, 5 intersections were all-way stop, and 2 were two-way stop intersections. As the primary focus of the model is to evaluate biking infrastructure expansion and improvements within Downtown and Midtown, freeway mainline segments were not included in the model. In addition to parking lots, off-ramps, and on-ramps to the regional freeways that are connected to downtown are served as origins and destinations in the VISSIM model.

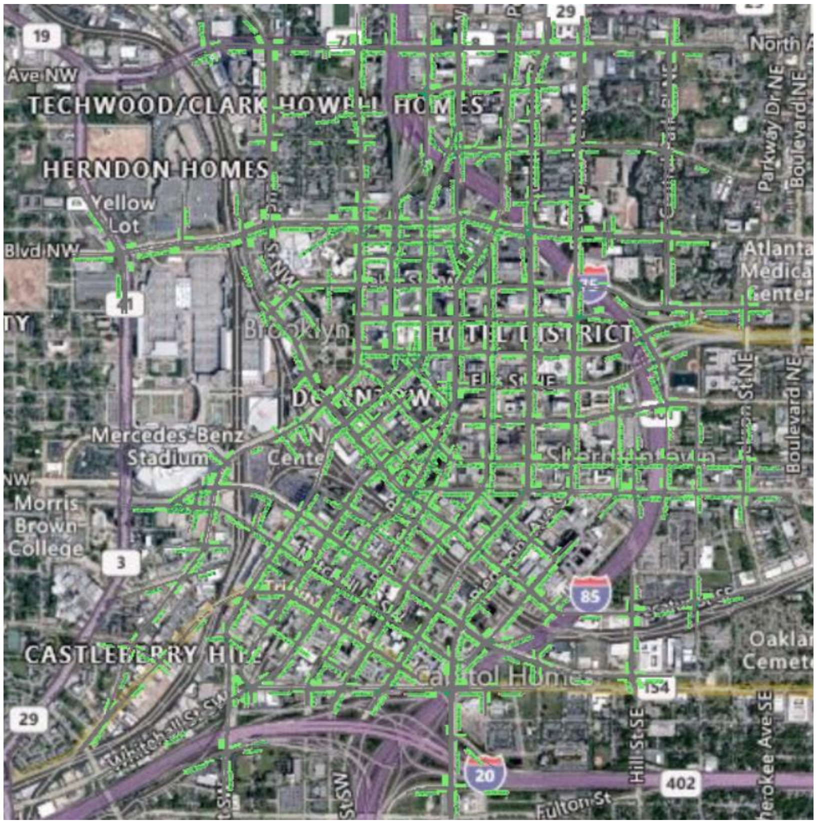


Figure 4. Synchro 11 Model for Downtown and Midtown

3.1.2 Importing Synchro Network into VISSIM

As the Synchro network included basic parameters for the study like speed, lane geometry, vehicle volume data, and signal timing, the most efficient way to accurately bring in all data and parameters was to import the whole Synchro network over to VISSIM. As a result, importing the network saved multiple steps of a preliminary setup such as determining vehicle data and composition, vehicle speed data, and signal timing data. However, the Synchro network that was transferred over to VISSIM only had vehicle data, so any parameters relating to the bike were manually inputted or adjusted; this includes any bike lanes, speed, vehicle compositions, and conflict areas. Figure 5 shows a visualization of the imported network in VISSIM.

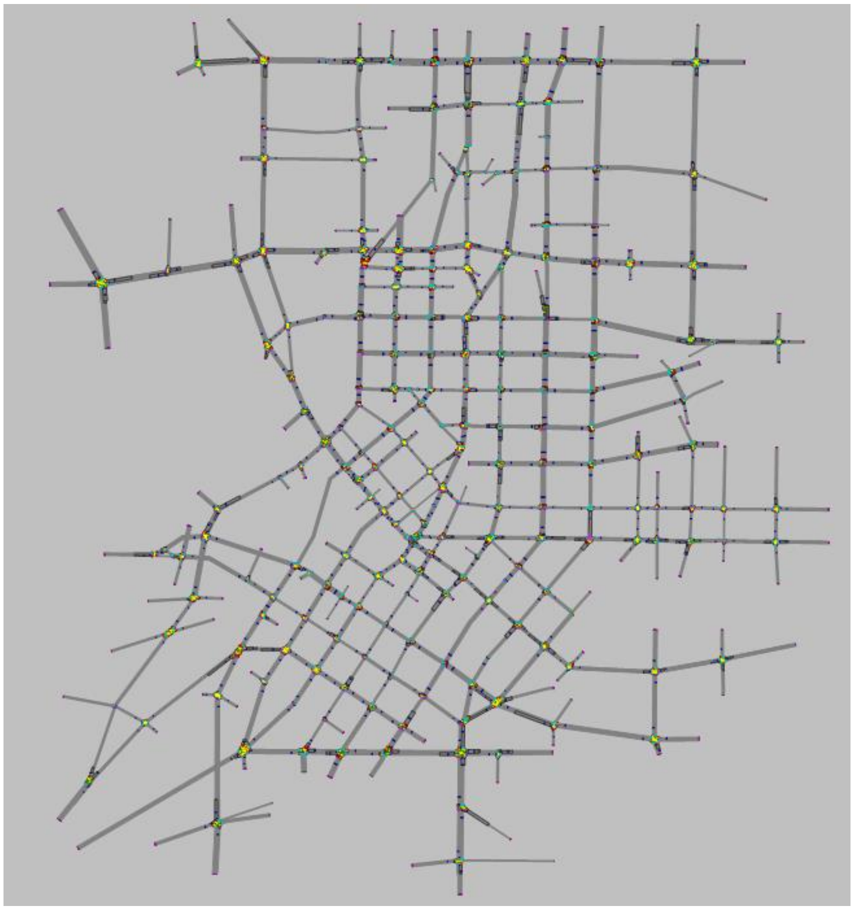


Figure 5. VISSIM Model for Downtown and Midtown

3.1.3 Existing Bike Infrastructure

Existing bike lane infrastructure that falls within the study area is listed in Table 1. Existing bike classifications are listed according to what is currently in Google Maps. A visualization of the existing bike infrastructure was done on ArcGIS ArcMap 10.8, shown in Figure 6.

Table 1. List of Existing Bike Infrastructure Within the Study Area

Street Name	From	To	Direction	Type
Marietta St	North Ave	Ivan Allen Jr Blvd	NB/SB	Class II
Luckie St	North Ave	Baker St	NB/SB	Class III
Peachtree Center Ave	Pine St	Edgewood Ave	NB/SB	Class II
Jackson St	Highland Ave	Irwin St	NB/SB	Class II
Jackson St	Irwin St	Auburn Ave	NB/SB	Class III
Jackson St	Auburn Ave	Edgewood Ave	NB/SB	Class II
Park Pl	Auburn Ave	Edgewood Ave	NB/SB	Class IV
Piedmont Ave	Baker St	Harris St	NB/SB	Class II
Peters St	Walker St	Spring St	EB/WB	Class II
Mitchell St	Mangum St	Spring St	EB/WB	Class II
Ivan Allen Jr Blvd	Northside Dr	Spring St	EB/WB	Class II
Ralph McGill Blvd	William St	West Peachtree St	EB/WB	Class II
Highland Ave	Piedmont Ave	Jackson St	EB/WB	Class IV
Harris St	Techwood Ave	Piedmont Ave	EB/WB	Class II
Edgewood Ave	Park Pl	Boulevard	EB/WB	Class II
Decatur St	Jesse Hill Dr	Jackson St	EB/WB	Class II

As bike lanes were manually drawn into the model in VISSIM, the following strategies were used to closely depict each bike classification in the simulation model. For Class II bike lanes, bike lanes were drawn along the relevant road. To depict the driving behavior along the routes with Class II bike lanes, bicycle volumes were put into the bike route and along the main road. The vehicle composition for these road segments is made sure to include bicycle composition. The reason for this is to describe the behavior of some bike users who bike outside the painted bike lanes along the road. For Class III, the road segment is routed to include bike volumes. This is done by making sure that the vehicle composition along the relevant routes like Jackson Street from Irwin Street to Auburn Avenue includes the bike composition. There are no separate bike lanes along this roadway. For Class IV, a separate bike lane was put along the relevant roadway segments. Bike volumes and composition are only put into the Class IV bike lanes; no bike volume is put into the main road to depict the separate bikeways.

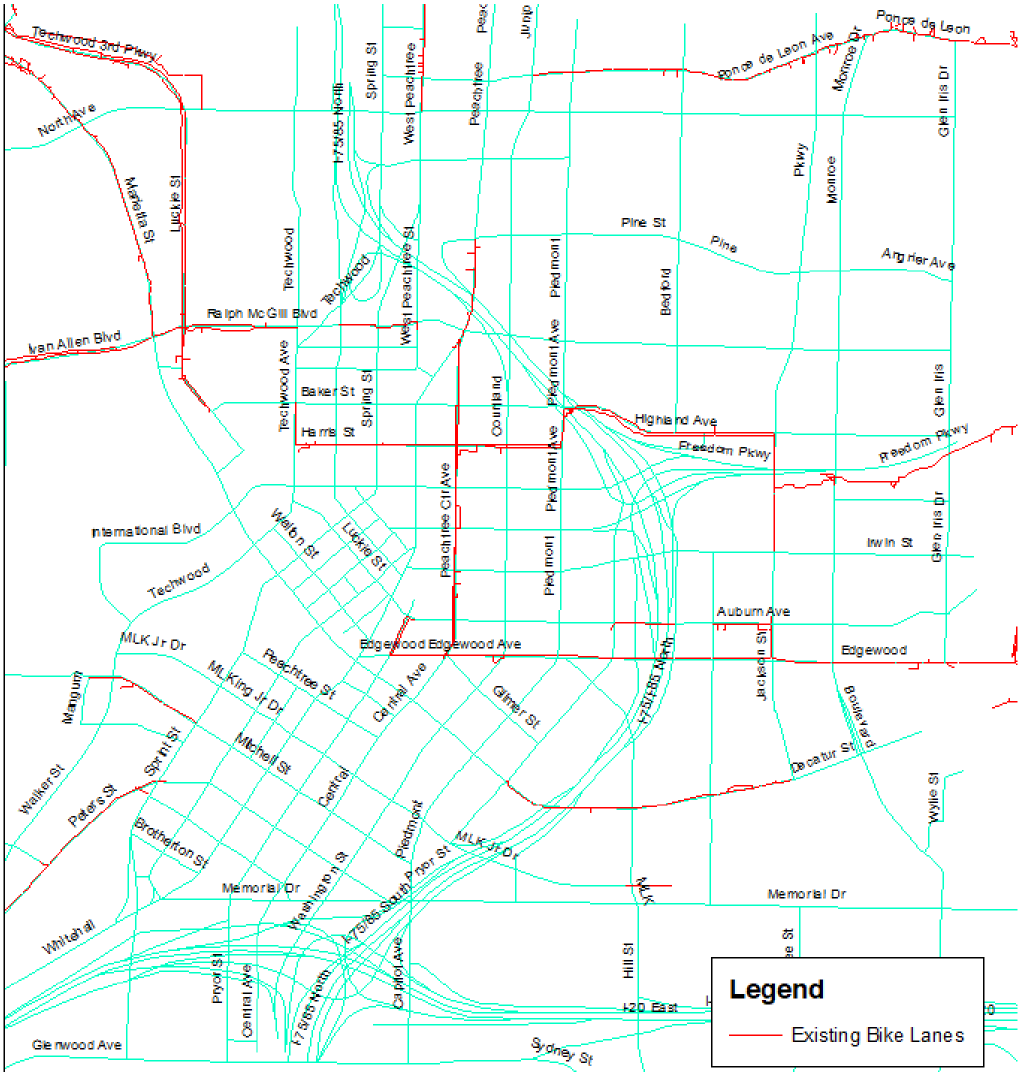


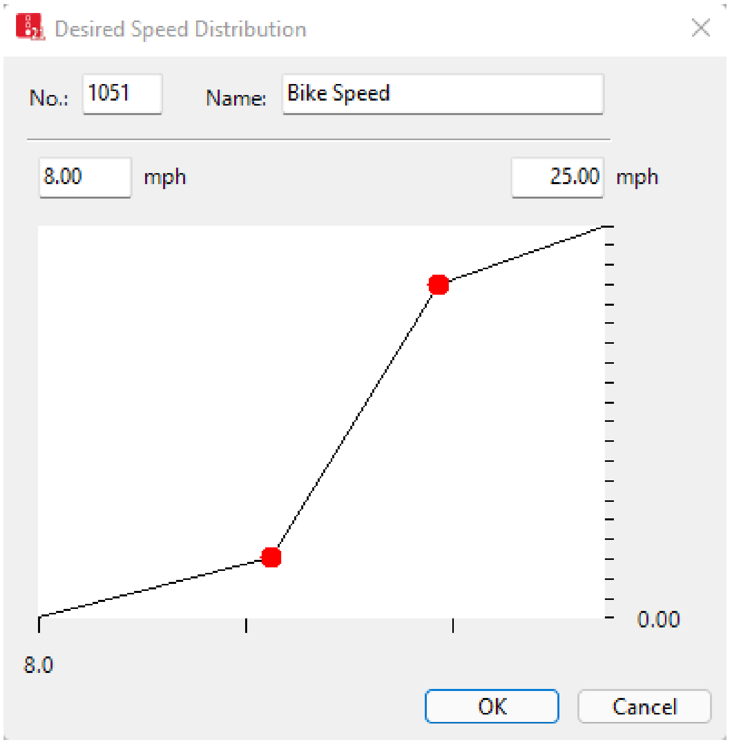
Figure 6. Existing Bike Lanes Within Study Area

3.1.4 Conflict Areas

Conflict areas within the network are areas that have overlapped links and connectors. To prevent vehicles, bicyclists, and pedestrians from appearing to be colliding or moving over each other in the simulation, conflict areas were assigned based on prioritized movements. Movement priorities were assigned at merge points for vehicles at intersections for left and right turn movements yielding through traffic.

