Safety Evaluation of a Shared Bus-Bike Lane (SBBL) using Video Recorded Conflict Data

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Focusing on promoting sustainable transportation, cities such as Pittsburgh have been implementing infrastructures to move alternative modes such as transit and bicycles. However, limited by the current road framework which focus on automobiles, decision makers have to creatively retrofit the streets to accommodate these modes. This dissertation research analyzes a newly-implemented Contra-Flow Shared Bus-Bike Lane (SBBL) in Downtown Pittsburgh and evaluates the safety level for cyclists by scrutinizing video data recorded for 192 hours in several corridor intersections. The evaluation compares the SBBL with the opposite General lane and it is based on both the amount of interactions that a cyclist had with a motor vehicle and number of instances that a cyclist did an unwanted maneuver.

Multiple conclusions could be taken from this study. Mainly, the safety benefits of a SBBL for the cyclists are palpable, as the conflict rate between cyclists that interact with motor vehicles against the total number of cyclists recorded goes down to half (42.84% interacted with vehicles the general lane while only 18.10% cyclists in SBBL had to interact with a bus). Regarding undesirable movements that may put the cyclists and/or others at risk, the SBBL cyclists did have higher rates (17.40% of all SBBL cyclists performed a high-risk maneuver vs. 8.82% General Lane's cyclists) however those number are interpreted as related to connectivity issues between the Smithfield corridor and another bike infrastructure.

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Preface

This research was instigated by the City of Pittsburgh's Department of Mobility and Infrastructure (DOMI) and its desire to evaluate the new Shared Bus-Bike Lane implemented at Smithfield Street in downtown Pittsburgh, Pennsylvania. A report is expected to be produced and delivered that contains the results of this study and its methodology for the Department's future reference. Thanks to Paige Anderson from DOMI for approaching the Department of Transportation Engineering at the University of Pittsburgh, giving us the opportunity to study a Shared Bus-Bike Lane up close.

The researcher wants to acknowledge his advisor, Keith Johnson, for being available throughout the whole process of thesis development and providing invaluable input and guidance, particularly with regards to methodology and data analysis. Thanks are due to the co-advisor, Mark Magalotti, for his great help in guiding the literature review and development of the methodology, also for inviting me to pursue my Master's degree at the University of Pittsburgh.

On a personal note, I want to acknowledge my family for providing me emotional support, even from far away, to pursue my dream of continuing the academic path and thanks to my friends, in Pittsburgh or elsewhere, for helping me in this path.

1.0 Introduction

In this introductory section, the author sets an overview on the urban transportation network dependence on motor vehicles and the needed promotion of alternative modes, in particular buses and bikes and how the lack of road space pushes those modes to frequently share the same paths, leading to this study analyzed infrastructure, the Shared Bus-Bike Lane (SBBL), and its implementation in Downtown Pittsburgh.

Beyond, it presents the hypothesis that a SBBL are a safe infrastructure for cyclists and a safer infrastructure than a general traffic lane. For that, a methodology was developed based on cyclists' interactions with vehicles and unexpected maneuvers to test the hypothesis. The operation was video-recorded and humanly analyzed in order to draw conclusions.

1.1 Background

In the 20th century, humankind saw major revolutions regarding road transportation with the popularization of automobiles. The private motor vehicles molded the urban road and highway planning for most part of the last century with an iron hand and setting aside other modes of transportation that could threaten its hegemony. As road speed limits are increased, pedestrians and cyclists had to withdraw their space in order to keep their own physical safety as the most vulnerable elements. On the other hand, the public transport, which had a peak during the beginning of the century, lost relevance for not being reliable enough to counter the comfort provided by a single occupancy vehicle.

However, in the last decades of the past century and beyond this century, a movement started to form against automobiles. This movement points out that after decades of providing roads for automobiles, traffic congestion has only gotten worse and the ever-increasing vehicular fleet has been one of the biggest contributors to emissions that are accelerating the climate change and has effectively worsen the quality of life in large urban conglomerations.

Multiple solutions have been proposed to reduce personal/single occupancy vehicle ridership. Two options given by multiple scholars and planners are the promotion of public transportation and cycling. An increase in the usage of public transportation would show instantaneous benefits to traffic congestion and could also reduce the fuel emissions considerable achieving equable distances to personal vehicles. On the other hand, increasing cycling would produce similar gains against traffic congestion but at the same time it would have far superior results in reducing emissions. Both modes have strong cases to be promoted going forward and cities around the world have been trying to balance the promotion of both modes concurrently, Pittsburgh included.

In the past few years, Pittsburgh have been promoting a higher usage of sustainable modes of transportation in its Downtown area. A separated bike route has been implemented in Penn Avenue and many of the main corridors are designated shared lanes between vehicles and bikes. Buses are also constant in the Downtown scenario. Over 80 bus routes travel inside the area and in 2017, the city implemented a bus only lane in part of Liberty Avenue.

However, there is not enough space to promote both modes while still accommodating private vehicle demand. To work around this limitation the City of Pittsburgh's Department of Mobility and Infrastructure has proposed and adopted a Shared Bus-Bike Lane (SBBL) in portions of 3 downtown corridors. This research is interested in evaluating the success of this policy in terms of safety, operations and promotion of both buses and bikes ridership, in particular, the one implemented in Smithfield Street, which is a contra-flow Shared Bus-Bike Lane. A Shared Bus-Bike Lane provides a lane free of automobiles for the buses to operate more efficiently but allowing bicycles to travel along the lane. The assumption is that the lower motorized traffic volume would give cyclists a similar feeling to traveling in a bike exclusive infrastructure. The analyzed infrastructure is also a contra-flow infrastructure which may add issues and controversy to the implementation, as it may increases some perceived risks adherent to the infrastructure.

The research provides conclusive data for cities and planners worldwide to make informed decisions on the implementation of Contra-Flow Shared Bus-Bike Lanes, Shared Bus-Bike Lanes and other shared facilities between buses and bikes. It also provides planners and scholars an innovative methodology to evaluate the operations on shared facilities and their safety for cyclists, based on conflicts with motor vehicles and risk maneuvers made by cyclists.

1.2 Hypothesis

The hypothesis of this work is that Contra-Flow Shared Bus-Bike Lanes (SBBL) are a viable roadway operational strategy that provides both sustainable transportation modes (Buses and Bicycles) and significant improvements in terms of safety and efficient mobility. Through implementing a SBBL it is expected that said shared lane with buses will provide cyclists a safer travel environment than the shared lanes with general traffic in an urban environment. Also, for the public transportation, the hypothesis also basis that the presence of bicycles in a lane that operate only buses will not hurt the operations and efficiency of the buses thanks to the short length of the SBBL corridor, the short distance between bus stops and the relative low speeds that are allowed for buses in the corridor.

However, there is very little research or operational experience to determine if this strategy for bicycles improves safety when compared to the use of shared lanes. This research will evaluate and compare general traffic lane usage to SBBL usage by bicyclists to determine if SBBLs create a safer environment.

And even the previous literature review on SBBL's around the world have limited influence under the research that will proceed in the Shared Bus-Bikes lanes in Downtown Pittsburgh as those lanes have two significant characteristics that are dissonant from most examples. First, the lanes where the sharing environment is operated have a limited capacity regarding comfortable width. The SBBL corridor has narrow portions of 10 and 11 feet wide and the widest sections goes to 12 feet, which is below the recommended in some guidelines. For that reason, overtakes are not recommended from either the bikes or the buses, au contraire than most shared lanes.

The second element is even more singular in the usual roadway configuration, let alone coupled with another rare element that is the Shared Bus-Bike Lane. Contra-flow lanes are implemented to provide a specific minority mode (e.g. Bus Rapid Transit) a path in the same corridor which could be still be named as a one-way road. In most cases, the contra-flow lane provides the path for a single mode, however, in Pittsburgh the contra-flow lane is shared between two minority modes, while the one-way flow is composed by general traffic with no prioritization.

To this extent, we are looking not just into a common Shared Bus-Bike Lane such as the ones famously used in Paris, or other examples used in American cities such as Philadelphia, Boston and Minneapolis. The Pittsburgh SBBLs had to be adjusted to fit the built environmental in the city's downtown district. The planners involved in this project connected a series of innovations based on previous experiences of other cities (While mainly of said innovations are applied individually) to surpass the infrastructure limitations.

1.3 Objectives

This research was developed in response to the City of Pittsburgh Department of Mobility and Infrastructure (DOMI) request to determine how practical the SBBL's are and what would be the correct methods to evaluate the safety of this strategy which was recently implemented in the central business district of the City of Pittsburgh.

The main goal for this research is, responding to the hypothesis, understand and evaluate the current operation of the studied SBBL and compare to the safety aspects for cyclists of said infrastructure to a general traffic lane. Objectives within the goal and scope of this project are: To collect and review literature on Shared Bus-Bike Lanes; Review established safety evaluation methodologies and safety data sources; Create a new methodology for safety that could be easily replicated by DOMI's officials; Observe and collect data on the operation of a Shared Bus-Bike Lane in Downtown Pittsburgh, Pennsylvania and Provide data totals and conclusions in organized manner, consistent to the proposed new methodology.

1.4 Methodology

The main methodology applied in this research study was the analysis of the interactions between buses and bicycles in the Smithfield SBBL and how those interactions would make the cyclists uncomfortable or feel unsafe while riding in the lane in comparison to shared lane, open to automobiles. These interactions were gathered through filming of four intersections in the corridor, selected in meetings and discussions with research stakeholders. Each intersection was filmed for a little over 48 hours during weekdays and weekends, providing a great off-peak database alongside 4 peak periods.

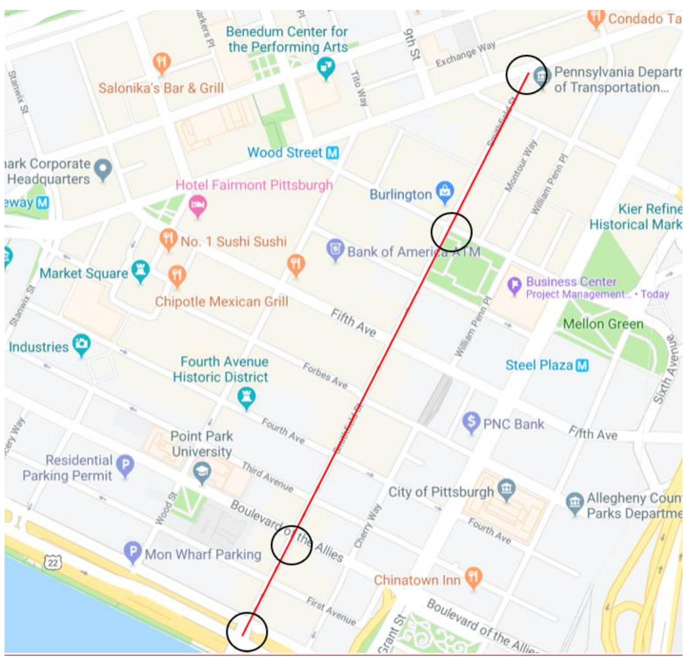


Figure 1: Smithfield Street and analyzed intersections

Interactions were categorized in three groups depending on the positioning of the bike and other vehicles involved and called “Conflicts” as those may result in potential interactions. Additionally, a second section of data was collected and analyzed to encompass movements that may be unlawful and dangerous or simply undesirable. This second subsection is named as "Issues" through this work. The analyses delve into comparisons between the Contra-flow SBBL and the opposing general lane and comparisons between the analyzed intersections. These analyses provide enough understanding to qualify the SBBL as a safe cycling environment and to note if any of the intersections picked had particular issues.