3.1.5 Speed Data

Speed distributions are required to be defined for all vehicle classes. As most speed distributions have been set when the network was imported from Synchro, the only speed distribution manually assigned in VISSIM was the bike speed distribution. The speed distribution used for VISSIM was set to be 8 mph for the minimum and 25 mph for the maximum. Speeds were determined according to the average speeds of bike riding comfort level found in *Guide for Development of Bicycle Facilities* written by AASHTO (AASHTO, 2012). Figure 7 shows the input for bicycle speed profile in VISSIM.



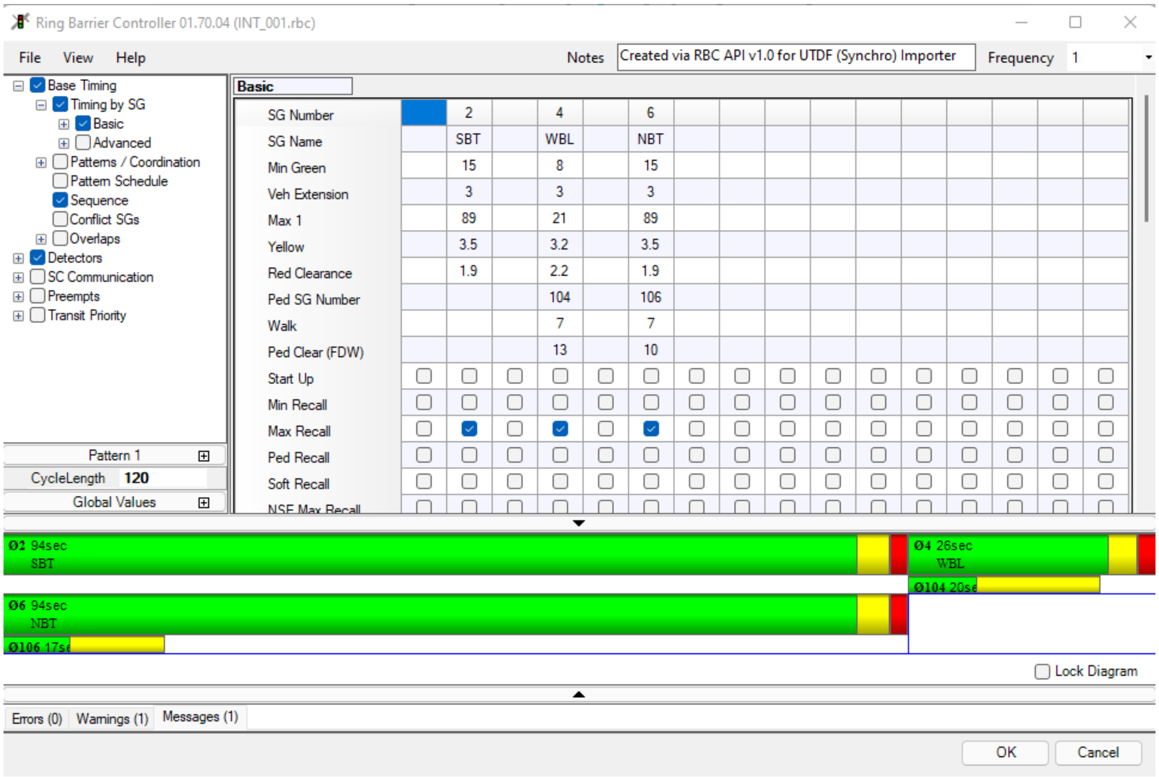
No.: 1051 Name: Bike Speed

8.00 mph 25.00 mph

Figure 7. Bike Speed Distribution in VISSIM

3.1.6 Signal Timing Data

No changes were done to the traffic signals within the network as all signal timing, sequences, and cycles were embedded in the Synchro network. Figure 8 shows an example of a standard signal timing template and entry that was carried over from the Synchro file. All signals were modeled as a Ring Barrier Controller (RBC) in VISSIM, which modeled actuated signal timing patterns as well as coordination. Each signal head and signal controller were assigned to each other through the RBC interface of VISSIM which fulfills our needs of protecting left turns and vehicle detectors. A total of 668 signal controllers were identified in this model.



Notes: Created via RBC API v1.0 for UTDF (Synchro) Importer

Frequency: 1

- ☑ Base Timing
  - ☑ Timing by SG
    - ☑ Basic
    - ☐ Advanced
  - ☐ Patterns / Coordination
  - ☐ Pattern Schedule
  - ☑ Sequence
  - ☐ Conflict SGs
  - ☐ Overlaps
- ☑ Detectors
- ☐ SC Communication
- ☐ Preempts
- ☐ Transit Priority

Pattern 1

CycleLength: 120

Global Values

SG Number		2		4		6										
SG Name		SBT		WBL		NBT										
Min Green		15		8		15										
Veh Extension		3		3		3										
Max 1		89		21		89										
Yellow		3.5		3.2		3.5										
Red Clearance		1.9		2.2		1.9										
Ped SG Number				104		106										
Walk				7		7										
Ped Clear (FDW)				13		10										
Start Up	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Min Recall	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Max Recall	☐	☑	☐	☑	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Ped Recall	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Soft Recall	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
NSE Max Recall	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

☐ Lock Diagram

Figure 8. Ring Barrier Controller Timing in VISSIM

3.1.7 Bicyclists

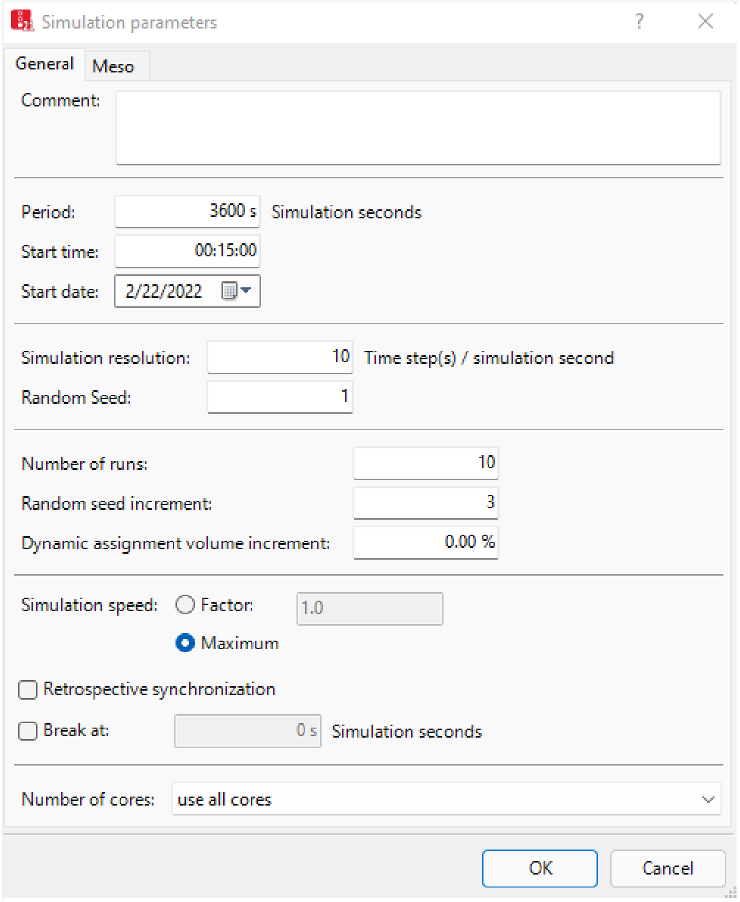
Bicyclists were coded in VISSIM as their vehicle class and routed through corridors. These corridors were identified based on the Current City Bike Infrastructure Map found in the City of Atlanta 2018 Annual Bicycle Report, found in Appendix A of this paper. An estimate of 5 bicyclists per hour in each corridor was coded into the network. The average hourly count of cyclists was based on the bike counts provided by the Annual Bicycle Report.

3.2 CALIBRATION

Calibration and validation are necessary steps to ensure the model’s accuracy and reliability. Azevedo et al. recommended calibration of microsimulation models considering key uncertainty sources such as data input, the methodology of calibration, the model structure, and its parameters (Azevedo, Ciuffo, Cardoso, & Ben-Akiva, 2015). The network is calibrated using automobile driving behavior and parameters.

3.2.1 Simulation Parameter

A well-calibrated model is essential to the system that is being modeled as it increases the reliability of the predicted traffic patterns and scenarios. The simulation period is set to be 3600 seconds (one hour) with a 15-minute start time. This means that VISSIM will start analyzing the vehicles and travel time after the 15 minutes into the run time. Figure 9 shows the simulation parameter set up for the simulation model.



Comment:

Period: 3600 s Simulation seconds

Start time: 00:15:00

Start date: 2/22/2022

Simulation resolution: 10 Time step(s) / simulation second

Random Seed: 1

Number of runs: 10

Random seed increment: 3

Dynamic assignment volume increment: 0.00 %

Simulation speed: ○ Factor: 1.0

● Maximum

☐ Retrospective synchronization

☐ Break at: 0 s Simulation seconds

Number of cores: use all cores

Figure 9. Simulation Parameter for the Model

3.2.2 Seed Numbers

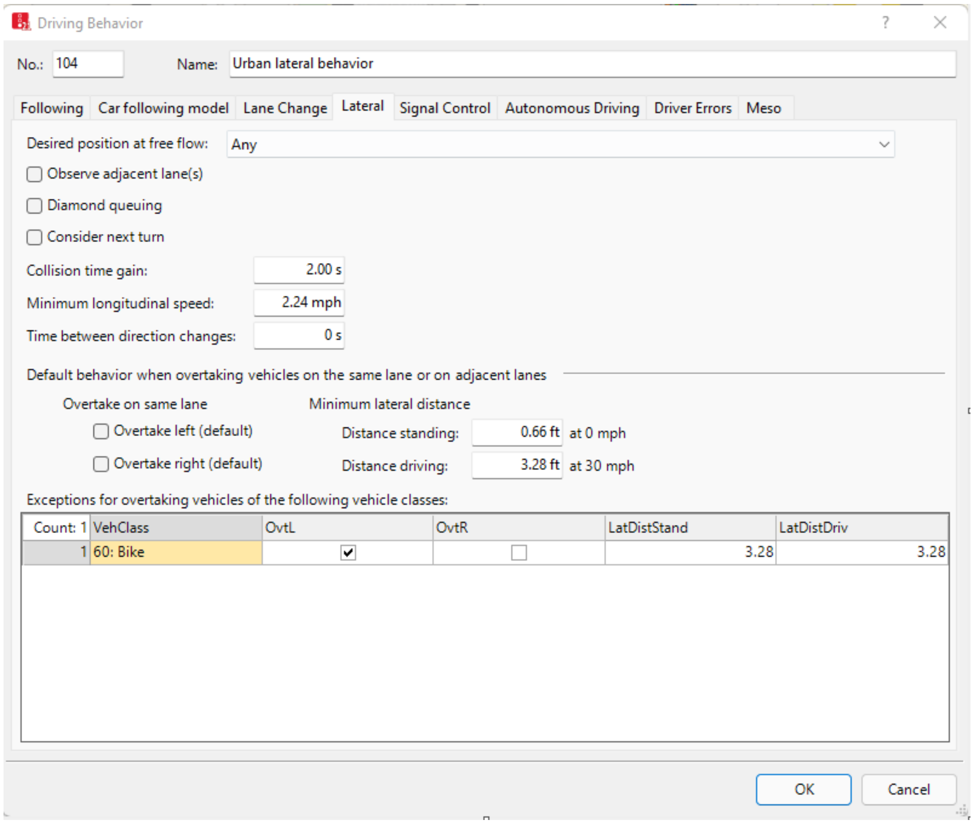
Validation of the model requires a series of runs of the simulation model at different seed numbers. Random seed numbers were put into VISSIM, which would affect the start values of random generators used internally in the model. This means that having random seeds would influence the arrival times of the vehicles within the network and the variability of the driving behaviors. Due to the stochastic nature of the simulation, random fluctuations occur in the results of the individual simulation runs (VISSIM 2021 User Manual, 2021). This allowed for the comparison of the changes in traffic patterns within the same location. If the same seed number was used for each simulation run, then the output data such as the volumes, speeds, and travel times, would be the same. According to the user manual, a more reliable assertion is reached by averaging the results of a sufficient number of simulation runs with different random seeds. Therefore, validation of each network is based on an average of 10 simulation runs. Fries et al. have suggested that models evaluating system-wide metrics such as average vehicle speeds or vehicle hours traveled were found to need at least 5 runs and models measuring arterial travel times or total delay were found to require 10 or more runs (Fries, Qi, & Leight, 2017). According to MDOT, a minimum of 5 simulation runs must be completed before average outputs of all runs can be used for analysis and additional runs may be necessary, up to 15 runs or by showing the convergence of the model (MDOT, 2017).

3.2.3 Vehicle Volume Input

Another calibration effort includes the comparison of the model's traffic volumes to those within Atlanta, Georgia, and making sure that the model's average speed of distribution of speed is observed in the real world. The traffic counts recorded in Synchro were from a PM peak hour data collection period. Real-world speed and travel time estimation were done by utilizing Google Maps; the time interval of 4:00 PM – 5:00 PM, the PM peak hour, was used to calibrate the model network.

3.2.4 Driving Behavior Parameters

Driver behavior parameters were adjusted to include urban bike behavior to make sure that the model's data closely resemble the actual data. Figure 10 shows an example of the urban bike behavior parameters set in VISSIM.



No.: 104

Name: Urban lateral behavior

Desired position at free flow: Any

☐ Observe adjacent lane(s)

☐ Diamond queuing

☐ Consider next turn

Collision time gain: 2.00 s

Minimum longitudinal speed: 2.24 mph

Time between direction changes: 0 s

Default behavior when overtaking vehicles on the same lane or on adjacent lanes

Overtake on same lane

☐ Overtake left (default)

☐ Overtake right (default)

Minimum lateral distance

Distance standing: 0.66 ft at 0 mph

Distance driving: 3.28 ft at 30 mph

Exceptions for overtaking vehicles of the following vehicle classes:

Count: 1	VehClass	OvtL	OvtR	LatDistStand	LatDistDriv
1	60: Bike	☑	☐	3.28	3.28

Figure 10. Urban Bike Behavior Parameters

3.3 VALIDATION

The validation process involved running multiple runs of the calibrated network and comparing the output data to the real world for accuracy. Below are the measures used to validate the microsimulation model in VISSIM.

3.3.1 Vehicle Record Data

A part of validation was based on the traffic output data from the VISSIM model using the elements of travel time measurements and vehicle network performance. Travel times were measured as the average travel time for vehicles to cross the origin and destination specified for the travel time measurement places on key corridors. Delay time measurements were obtained for any selected segment where travel time is measured. Delay time determines the average time delay calculated from all vehicles observed on a single or several link sections. Appendix B summarizes all locations of travel time corridors.

3.3.2 Speed Validation

Key corridors were selected within the network to perform speed validation. The following segments were selected as they either have existing biking infrastructure along the route or intersect with other biking infrastructure. Real-life estimated average speed range and time were collected on a Friday at 4:00 PM – 5:00 PM from Google Maps. This information was compared and matched with spot speed data from VISSIM to ensure the replication of the drivers' behavior. The average speed along the corridor recorded by VISSIM must fall within the range of speed calculated by Google Maps. Table 2 summarizes the average speed data from the 10 runs of the existing network compared to the corridor average speed range from Google Maps which provides a range based on historical data from the real-world conditions. All key corridors had the average speed within the distribution range of historical data other than Peachtree Street, which was just outside the range.

Table 2. Existing Baseline Speed Summary

Street Name	Length (mi)	Existing Baseline VISSIM model travel time (min)	Model Average Speed (mph)	Google Estimated Speed Range (mph)	Posted Speed Limit (mph)
North Ave (WB)	1.4	5.85	14.44	7-21	30
Ivan Allen Jr Blvd to Ralph McGill Blvd (EB)	1.7	9.91	10.29	6-18	30
Marietta St to Decatur St (EB)	2	12.05	9.95	7-20	30
Piedmont Ave to Capitol Ave (NB)	2.2	10.07	13.11	6-19	30
Juniper St to Washington St (SB)	1.9	15.22	7.49	10-23	25
Peachtree St (SB)	1.3	4.24	18.41	6-16	25

3.3.3 Travel Time Validation

The following key corridors were selected for travel time validation. Travel times of each route were recorded within VISSIM and compared to travel times obtained from Google Maps during Friday PM peak hour. Estimated real-life travel time ranges were collected from Google Maps since no real-time travel data was available. 83% of the travel times of the selected key corridors fall within Google Maps' estimated travel time range. Table 3 summarizes the travel time outputs from VISSIM compared to Google Maps. Travel time for each run can be found in Appendix C.

Table 3. Existing Baseline Travel Time Summary

Street Name	Length (mi)	Existing Baseline (min)	Google Range (min)
North Ave (WB)	1.4	5.85	4-12
Ivan Allen Jr Blvd to Ralph McGill Blvd (EB)	1.7	9.91	6-16
Marietta St to Decatur St (EB)	2.0	12.05	6-18
Piedmont Ave to Capitol Ave (NB)	2.2	10.07	7-20
Juniper St to Washington St (SB)	1.9	15.22	5-12
Peachtree St (SB)	1.3	4.24	5-14

In this chapter, the process of network creation, calibration, and validation were discussed. The network creation process was mostly done on Synchro 11. Calibration consisted of updating and adding any missing parameters and validation was done on the existing condition Scenario 0 by comparing the model's average speed and travel time data to real-world data. As a result of the calibration and validation process, the existing condition model is sufficient to be used to assist the other alternative conditions. The next chapter will discuss the different alternative bike infrastructure designs and modal demand adjustments to evaluate the effectiveness of the bike network improvement and extension.

4. ALTERNATIVE SCENARIOS

4.1 TRAVEL DEMAND ADJUSTMENTS

The initial plan is to test the existing condition and each alternative with the existing traffic volumes and then with adjustments in the traffic volumes. The first scenario, which will be labeled as Scenario 1 for the rest of the thesis, is the 5% adjustment within the vehicle and bicycle volumes. This means that 5% of vehicular volumes were substituted with a 5% in bicycle volume. The second scenario, with is referred to as Scenario 2 for the rest of the paper, is the 15% adjustment in the traffic volumes. Like the 5% adjustment, we decreased 15% of vehicular volume while increasing the bicycle volume by 15%. The reason for these scenarios is to see what the impact would be in terms of MOEs and conflicts within the study area if there was a modal shift between 5% to 15% range.

A research group at Georgia Institute of Technology provided proposed bike lanes along some streets, which will be considered as the Proposed Condition. The proposed conditions are essentially the ideal bike networks through midtown and downtown Atlanta that enable the most equitable connectivity of destinations. The City has also proposed its bike lane implementation and extension plans, which will be considered as the Alternative Condition. While there are some differences in the network, several bike lane connections are common between those networks. Each alternative was modeled in VISSIM as well as evaluating the different scenarios. A total of 3 scenarios (including Scenario 0 which is the base case) were analyzed for each condition (Existing, Proposed, and Alternative). Each alternative and scenario are described along with the network metrics collected using VISSIM for it in the subsequent subsections of this section.

4.2 EXISTING CONDITION DEMAND SCENARIOS 1 AND 2

As the existing condition baseline (scenario 0) results were summarized in the previous section, this part of the paper will describe the results of Scenarios 1 and 2 of the existing condition. 5% modal demand adjustment was done in Scenario 1 and 15% was done in Scenario 2.

4.2.1 Analysis and Network Measure of Effectiveness (MOEs)

Table 4 shows the network measures of effectiveness for Existing Condition Scenarios 1 and 2 compared to the baseline (Scenario 0). A full summary of Network MOEs for this scenario can be found in Appendix C.

Table 4. Existing Condition at Demand Scenarios 1 and 2 Network MOEs

	Existing Baseline	5% Modal Demand Adjustment	15% Modal Demand Adjustment
Average Speed (mph)	7.57	7.77	8.18
Average Delay (s)	252.16	243.12	213.96
Average Number of Stops	7.62	7.43	6.42
Average Stop Delay (s)	190.34	183.04	162.33

Results from Table 4 show a continuous decrease in average delay and stop delay and the average number of stops which increases the average speed from the baseline scenario to Scenario 2. This proves how fewer vehicles on the road and more bicycle riders will positively impact travel time and distance traveled. The reason for the decrease in the total and average delay is most likely due to fewer vehicles on the road which leads to a smaller number of stops, as shown in Table 4. Average speed is the only measure that increased as a result of the traffic volume adjustment which is also expected when there are fewer vehicles on the road.

4.3 PROPOSED CONDITION AT DEMAND SCENARIO 0

The proposed condition includes the addition of proposed bike lanes. Bike routes were updated to connect and include the proposed bike lanes. All bike lanes are modeled to depict Class II bike lanes unless specifically specified. The list of proposed bike infrastructure is in Table 5. Figure 11 is a visualization of the proposed bike lanes in ArcGIS ArcMap 10.8.

Table 5. List of Proposed Bike Infrastructure Within the Study Area

Street Name	From	To	Direction
North Ave	Techwood Pkwy	Peachtree St	EB/WB
Ralph McGill Blvd	Techwood Ave	Peachtree St	EB/WB
Baker St	Luckie St	Techwood Ave	EB/WB
Pine St	West Peachtree St	Peachtree St	EB/WB
Harris St	Techwood Ave	Piedmont Ave	EB/WB
Ellis St	Peachtree St	Peachtree Center Ave	EB/WB
Edgewood Ave	Peachtree St	Peachtree Center Ave	EB/WB
MLK Jr Dr	Forsyth St	Piedmont Ave	EB/WB
Mitchell St	Spring St	Capitol Ave	EB/WB
Brotherton St	Spring St	Peachtree St	EB/WB
Mitchell St	Northside Dr	Mangum St	EB/WB
Decatur Ave	Jackson St	Boulevard	EB/WB
Marietta St	Techwood Ave	Peachtree St	EB/WB
Peachtree St	Ponce de Leon Ave	Pine St	NB/SB
West Peachtree St	North Ave	Pine St	NB/SB
Peachtree Center Ave	West Peachtree St	Harris St	NB/SB
Peachtree St	Harris St	MLK Jr Dr	NB/SB
Jackson St	Highland Ave	Decatur At	NB/SB
Techwood Ave/Spring St	Ralph McGill Blvd	MLK Jr Dr	NB/SB
Peters St	Fair St	McDaniel St	NB/SB
Spring St	Mitchell St	Brotherton St	NB/SB
Forsyth St	Edgewood Ave	Trinity Ave	NB/SB
Piedmont Ave	Edgewood Ave	MLK Jr Dr	NB/SB
Central Ave	MLK Jr Dr	Memorial Dr	NB/SB

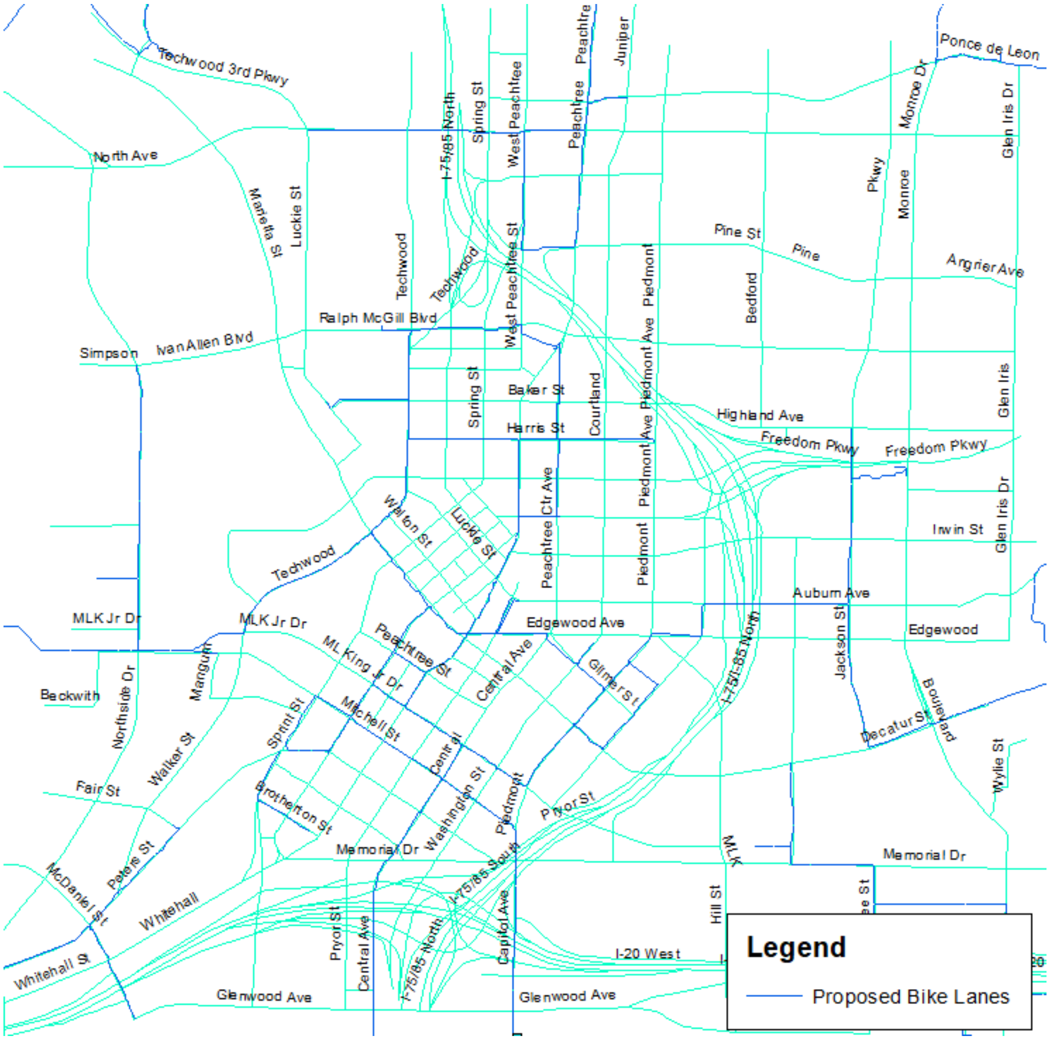


Figure 11. Proposed Bike Lane within Study Area

4.3.1 Analysis and Network Measure of Effectiveness (MOEs)

Proposed Condition Scenario 0 models the proposed bike network with existing traffic volumes. Table 6 shows the network measures of effectiveness for the Proposed baseline condition compared to Scenario 0 of the existing condition.

Table 6. Proposed Condition Scenario 0 MOEs

Per Vehicle		
	Existing Baseline	Proposed Baseline
Average Speed (mph)	7.57	8.21
Average Delay (s)	252.16	222.31
Average Number of Stops	7.62	7.12
Average Stop Delay (s)	190.34	164.46

From the results of the baseline proposed condition, it was observed to have a significant drop in the total travel time compared to the existing baseline condition. This shows that there is a positive impact to the study network as more bike infrastructure is implemented or extended within Downtown and Midtown Atlanta. There was also improvement in the average speed as average, total delay, and the number of stops decreased.

4.4 PROPOSED CONDITION SCENARIOS 1 AND 2

For proposed condition scenarios, the 5% modal demand adjustment was done on the first scenario and 15% adjustment on the second scenario. Bike routes remained the same from Proposed Condition Scenario 0.

4.4.1 Analysis and Network Measure of Effectiveness (MOEs)

Table 7 shows the network measures of effectiveness for Proposed Condition scenarios compared to the baseline scenario.

Table 7. Proposed Condition Scenarios 1 and 2 MOEs

Per Vehicle			
	Proposed Baseline	5% Modal Demand Adjustment	15% Modal Demand Adjustment
Average Speed (mph)	8.21	8.49	9.06
Average Delay (s)	222.31	212.52	193.82
Average Number of Stops	7.12	6.93	6.35
Average Stop Delay (s)	164.46	156.83	142.40

Comparing the results from the two scenarios to the baseline scenario, there was a significant drop in the total delay which proves the positive impact of the modal shift in demand. With the conversion of 15% of vehicular volumes to bike volume, the average delay dropped a total of 15% from the proposed baseline condition. The average speed also increased due to the decreased delay and the average number of stops. This means that traffic is flowing much more smoothly than at its base condition. Full network MOEs for each seed can be found in Appendix C.

4.5 ALTERNATIVE CONDITION SCENARIO 0

The alternative condition includes alternative bike lanes that are by the City. This model excludes the bike lanes from the proposed condition. Compared to the proposed bike network, most of the planned alternative bike lanes run in the northbound/southbound direction, connecting the north part of the city to the south. Bike routes were updated to connect and include the alternative bike lanes. All bike lanes are modeled to depict Class II bike lanes unless specifically specified. The list of proposed bike infrastructure is in Table 8. Figure 9 is a visualization of the proposed bike lanes in ArcGIS ArcMap 10.8.

Table 8. List of Alternative Bike Infrastructure Within the Study Area

Street Name	From	To	Direction
Ralph McGill Blvd	West Peachtree St	Boulevard	EB/WB
Highland Ave	Jackson St	Boulevard	EB/WB
West Peachtree Pl	West Peachtree St	Peachtree St	EB/WB
Baker St	Luckie St	Piedmont Ave	EB/WB
International Blvd	--	Marietta St	EB/WB
Walton St	Techwood Ave	Peachtree St	EB/WB
MLK Jr Dr	Techwood Ave	Grant St	EB/WB
Mitchell St	Northside Dr	Jesse Hill Jr Dr	EB/WB
Whitehall St	McDaniel St	Spring St	EB/WB
Memorial Dr	Peachtree St	Martin St	EB/WB
Piedmont Ave	Ponce de Leon Ave	Mitchell St	NB/SB
Capitol Ave	Mitchell St	Fulton St	NB/SB
Courtland Ave	Ponce de Leon Ave	Edgewood Ave	NB/SB
Washington St	Edgewood Ave	Memorial Dr	NB/SB
Peachtree St	West Peachtree St	Harris St	NB/SB
West Peachtree St	West Peachtree Pl	West Peachtree St	NB/SB
Peachtree St	Walton St	Memorial Dr	NB/SB
Spring St	Ponce de Leon Ave	North Ave	NB/SB
Techwood Ave	North Ave	Highland Ave	NB/SB
Techwood Ave	Harris St	Mitchell St	NB/SB
Walker St	Mitchell St	Peters St	NB/SB
Peters St	Walker St	McDaniel St	NB/SB
Forsyth St	Carnegie Way	Memorial Dr	NB/SB
Pryor St	MLK Jr Dr	Memorial Dr	NB/SB
Central Ave	MLK Jr Dr	Memorial Dr	NB/SB

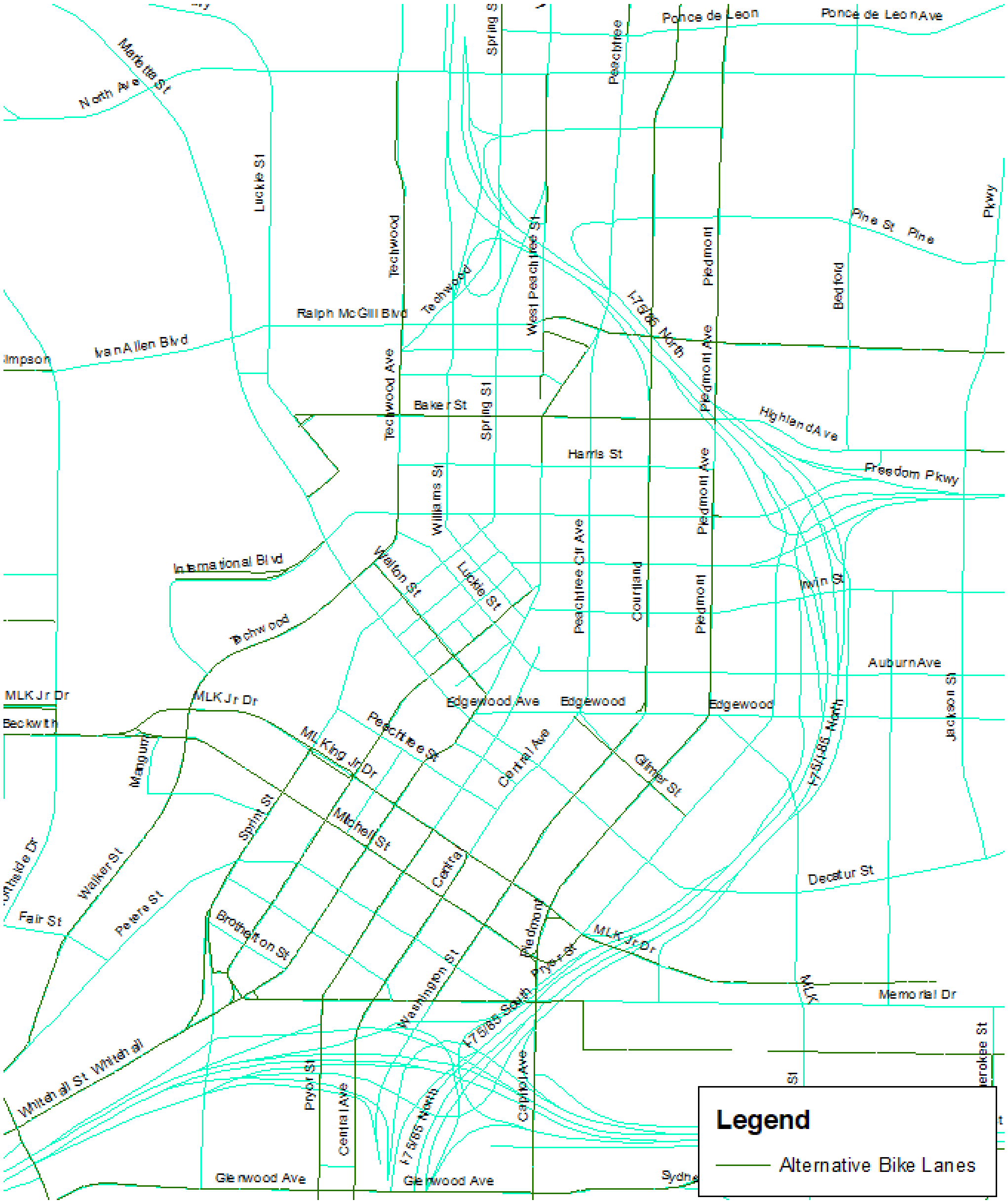


Figure 12. Alternative Bike Lane within Study Area

4.5.1 Analysis and Network Measure of Effectiveness (MOEs)

Table 9 shows the network measures of effectiveness for the baseline scenario for the alternative condition compared to the existing condition baseline scenario. Full network MOEs for each seed can be found in Appendix C.