1.5 Summary

This research arose from the need of City of Pittsburgh Planners to assess the safety levels that bike riders were exposed to when using the Shared Bus-Bike Lane implemented in Smithfield Street. The author of this study took advantage of this need and used this opportunity to evaluate the viability of SBBLs as a safe infrastructure to promote cycling. The author aimed to collect and comparatively analyze the amount of conflicts that cyclists are susceptible to and the number of unexpected maneuvers that cyclists started when using the SBBL compared to a general traffic lane, which does not have any vehicle restrictions. The methodology applied in this study is innovative because it evaluates an uncommon infrastructure in American cities in which the literature does not have a well-defined safety assessment method. The expected output of this work is a sound methodology that city planners from Pittsburgh and other cities around the United States and world can use in the future to assess the potential safety levels of a project such as Shared Bus-Bike Lane.

2.0 Literature and Context Review

The literature review of this study addresses three topics. The first two topics are used to contextualize their relevance to the sustainable transportation engineering scenario and the development of Pittsburgh city. The third topic focuses on the object of study, Shared Bus-Bike Lane, as a transportation infrastructure, implemented and evaluated around the world. In the first topic, we use the National Association of City Transportation Officials (NACTO) literature to provide context on both modes' desired infrastructure. Regarding Pittsburgh, newspapers, opinion articles and public announcements are used as main sources to give contextualization on the public perception. For our SBBL oriented topic, the author decided to use research articles and study reports as the respective topic that would go on to build the methodology.

2.1 Sustainable Transportation

Sustainable transportation has been an important topic of discussion as it will play a major role in the future of our cities that keep expanding exponentially. The following subsections touch on two alternatives modes of transportation that are presented as part of the solution for cities, their precepted benefits, infrastructure guidelines to accommodate each mode and how each mode is being promoted internationally and in the United States.

2.1.1 Bus Lanes and Bus Promotion

In order to achieve a satisfactory quality of life in large urban centers, it is necessary that their inhabitants have to move quickly and efficiently within cities. For most of the population, this mobility is achieved by private cars, which make the travel of its users fast and comfortable.

But once the mobility problem seems simple, most will try to migrate to the same mode. With most users within their own vehicles, the available road space becomes smaller and traffic jams more frequent. What was once a fast way of getting around is stuck in the face of long traffic jams and comfort gives way to the growing nervousness of being surrounded by air and noise pollution.

The increase in the car fleet in the second half of the last century continues to march upwards today, and scholars are already warning of the need for a paradigm shift in urban transport. Multiple alternatives have already been put to the table, but one of the most important solutions is already present in the urban environment but has its potential cut by the uneven volume of private cars.

When well planned, bus systems can provide benefits similar to those of private vehicles in terms of mobility and accessibility within the urban network. However, the main benefit of buses against private vehicles is their passenger capacity. According to FHWA *Average Vehicle Occupancy Factors for Computing Travel Time Reliability Measures and Total Peak Hour Excessive Delay Metrics*, the average number of passengers per car (PPC) is 1.7. For buses in Pittsburgh (area of study of this research) this number is 10.8 PPC and in a large urban center like New York this number is almost 10 times more (16.8) PPC than the average of cars.

However, when buses share the same road space as cars, the disadvantages of not having control over the route, sharing the same vehicle with strangers and possibly the discomfort of a crowded bus are exponentially delayed by congestion delays.

To avoid these delays, one of the infrastructure solutions is to provide buses with a physically separate road, thus preventing them from having to interact (and hence be delayed by) cars. A well-known example of such a solution would be bus passageways and major BRTs, Bus Rapid Transit.

As most urban centers are already consolidated, it is impossible to build a physically separate road. Thus, local authorities decide to provide the next best alternative by indicating by traffic signs or street markings that one of the lanes is for bus use only. Lane intrusions by inattentive drivers can still occur, but the uniqueness of at least one lane will make bus movement more efficient.

Taking a clearer definition from NACTO’s Transit Street Design Guide, bus lanes can be described as a delimited section of a corridor in which the local authorities, by the way of signs and pavement markings, provide preferential roadway for buses. As these lanes are not physically separated from the corridor, these lanes may be avoided by buses in the event of an accident but may also invaded by cars.

The decision to implement a bus lane should consider factors such as emphasis on transit, future demand and reduction of total person delay. Bus lanes are normally implemented as substitutes for general traffic lanes or parking lanes, making for a more efficient use of the roadway. Its application is highly recommended for corridors where traffic suffers with congestion and delays. Smaller side-streets are also candidates for bus lanes.

Public transit has been promoted as a solution for the 21st century problem of growing population and megacities but that could also be applied in smaller scale for medium and small cities with dispersed population. The European Union notes public transit was a major action in their package to incentivize efficient urban mobility, promoting projects such as the CIVITAS (CIty-VITAlity-Sustainability). Working with CIVITAS, Oktábcová (2012) proposes that to promote transit among other goals, it should highlight advantages over individual vehicles and improve accessibility to services.

While the United States is not in the same level of promotion of public transportation, specifically bus systems, when compared to European countries, the government has, at the very least, noticed that gap and put out statements encouraging cities to promote transit. Within the mission of the U.S. Department of Transportation, it is noted that transit brings not only mobility but improvements to public health. Benefits on reduction of air pollution, lower crash rates and promoting active transportation just to name a few.

2.1.2 Bike Lanes and Bike Promotion

The promotion of urban cycling has also been pushed as alternative for cities overpopulated with cars. While transit systems, like buses are presented as an alternative to move the highest amount of people in the quickest time possible, bikes cannot provide similar benefits, but they bring a new set of advantages to the table.

The first and main argument for a bike against other modes is the absence of fuel emissions. It is fair to say that the majority of the bicycle fleet current in the streets is composed by human-powered bike. A shift may be seen in the future with the growing popularity of electric-assisted bicycles (E-bikes) but most cyclists today uses their own strength to propel their vehicle. Common bikes will only produce significant emissions during its production and disposal while motorized vehicles will keep producing significant emissions during its use in addition to the aforementioned phases of its life cycle. Even e-bikes, with the electricity used, are expected to have a lower carbon footprint.

Another huge benefit for bikes against cars is that effective use of road space. First, thanks to its small size, bicycles are easy to maneuver and can fit into tight corridors of traffic jam, making the bicycle a faster mode than jammed vehicles. This is particularly better seen in urban downtowns and business districts, already overloaded with cars.

Still in-road space usage, while for buses, a good numeric indicator against car is the average number of passengers per vehicle, said number for bikes is ideally one (unless sidecar is provided). A better way to mathematically look at the benefits of bikes is the ratio between average numbers of passengers divided by the road space utilized by the vehicle. A crowded bus may have a higher ratio; however, bikes will provide the highest ratio in most scenarios due to its small frame.

Table 1: Ratio of Average Passenger per Vehicle Ocuppied Road Area

Vehicle	Average Passenger per Vehicle (PPC) (1)	Occupied Area per vehicle (sqft) (2)	Occupied Area/Passenger (sqft/PPC)
Car	1.7	133	78.24
Bus	10.8	386.75	35.81
Bicycle	1.0	12 (3)	12

Sources:
1: U.S, DOT, 2018
2: AASHTO, 2011
3: Ross, 2013

As it was done for the bus lane review, the following definition for bike lanes (shared or exclusive) or friendly infrastructure was referenced from NACTO's specific guidebook for this mode, *Urban Bikeway Design Guide*. The book characterizes bike infrastructure for a portion designed to accommodate cyclists alongside other vehicles. Those lanes are preferably on the same flow of the rest of the traffic (But could be designed for contra-flow) and cyclists are encouraged to ride near the curb to the right. Much like a bus lane, it suggested thoughtful consideration of traffic levels, current and future, as well as safety conditions before implementing a bike route. NACTO's guide also feature contra-flow bike lanes. It is noted that it may introduce new conflicts and it should be accompanied by buffers.

Europe as a continent is a huge exponent on the promotion of cycling. Through the European Commission, the European Union notes cycling as a transportation mode that is relative cheap, efficient in urban areas and provides health benefits. In the 2010 document, *The Promotion of Cycling*, the European Cyclists Federation in collaboration with the EU, calls on local authorities to invest planning efforts on accommodate cyclists. They note that it's not feasible to build separate infrastructure for cyclists in the short term and soft measures can be taken to then be followed by more audacious plans.

In the US, the cycling movement has steadily gaining relevance but on slow steps. In 2011, John Pucher et Al published a work noting how bikes had the potential to swipe away a good share of car trips but was mainly impeded especially by cultural differences and public image of bikes. Like others in the literature, Pucher notes that infrastructure by itself will not bring more bikers to the street, even though it certainly helps. For cycling to keep gain relevance across the United States, it has to engage public and political support while confronting automobiles as antagonists.

2.2 Area of Study: Pittsburgh

In order to better understand our body of study, it is important to understand the context in which the body is located. The following subsections present historical context of Pittsburgh in regards their boldness, successes and mistakes in regards to promoting transportation alternatives and sustainable urban development as the city tries to move away from their dirty past due to steel industry dependence and the pollution that came with it.

2.2.1 Transportation History

Pittsburgh has been nation-wide known as the city of bridges with over 400 bridges, crossing through its three rivers and various creeks and chasms around. This characteristic has been one of the major features in the transportation planning throughout the city's history, however it's not even one. Another very challenging characteristic of Pittsburgh for active transportation modes is its topography. The city has over 700 steps to help pedestrians overcome the slopes while cyclists must cope with steep roads all around. Not to mention that both suffer with the arrival of winter.

With the winter and topography working against active transportation, bicycles never had much of a say in the city's transportation planning. There are few records of Pittsburgh planning that discussed bicycle accommodation in the major corridors and that does not mean that Pittsburgh did not have innovative ideas regarding transportation. The history of streetcars in Pittsburgh is rich and the busway, at the time of its opening, as one of the very early bus-priority elements implemented in North America.

For most of U.S. history, Pittsburgh has been one of its largest cities and with that, the need for efficient mass transit is evident. The first record of public transit in Pittsburgh dates to 1859, carriage powered by horses. Thirty years later, streetcars and trolleys took over as the main mode of transportation for Pittsburghers, which would peak in ridership in the 1920s. However, like many other American cities, Pittsburgh suffered with increased levels of suburbanization, rendering public transit obsolete, as it can only take riders limited distances.

With the reduced numbers in ridership, the multiple transit companies that operated had to be consolidated in a single entity in order to better answer the transportation needs of the city, forming the Port Authority of Allegheny County (PAAC). In the second half of the last century, streetcars are phased out in favor of convectional buses. Years later, Pittsburgh would start working with light rail system, which can be qualified as heir to the streetcars, but in a much smaller scale.