Table 9. Alternative Condition Scenario 0 MOEs

Per Vehicle		
	Existing Baseline	Alternative Baseline
Average Speed (mph)	7.57	8.22
Average Delay (s)	252.16	222.18
Average Number of Stops	7.62	7.12
Average Stop Delay (s)	190.34	164.21

4.6 ALTERNATIVE CONDITION SCENARIOS 1 AND 2

Modal demand adjustments of 5% and 15% were made in Scenarios 1 and 2, respectively. Bike routes remained the same from Alternative Condition Scenario 0.

4.6.1 Analysis and Network Measure of Effectiveness (MOEs)

Table 14 shows the two alternative scenarios network measure of effectiveness compared to Scenario 0.

Table 10. Alternative Condition Scenarios 1 and 2 MOEs

Per Vehicle			
	Alternative Baseline	5% Modal Demand Adjustment	15% Modal Demand Adjustment
Average Speed (mph)	8.22	8.48	9.07
Average Delay (s)	222.18	212.32	193.57
Average Number of Stops	7.12	6.94	6.34
Average Stop Delay (s)	164.21	156.80	142.20

With the alternative condition scenarios, there is constant improvement due to the modal shift. This can be proven by the increase in the average speed of vehicles, the average number of stops, and the average stop delay. A study found that positive perceptions of the availability of bike lanes are associated with more cycling and the desire to cycle more. Higher levels of street connectivity were associated with more cycling for utilitarian trips (Dill & Voros, 2007). Figure 11 shows the comparison of all conditions and their scenarios.

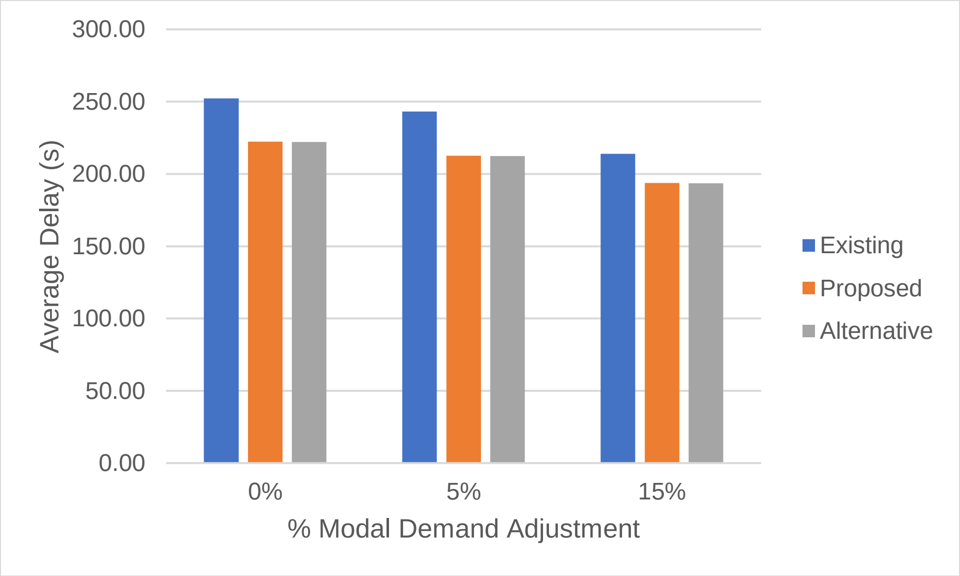


Figure 13. Average Delay Comparison of all Conditions and Scenarios

From the figure, the average delay for the proposed and alternative conditions was very similar. However, the alternative condition delays were slightly lower than the proposed condition delay. This could be due to the positive impact of the modal demand shift and fuller connectivity of the alternative condition as bike lanes are planned to connect the north side of the study area to the south side. With more complete bike networks, like the proposed and alternative conditions, people may be more encouraged and comfortable in using biking as an alternative mode of travel.

5. SAFETY ASSESSMENT

Surrogate Safety Assessment Model (SSAM) Version 3.0 was used to analyze the estimate the number of potential conflicts within the whole model network. SSAM works by analyzing the frequency of narrowly missed vehicle collisions in microscopic traffic simulation software, like VISSIM, to assess safety (Preston & Pulugurtha, 2021). The trajectory of each vehicle is analyzed for every tenth of a second and each overlapping trajectory is an indicator of real-world collisions. It is assumed that the expected number of crashes is proportional and represented by the simulated number of conflicts at each study intersection. Trajectory files for this project were generated for each simulation run in VISSIM. Each trajectory file is then inputted into SSAM to estimate the number of conflicts within the whole network. There are three categories of conflicts that are based on the type of crashes such as crossing collisions, rear-end collisions, and lane-change collisions. The output data also considers all vehicle types involved in the conflict: vehicle-vehicle conflicts, vehicle-bike conflicts, and bike-bike conflicts.

The time to collision (TTC) and post encroachment time (PET) values were set to default in SSAM for the conflict analysis. TTC represents the number of a second required for overlapping trajectories to be considered a conflict (Preston & Pulugurtha, 2021). PET has defined as the time between the moment that the first road user leaves the path of the second and the moment that the second reaches the path of the first (Allen, Shin, & Cooper, 1977). The range for TTC is set at a minimum of zero seconds and a maximum of 1.5 seconds and the range for PET is set to zero as the minimum and 5 seconds for the maximum.

Trajectory data from microscopic traffic simulation software, such as VISSIM, may underestimate the number of conflicts at intersections. In a study done by Wu et al., it was observed that VISSIM models underestimate the number of pedestrian-vehicle conflicts at intersections under specific circumstances such as involving illegal pedestrian behavior such as pedestrian signal violation

(Wu, Radwan, & Abou-Senna, 2017). It was eventually concluded that it was hard to cross-check illegal biking behaviors or signal violations as real-world trajectory data of vehicles/bicycles and related observations at or near the study intersection were not available (Preston & Pulugurtha, 2021). Even considering this limitation, the SSAM can provide a relative assessment of safety for the scenarios.

5.1 SAFETY EFFECT ON THE EXISTING CONDITION

SSAM generated outputs were divided by the total simulated number of vehicles within the entire network. Doing so would give us the average number of conflicts experienced per vehicle at the intersections instead of the total number of conflicts at the intersections within the network. Table 11 summarizes the number of conflicts per vehicle type from each scenario. A complete summary list of SSAM results can be found in Appendix D.

Table 11. Existing Condition SSAM Results

Average Number of Conflicts Per Vehicle by Type			
	Exiting Baseline	5% Modal Demand Adjustment	15% Modal Demand Adjustment
Crossing	0.17	0.16	0.09
Rear-End	0.54	0.53	0.45
Lane-Change	0.14	0.13	0.12
Total	0.85	0.83	0.67

With the 5% and 15% modal demand adjustments to the vehicles and bike volumes, the model experiences a significant decrease in each type of conflict and the total conflicts. From the existing baseline with no adjustments to the 15% change in modal demand, there was a 21% decrease in total conflicts and a 47% decrease in crossing conflicts. With the adjustment to the traffic volumes, it can be expected that there would be fewer interactions between vehicles and between vehicles and bicyclists resulting in a bigger difference in crossing conflicts compared to the other types of conflicts.

5.2 SAFETY EFFECT ON THE PROPOSED CONDITION

Outputs generated from SSAM for the proposed condition were also divided by the total simulated number of vehicles within the entire network, giving us the average number of conflicts experienced per vehicle within the model network. Table 12 compares the number of conflicts per vehicle type from each proposed scenario to the baseline scenario. A complete summary list of SSAM results can be found in Appendix D.

Table 12. Proposed Condition SSAM Results

Average Number of Conflicts Per Vehicle by Type			
	Proposed Baseline	5% Modal Demand Adjustment	15% Modal Demand Adjustment
Crossing	0.15	0.14	0.12
Rear-End	0.50	0.49	0.47
Lane-Change	0.13	0.13	0.12
Total	0.78	0.76	0.71

For the proposed baseline, results show that the number of conflicts per vehicle is lower than the existing baseline. The decrease in the number of baseline conflicts may be a result of a more connected bike network, as modal demand adjustments have not been applied for Scenario 0. Similar to the existing condition scenarios, the biggest change lies within the crossing and total conflicts. With the comparison of the proposed baseline scenario and the 15% modal demand adjustment scenario, crossing conflicts decreased by 20% while the total conflicts decreased by 8%.

5.3 SAFETY EFFECT ON THE ALTERNATIVE CONDITION

SSAM generated outputs for the alternative condition were divided by the total simulated number of vehicles within the entire network, giving us the average number of conflicts experienced per vehicle within the model network. Table 13 summarizes the number of conflicts per vehicle type from each alternative scenario to the alternative baseline scenario. A complete summary list of SSAM results can be found in Appendix D.

Table 13. Alternative Condition SSAM Results

Average Number of Conflicts Per Vehicle by Type			
	Alternative Baseline	5% Modal Demand Adjustment	15% Modal Demand Adjustment
Crossing	0.15	0.14	0.12
Rear-End	0.50	0.49	0.47
Lane-Change	0.13	0.13	0.12
Total	0.78	0.75	0.71

Like the proposed condition scenarios, the biggest change lies within the crossing and total conflicts. With the comparison of the alternative baseline scenario and the 15% modal demand adjustment scenario, crossing conflicts decreased by 20% while the total conflicts decreased by 8%. With a more connected bike network, bicyclists have separated from vehicular traffic therefore the greater difference in crossing conflicts shows the influence of a more connected bike network and modal demand shift. Figure 14 visually shows the comparison of the total conflicts between all conditions and scenarios.

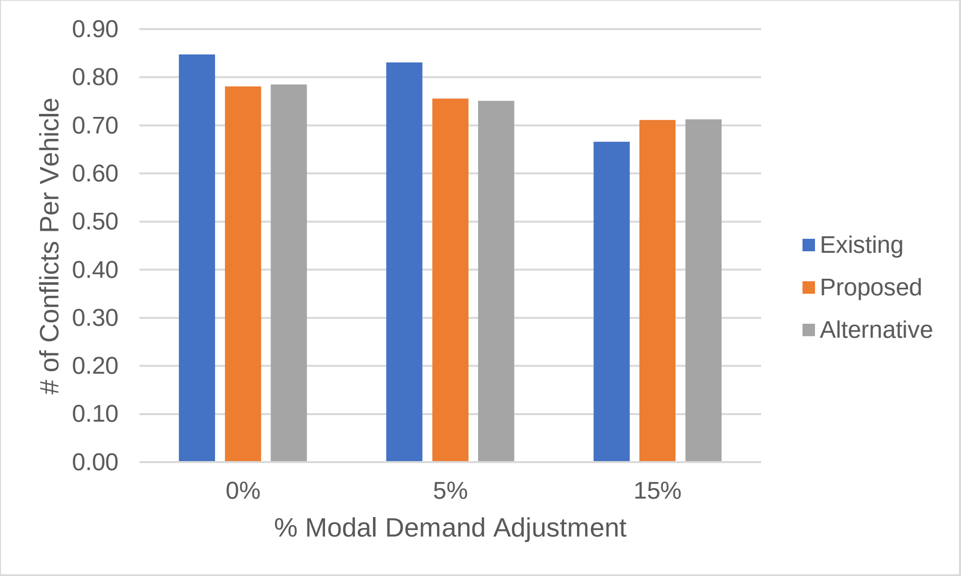


Figure 14. Total Conflicts Comparison Between all Conditions

When comparing SSAM results of all conditions and their scenarios, all conditions showed a decrease in conflicts per vehicle. This may be a result of the bike networks being more complete which decreases the interaction between vehicles and bicyclists. By having more complete bike networks, decreasing number of vehicles can be expected as people shift from driving to cycling as their mode of transportation. The decreasing number of vehicles on the road will decrease the overall conflict per vehicle.

6. CONCLUSION

6.1 SUMMARY AND EVALUATION

This study addressed the Complete Streets policy which is aimed at transforming streets to accommodate multiple modes of traffic such as active modes like biking and walking. The project looked at the effects of complete streets by analyzing the existing bike networks and the potential connections and implementation of new bike infrastructure to form complete networks that improve active mobility. Stakeholders and the City can use the results from the model to a) evaluate the strategies that were analyzed and evaluated as part of this effort; b) demonstrate before and after transportation network operations; c) run and evaluate future scenarios through the simulation model. The evaluation mainly focused on automobile and bicycle modes as the study focuses on the effect of the bike network in the Atlanta metropolitan region where biking and shared micromobility transportation modes are rapidly growing on the complete streets initiative.

To the broader research community, the proposed effort will provide a framework to evaluate combinations of strategies aimed to improve active mobility and build more “complete” streets. This research will help communities around North America that have been reluctant to develop scenarios due to lack of resources, capacity, or expertise by offering a more effective method to illustrate the impact of policy implementation. FHWA guidelines for applying microscopic traffic simulation indicated that to develop a reliable model, it is important to evaluate the calibration and fidelity of the model to real-world conditions present in the project analysis study area (Dowling, Skabardonis, & Alexiadis, 2002-2003).

6.2 RELIABILITY OF DATA

For the existing baseline model, the speed for the VISSIM model landed within the range estimated on Google Maps during PM peak hour on Friday. Travel time through key corridors within the network was also well-validated so we are confident that the model is capturing real-world driving behaviors within the base network model. The evaluation of the alternatives was based on Georgia

Institute of Technology and the City's input on the planned extension and implementation of bike infrastructure. The scenarios were evaluated to see the effect of the existing and potential bike infrastructure on the vehicles within the study network. These scenarios and alternatives account for the Complete Streets policy objectives. As a result of the output data from the microscopic traffic simulation models, the project team encourages the potential implementation and extension of bike networks throughout Midtown and Downtown Atlanta. All results documented in this report and VISSIM models will be provided to the City and Community stakeholders for any future uses.

6.3 RECOMMENDATION FOR FUTURE WORK

This project provided a framework to examine the design of complete streets by connecting isolated complete street segments to form complete networks that improve active mobility. Most of the previous research studies focus solely on the impact of automobiles from complete streets transformation. For the broader research community, this study shows an alternative way of evaluating complete networks, not just complete streets. Some future work that can utilize this method of evaluation includes using SSAM results for admission analysis or evaluating specific conflicts, such as bicycle conflicts, at selective locations, links, or intersections.

The model can produce measures of performance for other modes included within the networks like bicycles and pedestrians. This is the same for SSAM analysis. There is not an option in SSAM to specifically sort conflicts by vehicle type, making it difficult for this study to accurately analyze the safety of bicyclists in the model. However, SSAM does offer conflict information for each link, which may potentially provide a proxy for bicycle-related conflicts (Preston & Pulugurtha, 2021). This strategy to analyze the safety effects on bicyclists may be crucial for further evaluation of complete bike networks. Results documented in this report and the VISSIM models will be provided to stakeholders and can be used in the future to address future scenarios as they are proposed.

Further improvements that could be made to increase the accuracy of the model to real-world scenarios would include getting data on the potential growth of traffic within Atlanta, Georgia, instead of using our approach of 5% and 15% traffic volume adjustments. A well-calibrated model will lead to higher functionality on modeling travel behavior, which can assist transportation planners in balancing needs and investment.

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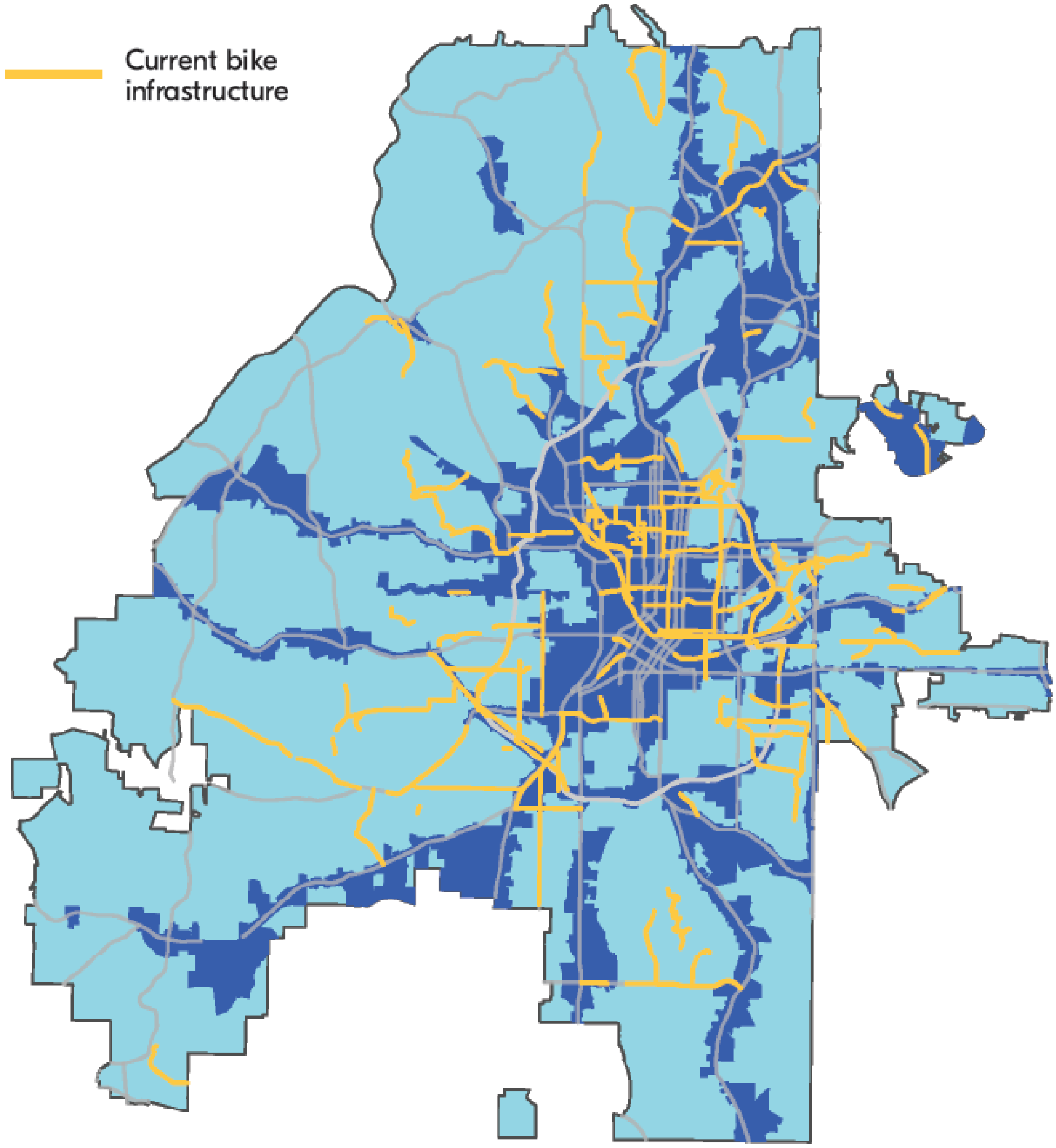
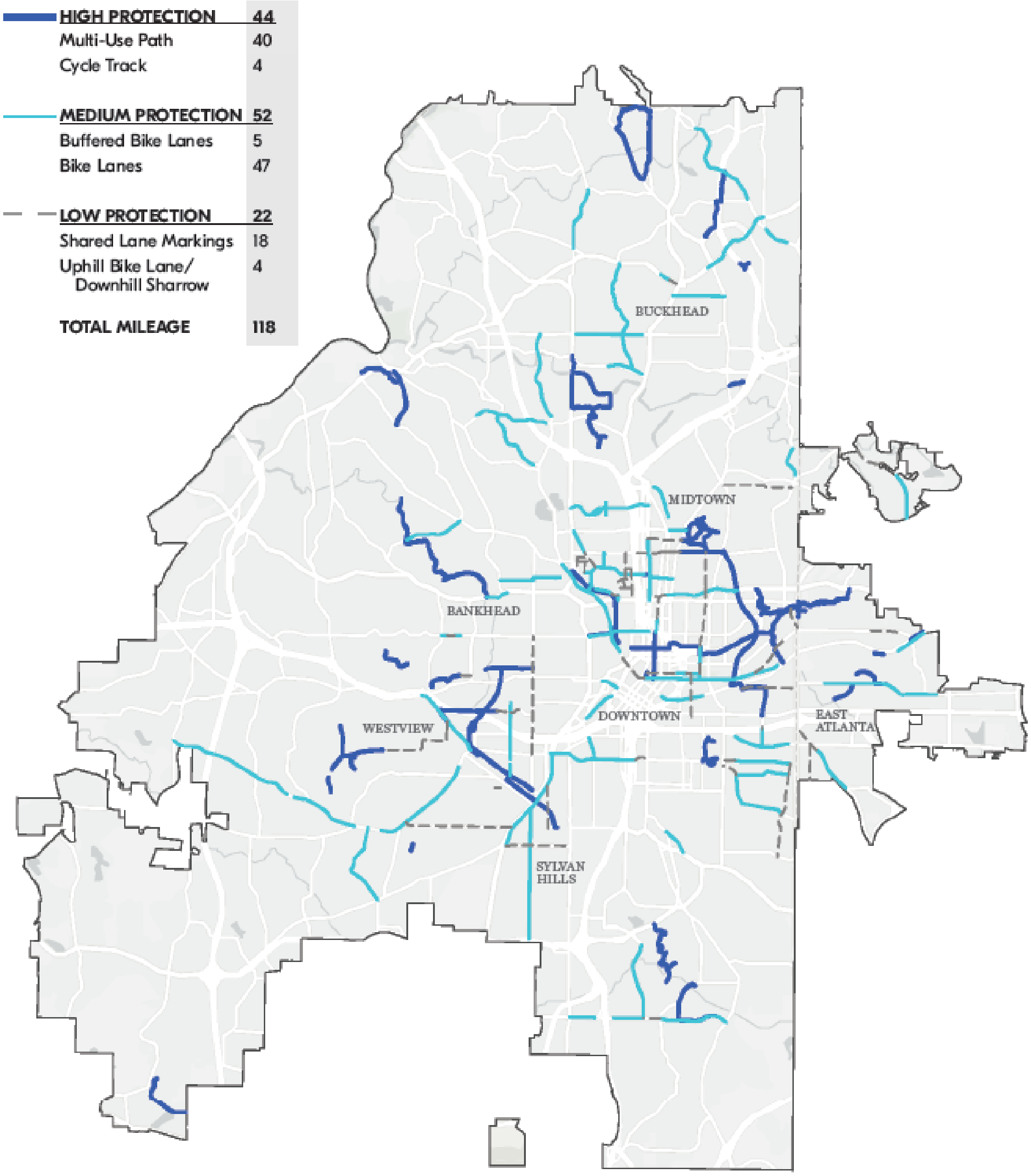
APPENDICES

APPENDIX A. CURRENT CITY BIKE INFRASTRUCTURE



Current City Bike Infrastructure Map



━	**HIGH PROTECTION**	**44**
	Multi-Use Path	40
	Cycle Track	4
—	**MEDIUM PROTECTION**	**52**
	Buffered Bike Lanes	5
	Bike Lanes	47
- -	**LOW PROTECTION**	**22**
	Shared Lane Markings	18
	Uphill Bike Lane/ Downhill Sharrow	4
	TOTAL MILEAGE	**118**