Shortly after its formation, PAAC started to plan how would serve Pittsburgh community in the following century. One of the steps taken was the planning and implementation of busways. Like Bus Rapid Transit, those busways would provide buses with roadway free of the general traffic, in which the buses could operate close to its ideal speed and schedule. Nowadays, the City of Pittsburgh possess three busways that extends over 18 miles and carries and forty thousand passengers per day according to BRTdata.org.

While having the busways has helped evolving the overall level of service of the bus operations in Pittsburgh, there is still room for improvement. For that, PAAC partnering with local authorities has implemented other works through the city. Examples of such are the Shared Bus-Bike lanes in Wood and Smithfield Streets, the Bus Only lane stretch in Liberty Avenue and the future opening of the Pittsburgh BRT system, connecting the two main neighborhoods of the City (Oakland and Downtown).

2.2.2 Sustainability Promotion

Public works like the SBBL in Smithfield Street have picked up steam in the past few years as Pittsburgh has committed itself to charge into a more sustainable future. Even beyond the “City of Bridges” moniker noted earlier the most popular nickname for Pittsburgh is “Steel City” regarding the city’s past as a major steel producer. The steel industry helped Pittsburgh develop through the 19th and 20th centuries and achieved an enviable position. However, such a development came with a high environmental price.

The various factories placed alongside the three rivers would deposit pollutants straight into the water, polluting the rivers water to a level that even today there is concern with the potability of Pittsburgh waters. Also, the furnaces from the steel factories would add air pollution to the city in the daily basis. The fumes produced by the factories would be such that there are historical records of streetlights being lit during the hours of sunshine such was the shadow cast by pollution over the city.

A second price would come in the socio-economic aspect with the deindustrialization, which saw steel manufacturers leave Pittsburgh and throw the city into a crisis for the last two decades of the past century.

For a return to thriving times, Pittsburgh has been betting on staying ahead, attracting and/or providing incentives companies like Google, Duolingo and Uber, who are leaders in new markets. Not to repeat the mistakes of the past in which he sought a hasty and relatively unconscionable development, Pittsburgh community and officials have been pushing hard to build a sustainable Pittsburgh on the back of the form Dirty Burgh.

Examples of the quest for sustainability and improvement in the quality of life in Pittsburgh from within the community are groups such as Group Against Smog and Pollution (GASP), which is over 50 years old promoting clean air in Pittsburgh or newer groups such as BikePGH, active participant in the city's discussions on pushing the active transportation forward.

This section was focused on presenting that the SBBL implementation is not happening in a vacuum but is an expected step in the Pittsburgh evolution both in the transportation aspect but in the sustainability one. However, this research objective is to find out if this next step is the right one in regard of safety or if the hunt for these goals is overlooking serious safety problems.

2.3 Shared Bus-Bike Lanes and Interaction Between Modes

As already noted in previous parts of this study, Shared Bus-Bike Lanes are not a usual transportation infrastructure, so its unsurprisingly that its respective research on safety conditions is relatively small compared to other bike infrastructures. The following subsections goes in as much detail as possible in each article or report collected in order for the research have a strong scientific basis. The section is divided in three subsections. The first presents articles that discuss the interactions between buses and bikes and the intrinsic risks to crashes, however those articles only mention Shared Bus Lanes or Shared Bus-Bike Lanes as alternatives and do not go into detail about a Shared Lane Operation. The operation standpoint is presented on the second subsection, which contains both articles and a report of a traffic study on shared bus lanes in London, England. The final subsection present reports with multiple case studies on shared bus-bike lanes.

2.3.1 Articles on Interactions between buses and bicycles

For various decision makers and even in the public perception, bikes and buses should be maintained in separated lanes due their discrepancies. Such vision also influenced academia research that did not envision this type of facility very often. The first article found that mentioned the interactions and conflicts among both modes and a shared facility was *Buses and bicycles: Design alternatives for Sharing the Road* by Michelle DeRobertis and Rhonda Rae in 2001.

DeRobertis and Rae (2001) noted how major cities in the U.S. have tried to make the interactions between buses and bicycles more natural as early as the end of the last century. They discussed how those cities have turned their attention in optimizing the design and configuration of the travel lanes of said models in order to mitigate the conflicts between them and presented the choices that produced positive results. DeRobertis and Rae work is one of the earliest that regards the interaction between buses and bikes as possible and corroborates with empirical evidence.

To base their work on engineering solutions to mitigate possible conflicts, first DeRobertis and Rae had to present the possible conflicts that could happen between the modes in the usual traffic scenario (shared lanes). The first scenario regards the moment where a bus needs to stop in its predefined stop to load and unload passengers. Such stops make the buses pull over by the curb side, which in many cases (With or without a specific bike lane) is the preferred travel path of a cyclist (As it will give other vehicles easier overtaking opportunities). Another conflict, less frequent, noted by them is the case of a wider curb lane in which the bus is expected to cross through in cyclist path to reach the stop.

Even though buses are motor vehicles, DeRobertis and Rae argument that buses and bicycles travel at similar speeds in a city environment thanks to an abundance of buses stops, which can be interpreted as reasoning for these modes work together. But they also note that the benefits of this great number of stops will also produce constant leapfrogging between modes. The cyclist will feel impelled to overtake the bus during the boarding process in a stop to continue its travel while the bus driver will want to overtake the cyclist along the corridor after reaching a higher speed to maintain the bus on the schedule.

Finally, they argument there is also an issue with a cyclist traveling behind a bus that could be a conflict, as those riders are responsible for speed adjustment during the bus weave movement towards the bus stop. The cyclist must be aware enough to notice if the driver is trying to reach the curb and adjust accordingly. Still, they noted that both cyclist and bus driver are responsible for the interaction and must have awareness to maneuver along each other.

DeRobertis and Rae presented eight alternative designs of which this review will focus on only a few in which buses and bikes travel in the very same lane. It is notable that most of them are focused on providing a higher level of service for the public transit while the bicycle mode is allowed to use the infrastructure. *Bus HOV lanes* reduce the congestion in comparison to a usual traffic lane however cyclists would be sharing the road not only buses with high occupancy and, usually, right-turning vehicles. They noted that the design is very volatile, depending on enforcement and bus headway.

The Nicollet Mall in Minneapolis was transit-exclusive mall that allowed bicycles to travel along its 10 blocks of length. The two-way corridor total width varies between 6 and 7 meters (20 to 22 feet). Even in its widest section, the corridor can only provide 11 feet for traffic. For that reason, overtakes by either mode are not permitted. The Nicollet Mall had a series of controversies related to its implementation. In 1993, after a cyclist death, transit drivers moved towards banning cyclists altogether from the mall, which failed after rallying efforts from the bicycle community. However, in 1998, a ban was passed after additional bike-exclusive lanes are installed in an adjacent road. As of 2019, the ban on bikes has already be lifted and they can travel alongside buses and taxis along the Nicollet Mall.

Another example from Minneapolis is the use of a contra-flow lane for buses only. This example is similar to the design used in Downtown Pittsburgh but in Minneapolis, the bikes are expected to travel in the concurrent flow traffic lane with automobiles and the buses are isolated in their exclusive lanes. That would make the cyclists less vulnerable to bus stops and weaving movements.

Being the one of the first studies on shared traffic lanes between bikes and buses, DeRobertis and Rae presented the SBBL as a controversial infrastructure with serious pushback from transit drivers. DeRobertis and Rae would serve as base for future studies in the Shared Bus-Bike Lanes.

DeRobertis and Rae presented a corridor in the United States as an example, sharing between buses and bikes and is more frequently applied internationally. For example, in *David and Goliath: bikes and buses together without throwing stones,* Ian Ker et al. (2004) based his study on Australian and British experiences. Ker et al. presents the argument that while bikes and buses are extremely disparate modes, especially in regard to its physical attributes, more frequently than not they are driven to operate in the same lanes, adjacent to the curb. The authors argument that both modes are substitute alternatives for private automobiles in city environments. This premise hopes that both modes would work together and while such hope is valid, conflict between these modes is also usually seen. That makes local authorities question which mode should receive more attention and be prioritized in urban planning in which the authors arguments that no sustainable mode should receive prioritization above the other.

Ker et al., as other authors, reiterate how both modes are located in different opposites poles of the traffic composition but brings a characteristic that is sometimes overlooked, which is the visibility for each mode. The usual length of a bus is 30 to 50 feet. Blind spots for such large vehicle are expected and when coupled with a barely visible bicycle (Around 6 feet long and 2 feet wide, generously), possible accidents are brewing during any interactions. For Ker, the interactions between goes towards three ramifications: First, issues with infrastructure capacity; Secondly; operational performance, which includes the safety of the travelers; And finally, perceptions of the travelers towards their trip.

Ker notes that several strategies have been advanced in order to promote sustainable means of transport as substitutes for cars, which are the majority in traffic. Those strategies vary between restricting vehicles in congested areas or by promoting the use of sustainable modes through beneficial impacts. However, Ker notes that while focusing strictly in the improvements generated, most of those strategies fail to observe the relationship between buses and bicycles. The provision of facilities for either mode hardly investigates providing adequate accommodations for the other.

Through review of several Australian and British plans and guidelines, Ker verified that documents focused on either of the sustainable modes and plans cared very little about the interactions between modes, looking at them separately. When looking at crashes involving both modes, Ker noted that only less 2% of the bicycle accidents in Western Australia involved a bus from 1987 to 1996. On fatal and serious injury crash data, Ker noted that one in each seven cyclists was severed injured in a crash do not survive.

Ker notes that while transportation planners can work in providing a safe travel for all users through design and management, there is a dimension which he holds little control over and that is the perception of travelers among themselves, especially those in privileged positions. About the perception of drivers towards cyclists, a UK survey among drivers pointed that bicycles are the third most disliked mode, behind only taxis and buses. For automobile drivers, cyclists are unaware of the visibility issues that come from using such a small vehicle among larger vehicles, opinion on that is more radical among drivers of heavy vehicles.

Regarding Shared Bus-Bike Lanes, Ker et al. looked at Australian and British guidelines for the best implementation of such infrastructure. They question if the gap between the modes' operational speed and the required bus stops would create issues in overtake maneuvers. Based on the guidelines, the authors recommend that when implemented, Shared Bus-Bike lanes must have adequate width throughout a continuous stretch so that overtakes are possible. The recommended width would be from 12 to 14 feet. Shared lanes below 12 feet are not recommended for not having enough space for a safe overtake maneuver, unless a localized widening is provided in points of interest such as bus stops. The corridor studied in our research provides 12 feet at it widest and goes down to 11 and 10 feet in parts of the corridor, below the width recommended by Ker et al. and their review.

Another early study about roadway sharing between buses and bikes used Montreal as its case study. As Montreal wanted to increase the bicycle usage in its Downtown area, Jolicouer (2005) analyzed issues that are working as barriers for that movement. The city, in partnership with nonprofit organization Velo Quebec, wanted to know what could be done to improve the experience of cyclists in terms of safety. Velo Quebec and Jolicouer researched practices from ten comparable cities and, based on such, formulated designs and scenarios to be implemented in the area to facilitate access and improve safety. The suggested schemes were also careful to maintain respect for other modes of sustainable transport (pedestrians and public transport).

Jolicoeur notes that the best way to promote and get the community involved in cycling is to invest in providing and maintaining bicycle facilities. During the preliminary planning for Downtown Montreal, the team at Velo Quebec came up with the *Plan d'accessibilité et de mobilité à vélo au centre-ville de Montréal* (Bicycle Accessibility and Mobility in Downtown Montréal) which compiles the research done and proposals for the City. The plan follows six guiding principles in its core. Two of those principles should be highlighted: First, the plan recommends to **ensure the continuity, homogeneity, and efficiency of bicycle routes;** The second principle recommends to **respect the priority of public transportation.**

Reviewing both principles, one would assume that the team at Velo Quebec would oppose a measure like an SBBL in a common case. The principle of homogeneity would mean that a bicycle facility should be used exclusively by cyclists, whom should not have to worry with sharing the path with motor vehicles. For the second principle, in order to respect the priority for buses, one would understand that it means giving them the priority for overtaking in the case they achieve a higher speed than a leading cyclist.

However, another part of the first mention principle can be used as argument for a SBBL. To provide continuity for bicycle facility, sometimes it is necessary to compromise and allow bicycle to travel with the general traffic or at very least traveling with limited modes, even if it's not the safest option. Velo Quebec and Jolicoeur themselves proposed to the city to allow cyclists to travel alongside a boulevard lane that is restricted to buses and taxis.

Said lane would be approximately 15 feet wide, giving motorized vehicles enough space to safely pass cyclists. Another point made by Jolicoeur to reinforce the safety improvement for cyclists is that the drivers in the shared lanes would be skilled, professional drivers. The public transportation would also see benefits in travel time and efficiency by no longer having to share the road with all general traffic but only with taxis and bikes, modes with a low number of the total mode split.

Jolicoeur points out that by implementing contra-flow lanes, the city of Montreal would be giving cyclists the opportunity to travel both directions in a one-way street, while the cyclist travelling with the flow would travel along the general traffic lane, the contra-flow cyclist would travel within a separate lane. These facilities are ideally implemented in one-way streets connected to major destinations.

In summary, the early works from DeRobertis and Rae, Ker et al. and Jolicouer et al. presented Shared Bus-Bike Lanes as a viable infrastructure option, opening the way to more detailed studies regarding the safety of those interactions. Following studies looked at the crashes that occurred during these interactions, in particular the rates of those compared to crashes involving bicycle and automobiles and the severity of crashes involving bikes and buses.as

Newcombe and Wilson (2011) investigated bicycle accidents that happened within a bus lane route in the City of Auckland, Australia. The authors noted that the Australian Transportation strategies do not point at which mode should be prioritized, either in the planning and design of the infrastructures or simply during a daily interaction. The lack of clarity is believed to facilitate accidents in interactions between those modes and the authors proposed to investigate if the decision of allowing two-wheeled vehicles into bus lanes created a safety hazard.

Newcombe and Wilson noted that cyclists are more vulnerable to casualties analyzing percentages in transportation splits and traffic fatalities related to mode. They also point out that out of all incidents involving cyclists, less than 5% of those are classified as the cyclist fault and the majority comes from either poor observation or failure to give way from the other parties involved. Cyclists are a vulnerable group in which crashes takes a harder toll and most often than not are not responsible for said crash.

The authors looked at four bus lanes routes implemented through the city. Three of the four lanes had a width of around 10 to 11 feet while the fourth one as 15 feet wide. They looked at crash records from each route of five years before and after the implementation. The general showed no conclusive pattern, with three of the four routes similar to slightly increased numbers that the authors considered to be related to the growth in the volume of cyclists. When looking at overtaking crashes all but one road showed increase in number. The one road that maintained the same number of crashes was the widest road observed while the road with biggest growth in crashes was the narrowest one.

The authors conclude that providing more width for shared bus lanes would reduce or at least maintain the number of crashes stable, while a narrow lane would likely increase the number. However, another option that was left unanswered by the authors, who are limited by the traffic enforcement, was the case of which neither the cyclist nor the driver is allowed to overtake. Other than the width and overtaking issues, the authors have not found other problems with the use of bus lanes by cyclists, but they also do not point out benefits of it as their results shows little effect of bus lanes in the safety of cyclists.

Another study on crashes was Morrison et al. (2019) where they looked into what characteristics of the bicycle infrastructure could lead up or prevent possible bicycle crashes. As bicycle volumes are considerably lower than vehicle volume in general traffic, Morrison et al. decided to focus on data that is more reliable as the physical characteristics can easily measure and compared through different application. However, an issue with such approach is that context on the surrounding area, culture of cycling and traffic law enforcement may be neglected.

Through previous studies, Morrison and his team noted how certain infrastructures are perceived as providing more safety to cyclists than others and his objective in this work was to provide a clear identification between the best solutions. The team compiled a database of close to 90,000 intersections and streets segments in Melbourne, Australia. Each of those observations contained the physical characteristics of the road (i.e. such as presence of bike lane, speed limits, traffic lane width). Additional to those variables, an extra dichotomous variable that indicated if there were any bicycle crashes in that segment in a three-year period. After that, the team modeled the data into regressive models.

The results from their work showed that all types of bike lanes do have a crash reduction effect on the streets they are implemented, as was expected. The study also found that bike lanes implemented alongside a bus route also reduces the crashes odds during interactions. It's good to note that Morrison and his team are focused on bicycle lanes as a homogenous path for the cyclist to travel, on the contrary of a shared bike/bus lane, where both modes would be interacting. This is the team reasoning behind the positive result for bike lanes on bus routes: That the infrastructure is making those modes work separately. The results also showed that bike lanes presence in narrow traffic lanes have a positive effect on crash safety.

Away from academia, a few traffic studies are also done by government organization. Under the Delaware Valley Regional Planning Commission (DVRPC), Krykewycz (2009) studied the conflicts in the interactions between buses and bikes, in Philadelphia, Pennsylvania while reviewing other instances where the lane sharing between these modes was allowed. The body of study for Krykewycz was for Walnut Street, which is a bus exclusive lane, and his focus was in the bus stops along the road. He coupled the five-year PennDOT crash data (Involving bicycles or bicycles and buses) through the whole city of Philadelphia with video recording of the selected bus stops to collect conflicts that did not result in an accident.

Out of the 46 crashes in Philadelphia that involved both a bus and bike, only one happened in the Walnut Street while just 10 of the 46 crashes happened in streets with bike lanes, even with the expected increased volume. The prevalent types of collision between these modes presented in the data was sideswipe (46%) and angle collisions (33%). Both of those types of crashes are frequent in unsuccessful overtaking movements. The video recordings are made in three intersections of Walnut street during a day each recording three AM peak hours and three midday peak hours. The records totalized 966 bikes counts, 131 bus counts and 47 conflict incidents.

In the survey of current practices, it was noted that the Pennsylvania Vehicle Code specifies to cars that they must yield to crossing bikes, but the similar enforcement is not indicated for buses. The code also indicates to cyclist to travel along the right side of the road. In the worldwide survey, the author found a couple of strategies that could be applied with very little changes in the physical characteristics. Firstly, there is the use of colored bike lanes in conflict areas to raise awareness on cyclists' presence on the road. Another method would be using unique markings and signage to instruct in the better shared use of the road.

At the end of his study, Krykewycz recommended the elaboration of a yield responsibility pyramid to make it clear for everyone involved who needs to give the right of way during any interaction. He also recommends the discourage of cyclists to pass the buses to the right in order to reduce conflict between cyclists and bus passengers.

2.3.2 Articles and Reports or Shared lane operations

The studies presented in the section above showed that shared lanes between buses and bikes could be applied safely. However, there was still the need to evaluate those infrastructures factually, outside of hypothetical scenarios or looking only at crashes against other cycling infrastructures and into the real-world operations of a shared bus-bike lane. While North America was still wary of bikes and buses interactions, European cities were more audacious in allowing cyclists into their bus lane and it is unsurprisingly that the first major study on operations would coming from Europe.

In 2004, one of the most complete quantitative and qualitative studies on the relationship between buses and cyclists traveling alongside each other was published also providing the perspectives of cyclists by the way of surveys in Great Britain. Done by Reid and Guthrie (2004), this work was elaborated by the Transportation Research Laboratory for the Charging and Local Transport Division of the Department for Transport, which in turn is the responsible department for the planning and development of transportation solutions in the United Kingdom.

Bus prioritized and bus exclusive lanes are already a well-established and popular policy in the United Kingdom, even since the second half of the past century, which cannot be said the in the United States, as those are starting to appear more in these early decades of the new century. The authors noted that cyclists in the U.K. are commonly allowed to travel in the bus exclusive lanes, even in contra-flow bus lanes. That decision to allow cyclists into the bus lanes is based in two fundamentals: First, that cyclists are safer within the bus lanes than sharing lanes with general traffic, as buses travel in a lower speed among other motorized vehicles; The second motive, is that by allowing bicycles in bus lanes, that would be an opportunity to promote a sustainable mode of transportation.

The *Cycling in bus lanes* work was one of the few among the ones reviewed that mentioned shared bus-bike lanes in contra-flow direction. The guidelines found by Reid and Guthrie is that a contra-flow has to be at least 3-meter-wide (a little less than 10 feet) and the separation to the current flow has to be delimited by continuous pavement marking or a physical barrier. If the lane is expected to be shared between buses and bikes, the guideline recommends an even wider lane of at least 4 meters (around 13 feet). Similar width guidelines are found in the recommendations for with-flow shared bus lanes, for both cases the width recommended would allow the bus to overtake the cyclist safely. Previous researches by the U.K. government noted there is risks in allowing cyclists into contra-flow lanes, mainly in the intersections. Another guideline noted that 3-meter-wide lanes can be used by bicycles, as long as buses are not allowed to overtake them.

Reid and Guthrie interviewed cyclists in five bus lanes of different conditions. One of them being a narrow lane and other being a contra-flow lane. There were general questions for all five types of cyclists and specific questions for each road condition. In the narrowest of the lanes observed with 3.1 meters wide (10.1 feet), 45% of interviewees said that the width was just right, with other 41% answering that was a little too narrow and 10% saying it was too narrow to travel. In regard to safety perception, 80% believe that a path was quite safe while just 7% felt some risk.

In the contra-flow lane (12.5 feet wide), they observed that 47% believed the lane had the right width, while other 47% said it was a little too narrow and 4% noted that was too narrow. Regarding safe perceptions, 11% felt some risk traveling in the contra-flow lane, while 47% felt some safety benefit and 42% gave neutral answers. In comparison to a with-flow lane of similar width, the answers are quite negative for the contra-flow lane. For the with-flow lane, only 9% of interviewees felt some risk and 77% felt the lane had right width.

The contra-flow lane cyclists are questioned specific questions regarding the distinct condition. The authors are able to collect eight clear answers comparing the safety perceptions from travelling in the contra-flow against travelling in the with-flow lane. From those eight, six of them said that they do feel safer in traveling in the contra-flow while other cyclists noted *"...danger of pedestrians not looking for you"*. Majority of contra-flow cyclists noted problems in entry and exit points.