APPENDIX B. LOCATIONS FOR TRAVEL AND DELAY TIME MEASUREMENTS

Street Name	From	To	Direction
North Ave	Marietta St	Nutting St	EB/WB
Linden Ave	William St	Willow St	EB/WB
Marrietta Ave	Luckie St	William St	EB/WB
Pine St	Luckie St	COP Dr	EB/WB
Pine St	Spring St	Felton Dr	EB/WB
Currier St	Courtland St	Piedmont Ave	EB/WB
Joseph E Boone Blvd/ Ralph McGill Blvd	Maple St	Felton Dr	EB/WB
West Peachtree Pl	COP Dr	Peachtree St	EB/WB
Simpson St	COP Dr	Peachtree St	EB/WB
Baker St	Marietta St	COP Dr	EB/WB
Baker St/Highland Ave	Piedmont Ave	Jackson St	EB/WB
Baker St	Piedmont Ave	COP Dr	WB
JBP/Harris St	COP Dr	Piedmont Ave	EB/WB
AYI Blvd	COP Dr	William St	EB/WB
AYI Blvd	John Lewis Freedom Pkwy	William St	WB
Ellis St	Carnegie Way	Peachtree St	EB/WB
Ellis St	Peachtree St	John Lewis Freedom Pwky	EB
JWD Ave/Irwin St	Park Pl	Hillard St	EB/WB
Luckie St/Auburn Ave	COP Dr	Boulevard NE	EB/WB
Edgewood Dr	Peachtree St	Boulevard NE	EB/WB
Decatur St	Edgewood Sr	Jackson St	EB/WB
Mitchell St/Capitol Square	Jondelle Johnson Dr	Capitol Ave	EB/WB
Jesse Hill Dr	Capitol Ave	Gilmer St	NB/SB
Gilmer St	Peachtree Center Ave	Jesse Hill Dr	EB/WB
Mitchell St/MLK Jr Dr	Jondelle Johnson Dr	Fort St	EB/WB
Memorial Dr	Ted Turner Dr	Martin St	EB/WB
Marietta St	Ivan Allen Jr Blvd	Edgewood Dr	NB/SB
Peters St	Walker St	Ted Turner Dr	NB/SB
Walker St/COP Dr	Peters St	Marietta St	NB/SB
COP Dr	West Peachtree Pl	Marietta St	SB
COP Dr	West Peachtree Pl	North Ave	NB/SB
Whitehall St	McDaniel St	Forsyth St	NB/SB
Windsor St/Ted Turner Dr	Eugenia St	MLK Jr Dr	NB/SB

Ted Turner Dr	MLK Jr Dr	Ivan Allen Jr Blvd	NB
Spring St	Ivan Allen Jr Blvd	West Peachtree St	NB
West Peachtree St	Pine St	Ponce de Leon Ave	NB
West Peachtree St	Pine St	Peachtree St	NB/SB
Peachtree St	Ponce de Leon Ave	Memorial Dr	NB/SB
Forsyth St	Carnegie Way	Memorial Dr	NB/SB
Park Pl/Pryor St	Auburn Ave	Memorial Dr	SB
Central Ave/Peachtree Center	Memorial Dr	Peachtree St	NB
Juniper St/Courtland St/Washington St	Ponce de Leon Ave	Memorial Dr	SB
Argonne Ave/Central Park Pl	Ponce de Leon Ave	Baker St	NB/SB
Tech Pkwy/Luckie St	North Ave	Marietta St	NB/SB
Northside Dr	John St	Thurmond St	NB/SB

APPENDIX C. NETWORK EVALUATION PERFORMANCE MEASURE

				Network							
	Existing Baseline	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Number of Vehicles	1,992	2,144	1,953	2,044	2,001	1,943	1,964	2,030	2,018	1,887	1,936
Total Travel Time (h)	12,727	14,723	12,364	12,872	11,201	13,257	12,945	13,643	13,507	10,733	12,020
Total Distance (mi)	215,772	236,571	203,526	223,283	189,768	226,326	217,911	233,863	227,076	190,511	208,883
Total Delay (h)	6,855,910	7,016,752	6,483,034	6,894,441	6,710,521	6,554,902	7,269,951	6,615,969	6,873,162	7,291,700	6,848,669

				Per Vehicle							
	Existing Baseline	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Average Speed (mph)	7.57	7.41	7.86	7.57	7.66	7.83	7.26	7.75	7.53	7.26	7.54
Average Delay (s)	252.16	257.28	241.18	253.10	249.44	241.42	264.19	244.85	252.52	266.05	251.57
Average Number of Stops	7.62	7.44	7.53	7.73	7.56	7.36	7.77	7.67	7.56	8.10	7.52
Average Stop Delay (s)	190.34	195.55	180.36	191.00	188.91	180.95	201.45	182.92	191.08	200.56	190.61

				Network							
	Existing plus 5% Demand	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Number of Vehicles	1,931	2,078	1,904	1,958	1,924	1,879	1,924	1,957	1,948	1,823	1,915
Total Travel Time (h)	12,597	12,150	13,482	11,430	11,742	12,798	12,398	14,170	11,881	11,750	14,174
Total Distance (mi)	217,803	208,134	223,932	206,912	197,844	218,050	209,534	240,456	209,414	206,903	256,845
Total Delay (h)	6,418,012	6,278,391	6,133,142	6,379,163	6,367,296	6,514,110	6,694,622	6,243,830	6,437,267	6,675,764	6,456,533

				Per Vehicle							
	Existing plus 5% Demand	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Average Speed (mph)	7.77	7.88	8.02	7.86	7.81	7.67	7.59	7.87	7.75	7.56	7.69
Average Delay (s)	243.12	237.31	234.12	241.96	243.05	247.74	249.95	237.97	243.38	251.18	244.58

Average Number of Stops	7.43	7.18	7.07	7.60	7.53	7.58	7.81	7.13	7.34	7.85	7.26
Average Stop Delay (s)	183.04	178.13	175.05	182.41	182.96	187.29	187.20	179.28	183.50	189.07	185.50

Network											
	Existing plus 15% Demand	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Number of Vehicles	1,641	1,702	1,622	1,638	1,659	1,612	1,635	1,659	1,659	1,601	1,621
Total Travel Time (h)	11,138	11,236	11,211	12,359	9,309	11,186	12,191	9,926	11,104	11,437	11,414
Total Distance (mi)	193,689	196,093	197,481	218,744	154,332	198,517	207,216	178,875	193,517	199,878	192,228
Total Delay (h)	4,772,467	4,886,889	4,571,953	4,815,702	4,795,964	4,636,513	4,768,492	4,618,455	4,877,266	4,804,318	4,949,115
Per Vehicle											
	Existing plus 15% Demand	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Average Speed (mph)	8.18	8.02	8.36	8.18	8.11	8.31	8.25	8.28	8.07	8.18	8.06
Average Delay (s)	213.96	218.28	206.38	214.50	217.27	209.29	212.21	208.50	218.66	214.01	220.46
Average Number of Stops	6.42	6.31	6.20	6.67	6.61	6.23	6.60	6.27	6.42	6.35	6.54
Average Stop Delay (s)	162.33	166.08	156.93	161.75	164.80	159.25	159.88	158.58	166.59	161.94	167.45

Network											
	Proposed Baseline	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Number of Vehicles	2,837	2,839	2,793	2,927	2,860	2,855	2,818	2,984	2,810	2,760	2,722
Total Travel Time (h)	9,434	10,179	8,884	8,714	8,640	10,076	9,919	9,707	9,397	9,023	9,803
Total Distance (mi)	189,980	180,324	188,233	179,040	175,632	204,503	196,296	200,698	207,232	191,097	176,750
Total Delay (h)	6,160,418	6,094,603	5,831,004	6,222,147	6,179,009	6,082,195	6,482,002	5,918,743	6,132,458	6,537,847	6,124,169
Per Vehicle											

	Proposed Baseline	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Average Speed (mph)	8.21	8.25	8.51	8.16	8.15	8.31	7.95	8.42	8.26	7.90	8.22
Average Delay (s)	222.31	219.85	212.81	225.11	225.02	219.32	230.65	214.80	220.57	234.12	220.88
Average Number of Stops	7.12	7.15	6.91	7.15	7.10	7.15	7.28	6.87	7.01	7.43	7.12
Average Stop Delay (s)	164.46	162.27	156.43	168.13	168.53	161.58	170.88	157.85	163.34	173.00	162.62

Network

	Proposed plus 5% Demand	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Number of Vehicles	2,731	2,754	2,698	2,794	2,743	2,721	2,729	2,861	2,680	2,684	2,639
Total Travel Time (h)	9,324	8,757	9,159	9,432	8,972	9,265	9,361	9,724	9,505	9,009	10,051
Total Distance (mi)	169,493	162,683	168,485	173,822	156,144	168,892	165,883	174,002	174,205	164,033	186,772
Total Delay (h)	5,694,698	5,672,318	5,400,164	5,688,011	5,902,166	5,552,144	5,785,518	5,575,665	5,751,568	5,833,527	5,785,902

Per Vehicle

	Proposed plus 5% Demand	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Average Speed (mph)	8.49	8.48	8.82	8.49	8.24	8.66	8.45	8.56	8.45	8.36	8.34
Average Delay (s)	212.52	210.84	203.29	213.22	222.45	207.20	213.56	209.49	213.65	216.24	215.25
Average Number of Stops	6.93	6.58	6.66	7.11	6.86	6.92	7.31	6.98	6.76	7.33	6.76
Average Stop Delay (s)	156.83	156.79	148.53	158.04	167.28	151.39	156.31	154.02	157.92	158.34	159.69

Network

	Proposed plus 15% Demand	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28

Number of Vehicles	2,485	2,508	2,454	2,508	2,518	2,497	2,507	2,597	2,486	2,419	2,356
Total Travel Time (h)	8,926	9,453	8,978	8,619	8,349	9,393	9,233	9,027	8,895	8,368	8,950
Total Distance (mi)	167,002	175,801	163,597	167,440	158,689	174,955	167,582	165,808	169,202	155,609	171,336
Total Delay (h)	4,802,775	4,847,984	4,511,795	5,037,585	4,814,587	4,923,724	4,790,394	4,701,937	4,720,494	4,862,493	4,816,756

Per Vehicle

	Proposed plus 15% Demand	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Average Speed (mph)	9.06	8.97	9.42	8.80	9.04	8.93	9.11	9.15	9.17	9.03	9.01
Average Delay (s)	193.82	195.66	183.69	204.29	195.06	197.94	191.68	190.41	189.87	195.44	194.22
Average Number of Stops	6.35	6.28	6.08	6.69	6.19	6.14	6.36	6.24	6.32	6.62	6.53
Average Stop Delay (s)	142.40	144.31	133.21	152.19	144.42	146.53	139.63	140.29	138.75	142.32	142.38

Network

	Alternative Baseline	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Number of Vehicles	2,835	2,839	2,791	2,927	2,851	2,852	2,816	2,984	2,805	2,764	2,720
Total Travel Time (h)	9,317	10,179	8,877	8,714	9,397	8,417	9,993	9,921	9,705	9,022	9,805
Total Distance (mi)	217,965	236,571	206,267	226,024	192,509	226,326	220,652	236,604	229,818	193,252	211,624
Total Delay (h)	6,154,968	6,107,839	5,897,642	6,153,857	6,118,717	6,130,245	6,474,060	5,914,109	6,141,208	6,511,867	6,100,133

Per Vehicle

	Alternative Baseline	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Average Speed (mph)	8.22	8.21	8.44	8.23	8.22	8.24	7.97	8.43	8.26	7.93	8.24
Average Delay (s)	222.18	220.37	215.27	223.05	222.93	221.61	230.08	214.18	220.84	233.08	220.37
Average Number of Stops	7.12	6.94	6.97	7.05	7.13	7.04	7.36	7.06	7.04	7.41	7.22
Average Stop Delay (s)	164.21	163.21	158.42	166.07	165.95	163.42	170.32	157.29	163.35	172.08	162.01

Network

	Alt. plus 5% Demand	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Number of Vehicles	2,729	2,754	2,698	2,794	2,741	2,717	2,727	2,861	2,671	2,686	2,638
Total Travel Time (h)	9,307	8,713	9,150	9,432	8,974	9,154	9,362	9,724	9,509	9,003	10,047
Total Distance (mi)	169,225	161,896	168,485	173,822	156,144	167,013	165,883	174,002	174,205	164,033	186,772
Total Delay (h)	5,687,640	5,634,624	5,415,839	5,687,721	5,900,812	5,561,549	5,812,901	5,583,397	5,668,849	5,833,394	5,777,318

Per Vehicle

	Alt. plus 5% Demand	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Average Speed (mph)	8.48	8.52	8.78	8.49	8.24	8.64	8.39	8.53	8.53	8.36	8.33
Average Delay (s)	212.32	209.54	203.81	213.29	222.09	207.48	214.36	210.15	211.02	216.16	215.30
Average Number of Stops	6.94	6.62	6.61	7.10	7.00	6.91	7.15	7.05	6.86	7.33	6.80
Average Stop Delay (s)	156.80	155.15	149.18	158.11	166.92	151.99	157.98	154.80	155.51	158.29	160.11

Network

	Alt. plus 15% Demand	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Number of Vehicles	2,486	2,508	2,454	2,508	2,518	2,497	2,507	2,597	2,486	2,425	2,356
Total Travel Time (h)	8,926	9,453	8,978	8,619	8,349	9,393	9,233	9,027	8,895	8,367	8,950
Total Distance (mi)	167,002	175,801	163,597	167,440	158,689	174,955	167,582	165,808	169,202	155,609	171,336
Total Delay (h)	4,800,348	4,851,905	4,493,245	5,037,520	4,814,579	4,923,869	4,790,410	4,702,068	4,710,415	4,862,650	4,816,824

Per Vehicle

	Alt. plus 15% Demand	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Average Speed (mph)	9.07	8.96	9.45	8.80	9.04	8.93	9.12	9.15	9.20	9.03	9.02
Average Delay (s)	193.57	195.70	182.98	204.14	194.92	197.76	191.53	190.22	189.20	195.25	194.02

Average Number of Stops	6.34	6.24	6.11	6.69	6.18	6.14	6.36	6.24	6.27	6.61	6.52
Average Stop Delay (s)	142.20	144.23	132.70	152.08	144.32	146.40	139.52	140.15	138.17	142.18	142.23

APPENDIX D. SURROGATE SAFTEY ASSESSMENT MODEL

Raw Data

Existing Bikes Baseline

	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	4962	4316	4345	4501	4371	4796	4459	4450	4700	4567
Rear-End	14448	14173	14548	13804	14034	15188	14410	14638	15237	14287
Lane-Change	3743	3520	3715	3600	3646	3978	3881	3734	4123	3830
Average	7717.67	7336.33	7536.00	7301.67	7350.33	7987.33	7583.33	7607.33	8020.00	7561.33
Total	23,153.00	22,009.00	22,608.00	21,905.00	22,051.00	23,962.00	22,750.00	22,822.00	24,060.00	22,684.00

Existing Bikes plus 5% Demand

	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	4413	3820	4091	4279	3969	4223	4329	4084	4185	4227
Rear-End	13286	13427	13888	13251	13627	14393	13496	13642	14217	13402
Lane-Change	3532	3205	3378	3476	3267	3584	3453	3641	3590	3383
Average	7077.00	6817.33	7119.00	7002.00	6954.33	7400.00	7092.67	7122.33	7330.67	7004.00
Total	21,231.00	20,452.00	21,357.00	21,006.00	20,863.00	22,200.00	21,278.00	21,367.00	21,992.00	21,012.00

Existing Bike plus 15% Demand

	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	2310	2014	2254	1994	1952	2093	1806	1811	2071	2045
Rear-End	10428	9619	10405	10234	9760	10539	9745	10249	10386	10654
Lane-Change	2819	2606	2788	2884	2410	2834	2567	2834	2867	2875
Average	5185.667	4746.333	5149	5037.333	4707.333	5155.333	4706	4964.667	5108	5191.333
Total	15,557.00	14,239.00	15,447.00	15,112.00	14,122.00	15,466.00	14,118.00	14,894.00	15,324.00	15,574.00

Average Number of Conflicts Per Vehicle by Type

Existing Bikes Baseline										
	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	0.18	0.16	0.16	0.17	0.16	0.18	0.17	0.17	0.17	0.17
Rear-End	0.54	0.53	0.54	0.51	0.52	0.56	0.54	0.54	0.57	0.53
Lane-Change	0.14	0.13	0.14	0.13	0.14	0.15	0.14	0.14	0.15	0.14
Average	0.29	0.27	0.28	0.27	0.27	0.30	0.28	0.28	0.30	0.28
Total	0.86	0.82	0.84	0.81	0.82	0.89	0.85	0.85	0.89	0.84

Existing Bikes plus 5% Demand										
	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	0.17	0.15	0.16	0.17	0.15	0.16	0.17	0.16	0.16	0.17
Rear-End	0.52	0.52	0.54	0.52	0.53	0.56	0.53	0.53	0.56	0.52
Lane-Change	0.14	0.13	0.13	0.14	0.13	0.14	0.13	0.14	0.14	0.13
Average	0.28	0.27	0.28	0.27	0.27	0.29	0.28	0.28	0.29	0.27
Total	0.83	0.80	0.83	0.82	0.81	0.87	0.83	0.83	0.86	0.82

Existing Bike plus 15% Demand										
	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	0.10	0.09	0.10	0.09	0.09	0.09	0.08	0.08	0.09	0.09
Rear-End	0.46	0.43	0.46	0.45	0.43	0.47	0.43	0.46	0.46	0.47
Lane-Change	0.13	0.12	0.12	0.13	0.11	0.13	0.11	0.13	0.13	0.13
Average	0.23	0.21	0.23	0.22	0.21	0.23	0.21	0.22	0.23	0.23
Total	0.69	0.63	0.69	0.67	0.63	0.69	0.63	0.66	0.68	0.69

Raw Data

Proposed Bike Baseline

	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	4255	3609	3842	4325	3736	4192	3642	3907	4052	3851
Rear-End	13360	13111	13451	12829	13249	14336	13430	13282	14514	13449
Lane-Change	3429	3232	3564	3399	3378	3727	3356	3623	4193	3787
Average	7014.667	6650.667	6952.333	6851	6787.667	7418.333	6809.333	6937.333	7586.333	7029
Total	21,044.00	19,952.00	20,857.00	20,553.00	20,363.00	22,255.00	20,428.00	20,812.00	22,759.00	21,087.00

Proposed Bike plus 5% Demand

	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	3668	3129	3436	3678	3355	3689	3391	3496	3682	3564
Rear-End	12415	12237	12264	12293	12818	12900	12393	12757	12864	12510
Lane-Change	3279	3074	3460	3023	3113	3434	3282	3638	3272	3356
Average	6454	6146.667	6386.667	6331.333	6428.667	6674.333	6355.333	6630.333	6606	6476.667
Total	19,362.00	18,440.00	19,160.00	18,994.00	19,286.00	20,023.00	19,066.00	19,891.00	19,818.00	19,430.00

Proposed Bike plus 15% Demand

	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	2973	2460	2720	2759	2382	2881	2580	2737	2826	2789
Rear-End	10709	10393	10637	10519	10457	10695	10483	10542	11031	10809
Lane-Change	2661	2271	2927	2649	2501	2585	2596	2763	2807	2907
Average	5447.667	5041.333	5428	5309	5113.333	5387	5219.667	5347.333	5554.667	5501.667
Total	16,343.00	15,124.00	16,284.00	15,927.00	15,340.00	16,161.00	15,659.00	16,042.00	16,664.00	16,505.00

Average Number of Conflicts Per Vehicle by Type

Proposed Bike Baseline										
	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	0.16	0.13	0.14	0.16	0.14	0.16	0.14	0.15	0.15	0.14
Rear-End	0.50	0.49	0.50	0.48	0.49	0.53	0.50	0.49	0.54	0.50
Lane-Change	0.13	0.12	0.13	0.13	0.13	0.14	0.12	0.13	0.16	0.14
Average	0.26	0.25	0.26	0.25	0.25	0.28	0.25	0.26	0.28	0.26
Total	0.78	0.74	0.77	0.76	0.76	0.83	0.76	0.77	0.85	0.78

Proposed Bike plus 5% Demand										
	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	0.14	0.12	0.13	0.14	0.13	0.14	0.13	0.14	0.14	0.14
Rear-End	0.48	0.48	0.48	0.48	0.50	0.50	0.48	0.50	0.50	0.49
Lane-Change	0.13	0.12	0.14	0.12	0.12	0.13	0.13	0.14	0.13	0.13
Average	0.25	0.24	0.25	0.25	0.25	0.26	0.25	0.26	0.26	0.25
Total	0.76	0.72	0.75	0.74	0.75	0.78	0.74	0.78	0.77	0.76

Proposed Bike plus 15% Demand										
	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	0.13	0.11	0.12	0.12	0.11	0.13	0.11	0.12	0.13	0.12
Rear-End	0.48	0.46	0.47	0.47	0.46	0.48	0.47	0.47	0.49	0.48
Lane-Change	0.12	0.10	0.13	0.12	0.11	0.11	0.12	0.12	0.12	0.13
Average	0.24	0.22	0.24	0.24	0.23	0.24	0.23	0.24	0.25	0.24
Total	0.73	0.67	0.72	0.71	0.68	0.72	0.70	0.71	0.74	0.73

Raw Data

Alternative Bike Baseline

	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	4068	3674	3871	4371	3746	4210	3671	3906	4075	4028
Rear-End	13562	13390	13400	12830	13518	14208	13430	13429	14515	13298
Lane-Change	3534	3364	3816	3409	3364	3863	3364	3545	4198	3586
Average	7054.667	6809.333	7029	6870	6876	7427	6821.667	6960	7596	6970.667
Total	21,164.00	20,428.00	21,087.00	20,610.00	20,628.00	22,281.00	20,465.00	20,880.00	22,788.00	20,912.00

Alternative Bike plus 5% Demand

	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	3746	3189	3444	3650	3365	3724	3288	3504	3689	3528
Rear-End	12322	12262	12278	12320	12879	12657	12324	12390	12860	12418
Lane-Change	3286	3093	3452	3130	3013	3327	3334	3199	3274	3296
Average	6451.333	6181.333	6391.333	6366.667	6419	6569.333	6315.333	6364.333	6607.667	6414
Total	19354.00	18544.00	19174.00	19100.00	19257.00	19708.00	18946.00	19093.00	19823.00	19242.00

Alternative Bike plus 15% Demand

	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	3004	2427	2756	2804	2438	2936	2619	2815	2871	2853
Rear-End	10710	10384	10644	10522	10455	10698	10483	10504	11032	10811
Lane-Change	2687	2117	2927	2657	2506	2595	2599	2753	2817	2911
Average	5467	4976	5442.333	5327.667	5133	5409.667	5233.667	5357.333	5573.333	5525
Total	16401.00	14928.00	16327.00	15983.00	15399.00	16229.00	15701.00	16072.00	16720.00	16575.00

Average Number of Conflicts Per Vehicle by Type

Alternative Bike Baseline										
	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	0.15	0.14	0.14	0.16	0.14	0.16	0.14	0.15	0.15	0.15
Rear-End	0.50	0.50	0.50	0.48	0.50	0.53	0.50	0.50	0.54	0.49
Lane-Change	0.13	0.12	0.14	0.13	0.12	0.14	0.12	0.13	0.16	0.13
Average	0.26	0.25	0.26	0.26	0.26	0.28	0.25	0.26	0.28	0.26
Total	0.79	0.76	0.78	0.77	0.77	0.83	0.76	0.78	0.85	0.78

Alternative Bike plus 5% Demand										
	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	0.15	0.12	0.13	0.14	0.13	0.15	0.13	0.14	0.14	0.14
Rear-End	0.48	0.48	0.48	0.48	0.50	0.49	0.48	0.48	0.50	0.48
Lane-Change	0.13	0.12	0.13	0.12	0.12	0.13	0.13	0.12	0.13	0.13
Average	0.25	0.24	0.25	0.25	0.25	0.26	0.25	0.25	0.26	0.25
Total	0.76	0.72	0.75	0.75	0.75	0.77	0.74	0.75	0.77	0.75

Alternative Bike plus 15% Demand										
	Seed 1	Seed 4	Seed 7	Seed 10	Seed 13	Seed 16	Seed 19	Seed 22	Seed 25	Seed 28
Crossing	0.13	0.11	0.12	0.12	0.11	0.13	0.12	0.13	0.13	0.13
Rear-End	0.48	0.46	0.47	0.47	0.46	0.48	0.47	0.47	0.49	0.48
Lane-Change	0.12	0.09	0.13	0.12	0.11	0.12	0.12	0.12	0.13	0.13
Average	0.24	0.22	0.24	0.24	0.23	0.24	0.23	0.24	0.25	0.25
Total	0.73	0.66	0.73	0.71	0.68	0.72	0.70	0.71	0.74	0.74