Reid and Guthrie concluded that shared bus-bike lanes are a valid transportation policy to promote bicycle ridership while maintaining bus priority and that both modes can travel along in harmony. However, they present reservations for the use of a SBBL in conditions such was the ones presented in Downtown Pittsburgh. Narrow lanes are perceived by cyclists as "quite safe" paths while not being the ideal scenario, where cyclists stated they would like if the lane was a little wider. The contra-flow lane was the only road which most interviewees did not feel safer cycling in this bus lane (In a split with the neutral answer) in comparison to other bus lanes. But it is also noted that the contra-flow lane cyclists felt safer traveling along in the contra-flow bus lane in comparison to a general traffic lane.

Among the recommendations, Reid and Guthrie pointed out that the bus lanes have value for cycling planning as an optional road to connect the bike network and thus all bus-priority lanes should be designed taking into consideration that it will be used by bicycles. They recommend that SBBL should not be made narrower to prevent overtaking and that contra-flow lanes must be wider than they with-concurrent flow counterparts.

A very similar study to the one proposed in this Thesis was made by De Ceunynck et al. (2017). De Ceunynck and his team evaluated two bus lanes in the city of Kortrijk, Belgium in regard to the safety issues to cyclist that use the infrastructure. The Belgian transportation policies allows for bicycles to use bus-priority lanes in two scenarios regarding the width of the bus lane. In the first scenario, the lane is expected to have 4.5 meters (just under 15 feet) of width or more. With this width, the authorities expect that the overtaking movements made by buses will give the cyclist a safe travel width with a lateral separation of over 1 m (3 ft) between the vehicles during the maneuver.

The second scenario is more similar to the analyzed situation in this thesis. The Belgian guidelines recommends that when a 15 feet lane is not possible the shared lane must be narrower than 3.5 meters (11.5 feet). With such narrow lane, the bus drivers will feel warier in overtaking cyclists with the bus lane. However, it is noted that they may try to overtake the cyclists anyway by going outside of the bus lane into the general traffic lane. These narrow lanes are recommended be used for short distance only.

The lanes observed by De Ceunynck in his work had 3.1 meters (10.2 feet) and 4.2 meters (13.8 feet) of width. As it can be noted, the second lane is not within the recommended guidelines of the Belgian transportation policies. That can be explained as whenever a bus lane over 15 feet is noted to share the lane with bicyclists, the common move is to reduce the width of the original bus lane and install a separated bicycle lane, making wider shared bus-bike lanes a rare infrastructure in Belgium.

De Ceunynck collected continuous video recording for two full weeks during the Fall of 2014, six weeks after the opening of the wider bus lane, while the narrow lane as in operation since 2009. Is important to note that the ratio of Bicycles to Buses for the newer and wider lane is almost two times bigger than the narrow lane (6.55 cyclists for each bus against 3.45). He collected a series of variables among interactions between buses and bicycles or simply free-flow bicyclist that did not encounter a bus during its travel. Four of those variables focused on the speed of the vehicles and the lateral position regarding the curb. Other variables observed overtaking situations, such as proximity between vehicles and position of the bus in the lane. Finally, site conditions such as daylight, weather and presence of unexpected vehicles are also collected.

From his study, De Ceunynck and his team could not reach a conclusion on whether or not the recommended narrow shared bus-bikes lanes are a safer option than a SBBL with a width between 3.5 meters and 4.5 m. The study noted that during the two weeks of recording, the narrow lane had higher rates of interactions between buses and bicycles (57% of cyclists in the narrow lane had to interact with buses compared to only 29% in the wider lane).

Regarding overtakes, the narrow lane also did not perform relatively better than the too wide, non-recommended lane as cyclists had to deal with overtakes far more frequently (34% of cyclists are overtaken in the narrow lane against 21% in the wider lane). In both bus lanes observed the median lateral separation between the vehicle as 1.1 meter (or 3.6 feet), still considered a safe width for overtake. However, De Ceunynck makes a point in remembering that in cases where the bus wanted to go towards the general traffic to pass the bike safely and was blocked by a car in the lane, the bus driver was still able pass the cyclist because the latter went so close to the curb edge that part of its physical width are outside of the lane. This type of travel pattern is dangerous for cyclist because the presence of gutters and uneven grade can destabilize the rider.

The percentages noted from the overtaking interactions and total interactions shows that the majority of interactions between the modes leads up to an overtake, in which the wider lane have a majority of interactions being overtakes while the narrow lane has a more evenly split. De Ceunynck notes issue in whether is more desirable to allow overtake maneuvers or not. The speed of cyclists was also observed to reach higher values in the narrow lane whenever the cyclist was being followed by a bus, while the buses had lower speed values in the narrow lane compared to the wider one.

The push for shared bus-bike lanes also reached Asia, where Wang et al. (2018) looked at how the conditions of the bicycle infrastructure and network affected the ridership behavior of cyclist in the Xi'an, China. The authors surveyed 803 bike-sharing riders and focused on studying five types of bicycle infrastructures, ranging from separated lanes to mixed lanes shared with public transit. Wang et al. findings support the findings of Reid and Gurthrie on the entry and exit points on contra-flow shared bus-bike lanes, as the users surveyed by Wang felt more affected by the condition of the entire bicycle network than the conditions of a single bicycle corridor.

Specifically, about Shared Bus-Bike Lanes, Wang found those to be popular among questioned cyclists, behind only physically separated lanes and in front of lanes shared with general traffic or separated only by pavement markings. This would mean that even for a casual cycling group like the users of shared bikes, a shared track between buses and bikes is not a terrible option.

2.3.3 Reports and Case studies on Shared Bus-Bike Lanes

As shared bus-bike lanes have become more established (Even if slowly) and more started to implement them, enough applications were out there that scholars and planners could start to formulate reports on case studies on those operations.

One of those reports on shared bus lane operations was produced by Agrawal et al. (2012). Agrawal reviewed bus-priority shared lanes implementations in both the national and the international level. Out of the seven cities reviewed by the authors, four allowed bicycles to travel along with the buses. However, bikes are not the only other mode allowed to travel in the reviewed shared lanes: Taxis and right-turning vehicles are allowed in all four cities reviewed and utility vehicles are allowed in all but one of those. The cities that allowed bicycles in it bus lanes are London, Los Angeles, Paris and Sydney. Those cities for the most part allow the use by bikes, except points where safety issues are raised, while the other argument that those modes move at too distinct paces (Bicycle constant speed vs Bus Start and Stop) for them to share the road harmoniously. Regarding enforcements of exclusivity lane usage, Agrawal found that such responsibility is often divided among multiple actors in which ticketing appear to be the most popular method. The main enforcer is normally decided by the nature of the infractions.

A similar study to Agrawal's, but more focused on SBBL instead of shared bus lanes, was prepared by Hillsman et al. (2012). Hillsman compiled a series of strategies applied in cities around the United States coupled with studies made in other cities worldwide. The study was suggested by the Florida Department of Transportation. The authors noted as a motive to implement shared bus-bike lanes that this infrastructure will provide time advantages to the public transportation and to provide a more direct and safe travel to cyclist than in a general traffic lane. The study was based on the questions if these two modes, so contrasting, could share the same road space safely.

The authors point out that SBBL are normally adopted where there are physical constraints to implement an exclusive bicycle lane and the authorities want to promote both buses and bikes usage. The first appearance of a SBBL in the United States was in late 1980's but only in this past few years that it started to be implemented more frequently with over 12 being put in place in the past two decades. The study found 27 instances of SBBL in the U.S. of which 4 had enough data that a case study could be formulated on them: Ocean City, MD; Minneapolis, MN; Philadelphia, PA and Washington D.C. The other 23 are mentioned in instances.

The study clustered the SBBL instances into three groups: First, are the connector SBBLs, linking between bicycle-oriented infrastructure; Second are the urban SBBLs, which sees the highest volume of all groups and Thirdly are the suburban SBBLs, where there is a lower traffic and longer stretches of shared lane.

Hillsman notes that guidelines and references for SBBL application is far more frequent in local and municipal level than in state-wide. Only three states DOT's have presented any mention to SBBL in their design guidelines, two of them make it clear that said lanes must be wider than a common bus lane (In special Maryland that set a minimum width for a SBBL to 16.5 feet). Washington State do not specify width requirements but note that SBBL are recommends for areas where bus speed and volume are low. Another four guidelines are found at the municipal level. In those, 3 of them noted that a 10 feet lane would be enough to implement a SBBL.

For the international guidelines on SBBL, Hillsman et al. were able to identify a greater variety of applications. Examples are drawn from countries like Australia, Canada and United Kingdom, which are also noted to have some research on the SBBL topic. All three of the countries mentioned also have an approach to prefer much wider lanes for buses when the road is shared with bicycles. Most transit-only lanes have around 8.5 feet width recommended, which is increased by over 4.5 feet when is used by bikes.

Continental European countries are also familiar with bicycle ridership promotion. Larger countries such as France and Germany have set their specific guidelines. In Germany, lane widths are set between 13 and 14 feet, depending on the design speed for the buses. In France, the range between the SBBL width is from 11.5 ft to 14.8 ft. For minimum width lanes, the overtake cannot happen in the same lane and the passing vehicle mu go to an adjacent lane. On the other hand, Netherlands, well-known as the "Country of Bicycles", do not have a lot of experience with SBBL.

As the country focus on providing homogeneity between modes, the authorities always to either provide a bicycle-exclusive lane or not providing at all. However, the country policies set that bicycles can travel in bus lanes with design speeds of 30 km/h (18.6 mph) or lower.

Looking at the Ocean City, Maryland case study presented by Hillsman's report, one of the first points to be noted is that the city is far smaller town than the others that normally apply SBBL. During the year, the population is estimated to be 7,100 habitants but sees a huge spike during the summer season, reaching over 300,000. The SBBL corridor is 7.4-mile-long, operating in a with-flow direction and was opened in the 1980s. Since the corridor is such a long one the width varies from block to block, going from 11 ft to 12.5 ft.

The design speed limit also varies from 35 to 40 mph for the buses. The worst scenario for bicycles regarding interactions with buses is during the summer season. The bus schedule is changed, and headways are reduced to 10 minutes between each bus, while in the spring and the fall have headways of 15 minutes and winter have headways of 40 minutes. Another issue of cyclists' interactions is that the lane allows right-turning vehicles to merge into the lane along with non-common vehicles. Ocean City's bus operators have raised the issue that the leapfrogging between the modes as detrimental to the service and putting cyclists in risk.

In Minneapolis, the SBBL was opened in 2009 in an effort to promote mobility in the downtown area. The corridor received two SBBL, one for each direction and both going in a concurrent flow direction. The SBBL extended for 0.7 miles with a design speed of 30 mph. The width for the lane had a minimum of 13.5 ft but could reach 18.5 ft depending on the lane configuration.

Minneapolis was able to make studies on traffic volume in the corridor before and after the SBBL implementation and noted 20,000 estimated vehicles in the corridor, which was not changed after the modification. The bus operation in the corridor also did not appear to suffer any adjustment thanks to the SBBL. However, the number of cyclists was reduced by 17% after the implementation. The authorities attributed that loss to other infrastructure that was implemented in the surrounding area but is worth noting that the SBBLs replaced bi-directional bikes lanes, previously in the corridor.

The authors noted that the five feet interval between the minimum and maximum width of the SBBL may cause disconnect between cyclists and bus drivers on where is viable to overtake the slower vehicle. These riders may also have problem in identify in which part of the lane should they be travelling.

The Philadelphia case was represented by the Chestnut Avenue corridor. The SBBL corridor extended for a mile in the downtown part of the city. The corridor is a one-way, two lane corridor divided by the SBBL and a general traffic lane. The lane width is just 9 ft and the design speed limit is 25 mph. Previous to the SBBL implementation, the corridor served as a two-way bus corridor, which the authorities moved from for pedestrian safety and health issues. As the Philadelphia SBBL is a with-flow lane, right-turn vehicles are also allowed to enter the lane.

Regarding bus operations in the Chestnut example, the volume is considerably higher than other examples as the corridor is located in downtown Philadelphia. The biggest headways, during weekends, are of 15 minutes while in the worst moment for a cyclist that do not want to interact with a bus, the weekday morning peak, the headway can go as low as 2 minutes. Study reports on the corridor noted that in a peak 15-minute period, 58 autos and motorcycles enter the SBBL, almost half of those (47%) are not making the expected right turn. These results show that the lack of enforcement may turn the SBBL worthless.

The Washington example is divided in two SBBL, one in the 7th Street and another in 9th. Each going in a different direction, both being a with-flow lane couple with a general traffic lane. The design speed limit in the corridor is 30 mph and the lane width is 11 ft. Similar to the other cases, right-turn vehicles are allowed to enter the lane to make such movement.

The Washington shared lanes were found as an unpopular option among the majority of stakeholders. Issues such as the narrow width and the presence of parking between the shared lane and the curb are the highlights of the dissatisfaction. Physical changes such as lane coloring and physical barriers are pointed as possible solutions. Safety issues such as bus drivers' blind spots and passing distance perception are found particular worrisome.

Based on the case studies reviewed, Hillsman et al. provided some possible scenarios and solutions for a SBBL approach. Firstly, they noted the context and environment in which SBBL is implanted is an important consideration as a viable option. They point out that if SBBLs are feasible for areas whom are major destinations, however it should be avoided for high-speed corridors. The study could not find a conclusive width for a SBBL, as most of the examples were retrofitted from general traffic lanes, but majority of the guidelines give preference to lane over 12 and 13 ft.

Intersections in SBBLs are a two-edged sword. For one, the presence of frequent intersections will consequently reduce the speed of the buses, easing the anxiety of cyclists of travelling alongside a much bigger vehicle whose traveling two or three times faster than they are. On the other hand, intersections will make stopping more frequent for buses, which can develop into a conflict between buses and bikes at the green light or during turning movement. There are also the issues of cyclists' vulnerability to the buses fuel emissions.

The authors noted that, when a SBBL ends into a bicycle path or a traffic lane for the cyclist, no decisive length was found among the reviewed guidelines for a SBBL, ranging from half mile stretches to two miles corridors. The speeds found for a SBBL ranged from 25 to 45 mph with a median of 30 mph, reinforcing the urban aspect of a SBBL.

Hillsman et al classified SBBLs into two groups of widths. The narrow SBBL lanes are all lanes under 13 feet and are classified as such for not providing the recommended widths by Reid and Gurthrie and the AASHTO (1999) for safe passing, making the vehicles use the adjacent general traffic lane for the overtake. The wider SBBL lanes are those above that 13 feet threshold but normally go beyond. The authors noted that the narrow lanes examples are implemented in a less meticulous context regarding safety issues and that if such would be implemented again, the justifications for it outweigh the risks and the preference for a wider lane.

Regarding distance between buses stops, the authors noted that in central business districts (CBD), where the spaces between stops is far shorter, a new conflict may appear between buses and bikes. Most of the literature mentioned above discussed about the conflicts when a bus overtakes a cyclist but in CBD environment, we may have to deal with the potential conflict of a cyclist leapfrogging a stopped bus.

In a bus stop there is 4 possible conflicts in the interaction between the bicycle and the stopped bus mentioned by Hillsman et al. First, the cyclist may decide to merge into the adjacent general traffic lane to pass the bus. This would result in the cyclist sharing the road with vehicles faster than the bicycle. Second, when the cyclist is trying to pass the bus before the stop through the right side of the bus, the cyclist may be in the blind spot of the bus driver and ended up being pushed to the curb. Thirdly, when the cyclist is trying to pass the stopped bus through the right side of the bus, the bicycle may hit passengers. And fourthly, as the cyclist is completing the overtake maneuver by the left side, the bus may restart and collide with the merging cyclist. Is also noted that those conflicts can be avoided if the cyclists decide to stop behind the bus.

Regarding the behavior of the users, Hillsman et al. noted that leapfrogging is a consensus issues for both cyclists and bus operators, but very little research was done in the field and the case studies did not appear to reinforce the notion. The belief is that, instinctively, both cyclists and bus drivers try to avoid interactions and will adjust their speed to not interact with the other, however this adjustment raises the question that a SBBL may detrimental to the bus priority operation.

Training of bus drivers is also noted as good tool to maintain a good operation in the SBBL as the buses have significant blind spots. Mainly, the objective of such training is for the drivers to be aware of the cyclists' presence and understand cyclist's behavior.

Problems with SBBL enforcement arise in most cases studies with the main one being the abuse of the right-turning vehicles permission by other motor vehicles, who ended up traveling far more than they are supposed to. Other active transportation modes (e.g. skaters and joggers) also were noted to use the SBBL unpermitted. Previous surveys noted that a solution would be design the SBBL in such manner that enforcement would be unnecessary.

2.4 Summary of Literature Review

The review of literature and context was critical to this research in order to make the researcher more familiar with the project components and relevant findings. Buses and bikes are both important modes to be promoted and their respective infrastructure ideally would work exclusively with a single mode, but by understanding the physical limitations of the current road, decisions makers and advocates have to accept that in some situations those opposite modes will have to share the same path.

Pittsburgh history shows innovation and considerable importance for public transportation in city-wide decisions. From the now-defunct streetcars to the major busways, the SBBL can be another positive chapter in the city's transit history while also contributing to the promotion of sustainable transportation by providing bicycles a route in Downtown, where the bikers could, theoretically, travel without having to worry about interacting with motor vehicles most of the time. The possible growth in cycling and consequential reduction of automobile usage would reduce air pollution, helping Pittsburgh move away from its dirty past.

The literature on SBBL was relatively short in numbers in comparison to other sustainable transportation topics as most scholars and planners prefer to keep these modes separated. For that reason, literature on interactions between buses and bikes was also collected to, at the end, infer that the interactions between these modes actually doesn't happen often in the traffic environment and, even so, is not that more dangerous than an interaction between bikes and cars.

The majority of the literature recommends wide Shared Bus-Bike Lanes to allow passing movements for both modes, something that is not available for the Smithfield SBBL in Pittsburgh, however the narrowing of the lane was not found as a trigger for less safety. Research on England noted that the Contra-flow configuration (Another aspect present in the Smithfield SBBL) while being less prevalent than it is for same flow counterparts it was also considered a safer infrastructure for cycling by bikers in comparison to a general lane.

3.0 Methodology

This section will provide a full overview of the methodology used in this study. Firstly, it will review the possible data that can be used to evaluate safety in traffic studies and the setbacks this study has impending us to use traditional safety data such as crash data. From that, after presenting a group of possible secondary safety data, a new type of data will be selected for our study. The second subsection goes into the possible methods of analysis of our corridor and the selection of which would better respond our hypothesis. The third subsection presents the data that was collected in the field divide by two groups: “Conflicts” and “Issues”, the former relates to the position of the cyclist regarding the motor vehicle (Bus or automobiles) and the latter relates to a decision made by the cyclist that may put themselves or other in a risky situation or simply is qualified as unusual. Finally, the last subsection provides context of the selected corridor and reasoning for the intersections selected for analysis, as our research does not only look at the corridor operations but also how each intersection is operating in order to find outliers and/or particular problems.

3.1 Safety Issues and Evaluation

As noted per the literature review in the past chapter, SBBL are a great opportunity to provide both buses and bicycles with prioritized roadway space for traffic, which it is hypothesized can significantly improve their operation and safety measurements. However, is also noted that this implementation could have some negatives trade-off as neither receive full priority while sharing the road. The bus drivers may catch up to a bicycle ahead of them in a lengthy corridor and end up being stuck, driving at 15 mph when the bus could be reaching for 25 or 30 mph, depending on the posted speed could be a negative outcome.

However, the biggest risk noted in the literature for implementing SBBL's is the safety issues for cyclist. Reported traffic accidents are defined into two categories: Whenever there is property damage or whenever there are physical injuries among the involved cyclist. It's not unusual that the reported crashes for cyclists are the ones where a cyclist fatality occurred as they are more vulnerable than any other traveler outside of pedestrians.

Thus, the need to protect these cyclists is extremely important not only for a public health standpoint, to reduce the traffic mortality rates, but also for a good transportation planning, where cyclists may feel safe riding with the network and are not afraid to achieving their ideal mobility features (e.g. Higher speed, quicker reaction) because they are wary of a possible dangerous interaction with another vehicle.

For transportation engineers and planners to better plan to accommodate all types of users within the network, there is a demand for traffic data to be collected and analyzed in order to make data based and consistent decisions. Nowadays, thanks to the evolution of transportation engineering and the development of new technologies, a multitude of types of data are possible to be collected for analysis. In the following part, there is an analysis of some of these data types, established by the Federal Highway Association, that should or could be used to analyze safety issues within a traffic infrastructure. After presenting and selecting the data types to use in this study, the methodology of analysis is presented and discussed.

3.1.1 Possible Data Sources

In the primary source for safety evaluation methods in transportations studies nowadays, the FHWA Highway Safety Manual, the notes on Shared Bus-Bike Lanes are modest and uncertain. The Manual notes that SBBL appear to reduce crashes but do not provide the degree of change, only the importance of pavement markings to reduce conflict. For such reason, the researcher decided to review other literature sources regarding safety data collection.

The Federal Highway Association (FHWA) qualifies two types of safety measurements, Nominal and Substantive. Nominal safety is such that the roadway design met defined standards and guidelines while substantive safety is actual performance represented by the data collection. Changes in the nominal safety are driven by reviews, researches and studies of real-life experiences. FHWA provides a careful arrangement of types of data that can be collected in order to measures the safety of a roadway for its users. Unsurprisingly, the most frequently used data to corroborate if a corridor is safe for travel is the crash report data. Planners and engineers look at the historical crash data in order to assess problems. However, the use of such data may present a few problems. Three of these problems can be highlighted for either the high frequency in which they happen or by the risk they carry on the analysis.

The definition of a reportable crash by the FHWA is that at least one of the following conditions as met:

1 - The severity of the incident was such that at least one person involved in the incident (Which can be either drivers, passengers, pedestrians, etc.) had to be moved to a medical facility; 2 - The severity of the incident was such that one of the vehicles involved in the incident had to be towed away from the location.

This set of conditions may mask incidents that may not be severe to meet the conditions but happen frequently enough to be issues that needs to be addressed. A second problem is relying solely in crash data in that the data collection may have inconsistencies. Crash reports are usually long documents that are filled out by a diverse group of people, from incident responders to the victims themselves. This non-standardization in who fills the report, coupled with the length may create inconsistencies and incomplete data. Finally, the third most important problem is that by utilizing crash data, planners and engineers are being reactionary instead of occupying a vanguard position that is expected from such positions. Decisions on safety need to be made before the implementation and, in the case of safety, it cannot wait until sometime after implementation.

Other important data mentioned by FHWA that is needed for a well put safety measurement are the traffic volumes, which counts all traffic that traveled through a corridor or intersection in a specific time frame and makes splits of types of vehicle, turning traffic, among others; and road characteristics, which consists of the physical measures of the road, such as length, width, type of pavement, number of lanes among others. Crash Data, Traffic Volume and Road Characteristics are the three main data that needs to be collected for an ordinary traffic safety report. Nevertheless, FHWA also indicates other possible data sources to enhance a safety report. The so-called supplemental data sources are: Conflict and avoidance maneuvers; Injury surveillance and EMS; Drivers history; Vehicle registrations; Citations and enforcement; Naturalistic; Driving simulator; Public Opinion; Behavioral observation.

Of these nine auxiliary data sources, some sounded unrealistic for our research purposes while others may not appear to have significant impact in our proposal, which reduces the number of relevant data sources down to four:

- Conflict and avoidance maneuvers
- Injury surveillance and EMS
- Citations and enforcement
- Public Opinion

The following section reviews the data collection methods for all four sources cited above but first will review the three traditional traffic safety data with an emphasis on crash data and problems with crash data related to bicycles.

3.1.1.1 Primary Safety Data

As noted in the previous section, FHWA indicates three types of data as primary sources. Each of those are presented in the following subsections with context of its importance on traffic studies. Those types data are considered important for a traditional traffic safety study however they are not foolproof. The methods to collect each of the primary safety data is presented in their respective subsection but notable issues and questions on the collection or analysis process is also presented in each subsection.

3.1.1.1.1 Crash data

As referred in the FHWA textbook *Road Safety Fundamentals*, crashes are the most concrete type of information that an engineer can use to know if there are any problems with an intersection or corridor physical design or if the design speed was poorly chosen for example. With the right collection methods of crash data, planners will be able to not only know that incidents happened but also who was involved (e.g. Vehicle on vehicle collision or vehicle hit a pedestrian), the type of accident (Head-on, Rear-end, Side impact collision) and the severity of injuries of everyone involved (All related are able to walk away on their terms or if there was a need to call ambulance services or, in worst cases, if there were any fatalities). All these dimensions of information can help engineers make better decisions moving forward, however FHWA is clear that there are various problems with crash reporting.

As pointed out by Yamamoto et al. (2007), crashes that result in little damage are usually not reported to police or emergency services, which in turn makes the database of transportation conditions scarce of such minor incidents. While comparing the types of damages, Yamamoto points out that incidents with low property damage are more likely to be reported than accidents with an equivalent physical damage to those involved, from which it can be conclude that incidents involving pedestrians and cyclists (Major stakeholders in this research) are less likely to be reported that crashes with two vehicles.

Another obstacle for using crash data is that such reports are filled by human operators, whom are susceptible to errors. Imprialou and Quddus (2017) discussed that the crash report analysis has not been scrutinized relative to the quality of the data and that it needs to be reviewed in its processing of reporting so that the safety investigation produces a more efficient outcome.

They note that during in-depth investigations of crash datasets it is easy to find inconsistent observations, such as incorrect time, location and severity of injuries to even missing information on the demographics of the people involved. They propose that all crash reports must answers five "W" questions: When? Where? What? Who? and Why? Imprialou and Quddus critique of crash report data is not focused on the source but on the collection. They acknowledge that such is extremely valuable to traffic safety research but alert planners and scholars to proceed with caution as reports can be problematic.

3.1.1.1.2 Traffic Volume

Simple traffic volume counts are interested in the amounts of vehicles that are using the referent infrastructure, which could be a corridor or an intersection. The more sophisticated ones look not only at the rough numbers of vehicles but also at characteristics such as turning movement at intersections and types of vehicles that are being counted. The usual traffic volume data that is considered to symbolize the importance of a corridor are the Average Daily Traffic (ADT) and Annual Average Daily Traffic (AADT). Other relevant counts are: Peak hour traffic volume; Turning vehicles; Vehicle Miles Traveled (VMT); Percentage of Traffic for specific vehicles.

Most of this type of data used to be collected by an operator but with the advent of technology, nowadays the majority of traffic volume counts are collected by way of automatic tools that range from advanced camera recognition to simpler pneumatic tubes. These methods have been getting simpler to install and cheaper in the last few years but for transportation agencies interested in such data quickly or for a small period, sending a manual operator to the site is still the best option. Manual operators are also preferred for non-motorized traffic counts, such as pedestrians and bicycles.

FHWA points that challenges in using volume is to guarantee that the counts are dependable and a truthful representation of the traffic. Radars and camera detectors sometimes may miss some vehicles or add inexistent ones depending on interferences in their field vision or positioning and it is expensive to maintain and operate a camera outdoors for a long period of time. For that, agencies that decide to analyze traffic volume counts need to have well set parameters to do such estimations, for non-motorized traffic, who are more susceptible to changes from day to day.

3.1.1.1.3 Road characteristics

The final critical piece of data, as appointed by the FHWA, is the road characteristics data, also known as road inventory. The main feature of this data are basic physical features of the infrastructure, such as road name, road width, number of lanes and direction of traffic, but in a more detailed version of a database is also indicated characteristics like road classification and location coordinates. Again, such data can be collected both manually and automatically. Manual collection would be sending an operator in site to make the measurements on width and fill out a report, that would be entered into a database of the roads that are part of the transportation network.

Such data is necessary for transportation planners for two main reasons. First, to identify if the transportation infrastructure was built accordingly the design standards and guidelines. These standards are a great way for planners to balance between providing the most capacity for traffic in the infrastructure and a safe travel for its users. However, simply following the standards is not enough to ensure that accidents will occur.

The second reason is that various innovative transportation infrastructures have been proposed in the past decades but there is very little space still available to construct them. The idea for transportation agencies across the world is not to construct new roads for these infrastructures but to adapt the old roads to accommodate them and a database of roads inventory will provide planners grasp of the complete transportation network in order to conceive smart transportation plans.

Problems with this type of data are simple to understand and equally simple to avoid. On the contrary of the other types of critical data, the road characteristics are relatively immutable, and we can gather this data at any time with very little variation from day to day. The main problems with this data are that it can be very time and resource consuming and that, ideally, the interested transportation agency would collect not only collect data from the corridor in question but the whole network. An agency, backed by a competent local governance, would understand the importance of such information from the beginning and already have some sort of database, if not such data can be collected through technology tools such as GIS or from private companies.

3.1.1.2 Secondary Safety Data

Before the next subsections is important to make the follow distinction: The three types of data discussed above (Crash reports, Traffic Volume and Road Characteristics) are already consolidated inputs in traffic safety studies. Such that its collection methods have little variance between transportation agencies and transportation scholars are not worried in validating the importance of the data but to assure the quality of observations by standardizing. The following data types, called *Supplemental data*, are not unanimous among and are usually collected only for specific projects.

3.1.1.2.1 Conflicts

Moving into auxiliary data for safety evaluation, the first discussed is traffic conflicts. Traffic conflicts is used as an umbrella term for any unexpected interactions in traffic that may or may not result in crashes. While crash data is vulnerable to low numbers that may not tell the whole story, conflicts occur with far more frequency and are able to show transportation agencies safety issues in a transportation infrastructure. For example, users with good reaction time will be able to avoid incidents but if avoidance maneuvers are need again and again, transportation agencies need to act in order to accommodate users who does not have such good reaction time.

This data has started being collected in the past few years and there is little consensus on how it should be collected (FHWA refers to this data as *Surrogate measures)* and imprecision on conflict classification is common. Most of the collection for this is made by an operator in field and the classification is up to the operator judgement. Collection by video cameras for further analysis is also typical.

A good example of using conflict observation to reach conclusions related to traffic operations is the work done by Mahmud (2017). In his work Mahmud investigated the differences in operations between intersection traffic signal operation that implemented Exclusive Pedestrian Phase versus the conventional Concurrent Pedestrian Phase and which modality would encourage pedestrians into taking the less than ideal decision of crossing outside of their phase. Mahmud made sure to categorize and define the interactions between vehicles and crossing pedestrian before observing the operations in eight evenly split intersections. He concluded that while Exclusive Pedestrian Phase may be regarded as a pedestrian friendly innovation, it also encouraged more bad behavior from pedestrians. Mahmud efforts to categorize and define the types of conflicts ensured that his conclusions are based upon consistent observations to evade the surrogate problem with traffic conflict data and laid the foundation for future comparative works.

3.1.1.2.2 Injury and Emergency Medical Systems (EMS) Data

Injury reports and EMS data is supposed to work as a complementary data for crash reports. As noted, before, crash reports have issues related to misinformation filled in the reports, EMS reports would provide a secondary source for the transportation agencies to follow up on the severity of injuries in a crash and other outcomes such as costs and causes. FHWA also notes that this data can work to tie up traffic safety with public health. Another value portion of using medical reports data is that incidents involving non-motorized traffic is often not recorded by police, as property damage is considerably lower than other incidents and that those occur in non-roadway locations.

One of the issues with this type of data is that some medical facilities normally encloses all injuries that occurred in transit simply as a "Traffic-related injury" which nulls dimensions of data but to respond this issue the NHSTA developed the Crash Outcome Data Evaluation System (CODES), which requires information of the crash, vehicles involved and behaviors. Another issue is the access for this data is difficult and can consume a lot of time from the agency, which could be used in other areas. A well-done crash data collection would render the gathering of this data unnecessary for transportation agencies.

3.1.1.2.3 Citations and enforcements

Using FHWA definition, citation data is related to individual data of drivers records with any violations of law in the past. For our objectives in this research personal data is not important, but the best use for the data would be to look into historical data of traffic violations on new transportation infrastructures to see if there was any adaptation period where violations are frequent at early stage but went down to the norm in the following months and years. Another good use would be to investigate what are the most frequent types of violations in Pittsburgh, and even more specifically, at Downtown Pittsburgh.

Some problems with using citations and enforcements data to tackle safety issues are that generally jurisdictions have their own methods of collecting and maintaining their citations. Also, such data is not anonymized and the process to make the data practical encounters barriers thanks to privacy concerns.

3.1.1.2.4 Public Opinion

Lastly, the final piece of supplemental data can also be qualified as the most important data to understand the users as it collects the information straight from the source by simply asking them. Feedback from the public is a good tool to understand what users want and/or expect to encounter in their trips regarding reliability and safety of the transportation network. Unlike the other supplemental data types and more like the critical data, public opinion is also a consolidated type with various methods of collection (From general meetings to intercept surveys).

The reason for public opinion to not be considered a critical data type is that it is rarely used in traffic studies. While public involvement is always attributed as an important aspect of all planning processes that have impacts, most project teams use this to inform the general public of expected project outcomes and design choices instead of collecting input to re-evaluate their decisions.

A frequent issue with public opinion data is that the opinions collected about a transportation project (Or any project with high repercussions in society) may be biased. Community members who are interested in or are highly impacted, either positively or negatively, by the project will be more willing to seek out the project team and let their voices be heard and if the project team is not actively seeking out the opinions of everyone, they may be drove towards a choice of a vocal minority.

3.1.2 Selected Data Sources and Reasoning

After careful consideration, it was decided that this research would use conflicts and avoidance maneuvers as the main data for analysis and conclusions with the three critical data types pointed FHWA as the supplemental data. The decision to move towards a mix between qualitative and quantitative data analysis instead of a full quantitative analysis, usually done in transportation studies, at this time was made because the SBBL project implemented by the City of Pittsburgh is relatively new, which makes not only our crash data vulnerable but also our EMS and citations candidacy too. Ideally, the conflict data collected would be supported by a public opinion survey among cyclists, bus drivers and policy makers stating their preferences and perceived risks about a Shared Bus-Bike Lane in comparison to other infrastructures (Either a general traffic lane or bike exclusive lane).

3.2 Methods of Data Collection

With the final decision to analyze the conflicts and issues between buses and bicycles, the research moved on to deciding how the data would be collected. As pointed out multiple times by FHWA, nowadays we have two methods of collecting traffic data: Firstly, the traditional method, with a human traffic counter in site with the specific equipment for the data collection or secondly, a more advanced method, in which the research would dispose of technological equipment in the site to record the traffic data to be analyzed in the future.

With both methods having its intrinsic costs, it was decided to go the technological way and collect data through cameras. Using a human counter on site would be a simpler and cheaper way to acquire the data without having to deal with maintenance issues of the cameras. However, having the data collected through cameras would give the research the opportunity to analyze the traffic patterns in the SBBL corridor outside of the peak periods for longer periods of times and increased amounts of data for analysis.

Two issues with using cameras would be acquiring the cameras and how to mount the cameras in the poles. For acquiring the cameras, with our limited resources it was decided to use indoor cameras for the records. Indoor cameras relatively cheaper than outdoor ones however the gap between them is mainly because the weather protection that the latter possess. To overcome this obstacle, all cameras are covered with an appropriate housing to protective from natural events.

Regarding the second problem, the cameras used could not be permanently installed in the traffic poles but be portable as there will be multiple intersections analyzed and there was no authorization from the City of Pittsburgh to modify the poles to install the cameras. The use of indoor camera helped in that sense was those are usually lighter than outdoor cameras.

To make the indoor cameras portables, they are coupled with a power bank of 23600 mAh. Recording tests made with the camera pointed that while being supplied with the power bank, the camera was able to record and local storage over two days of videos. Finally, to stabilize the camera and the power bank in a pole, pipe straps and an acrylic sheet are used alongside the equipment. A schematic of the camera mounting and pictures of the mounting are presented in the Appendix A.

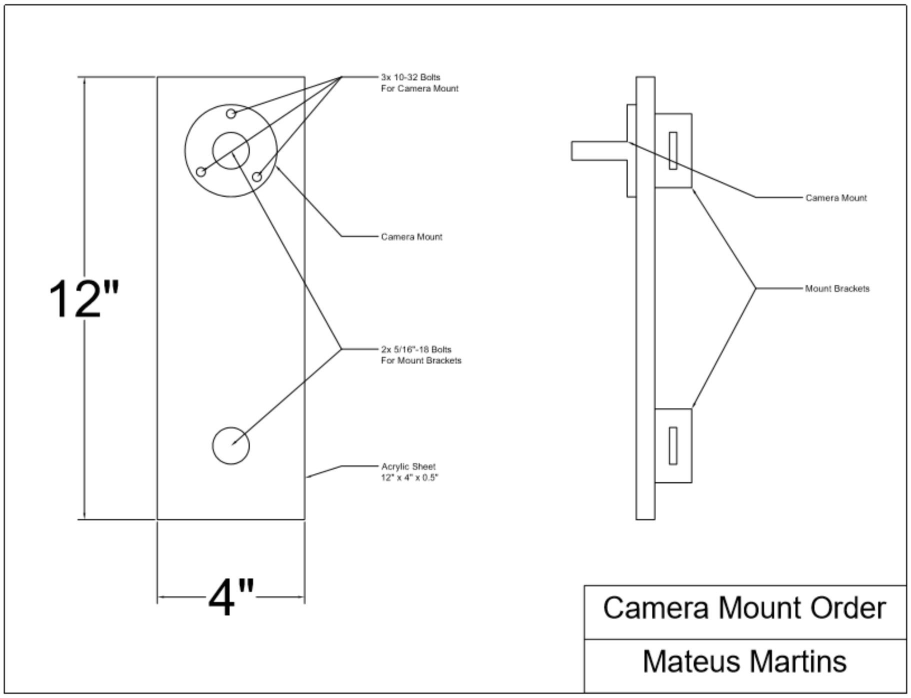


Figure 2: Schematic of camera mount

Figure 3: Front side of the final camera mount

3.3 Possible and Selected Method of Analysis

This research took a different approach than the majority of safety studies by first selecting which type of data was available and then analyzing it to then looking into the possible methods of comparison between the study object and what could be referred as the normal state. The normal state in this research refers to a general traffic lane in which bikes and buses can travel, however they do travel in a mixed traffic flow alongside automobiles.

During development of the methodology, three possible methods of analysis were considered: Firstly, a single camera would be placed in an intersection facing the Smithfield Street SBBL incoming traffic and the records would be analyzed by looking into the traffic volumes for each mode and the interactions between the modes. Rates of conflicts would be calculated comparing the number of cyclists that would travel freely and compared to the amount that encounter a bus in their trip. The same comparison would be done for buses.

The second method would be placing two cameras, one in the intersection facing the Smithfield Street SBBL recording incoming traffic and the second would be placed downstream in the corridor which would be able to video record both the view behind the bus and the general traffic lane. Once again, the video recording would be used to analyze the operation by documenting the interactions between the modes and traffic, however in this method the opposing general traffic lane would be used for comparison as the control scenario for the Contra-flow SBBL.

The third and final method would be once again placing two cameras, one in the intersection facing the SBBL incoming traffic while the second would be placed downstream in the corridor which would be able to video record both the rear of the bus and the general traffic lane coming in the opposite direction. The records would be used to collect and analyze the interactions between the modes and the overall operation of the SBBL. The difference between the second and third methods is that while the previous one would have the opposing general traffic lane as a control scenario while in the third method the Smithfield SBBL would be compared to the general lane going for the same at Wood Street.

It was decided to go ahead with the second method. The first method was rejected on account of limitations to the data collection and lack of established control scenario that could negatively affect the conclusions, specifically the conflicts in which a bicycle would stop behind a bus and not be caught on camera. Also, the lack of established control scenario. The third method was turned down as the Wood SBBL is not truly comparable to the Smithfield SBBL, mainly in length and bus routes. Also, it was noted through heat maps on bicycle usage, that cycling numbers in Smithfield Street (circled in red) are higher than in Wood Street (circled in yellow) (Figure 4 below). The heat map is publicly available by Strava, a social network that records cycling and running GPS data of its users.

Figure 4: Biking Heat map of Downtown Pittsburgh.

3.3.1 Types of Conflicts

With the choice of conflicts as the main data, it is important to define what is a conflict between the modes and how those conflicts can be a measurements of traffic safety. To select the conflicts, we firstly based on the literature review, in which the main issue for the safety of the cyclists was the overtaking maneuvers. However, as in the Smithfield SBBL, passing movement is prohibited because the studied SBBL is also a contra-flow lane and the lane is too narrow for the passing to be done with a safe distance between bike and bus, the passing movement data was expected to be too low for a conclusion. Thus, it was needed to define situations in which the cyclist may be disturbed by the presence of a bus or another vehicle. It was decided to categorize conflicts into the two categories that comprise occasions that both cyclists and drivers are interacting as both have to be aware of the presence of other in order to react. The categories are distinguished by the positioning of the cyclist in relation to the vehicle as they can be either behind or ahead the motor vehicle.

The nomenclature of "Conflicts" for these possible interactions between cyclists and motor vehicles is understandable not ideal but it was decided to progress the study with this name in interest of understandability of the work for future references. The word "Conflict" in traffic studies terms is normally used for interactions between vehicles that normally result in avoidance maneuvers by one or both involved parties to prevent a crash.

In this study, "Conflicts" encompass possible situations in which the cyclist and the vehicle driver have to be aware of each other's presence. The "Conflicts" counts in this study will count anytime in which the parties are within a reasonable distance that, for example, a sudden maneuver from the leading vehicle requires an avoidance maneuver from the following vehicle. Thus "Conflicts" in this study actually refers to situations that may lead to possible avoidance maneuvers and crashes, which are the conflicts in the classic traffic safety literature.

The following subsections describe each conflict situation and touch on how those can be problematic for the cyclist. A third category is also presented. However, this last one a combination of the first two in which the cyclist finds themselves either between vehicles or being overtake by a vehicle. It is important to note that the research does note argument for either conflict as a better or worse conflict but only notes their existence.

3.3.1.1 Cyclist behind vehicle

This condition is defined by the motor vehicle (Bus in the SBBL and any motor vehicle in the general traffic lane) as driving ahead while the cyclist follows closely but is impeded because the cyclist may be able to reach a higher speed, but it can't because of the bus speed. In discussions between researchers and stakeholders, it was noted that the situation is not ideal mainly because the cyclist would be susceptible to the bus fuel emissions, making it hard to breath and maybe distracting the cyclist.

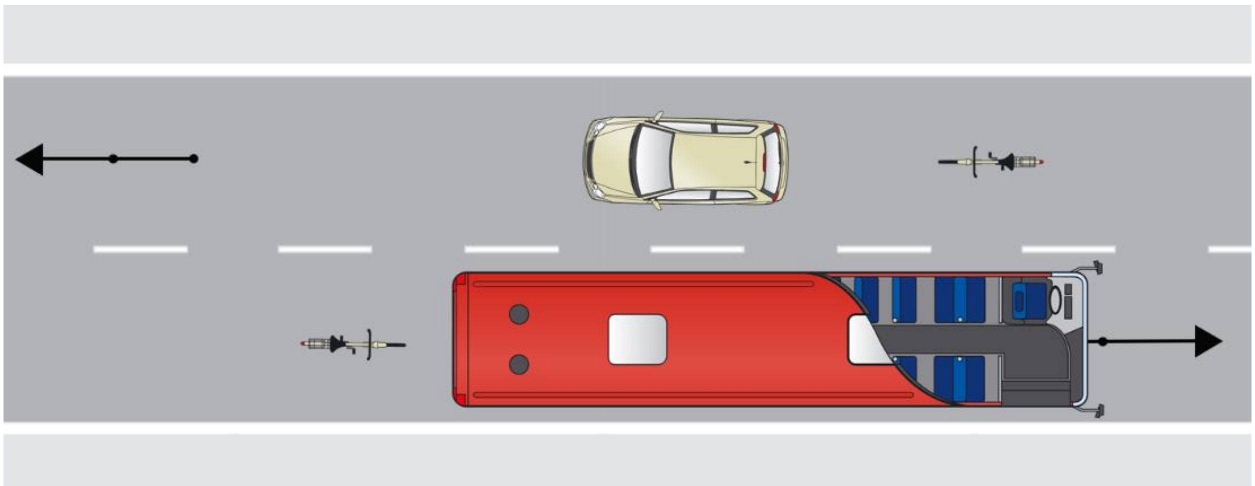


Figure 5: Cyclist behind Vehicle

3.3.1.2 Cyclist ahead vehicle

In this situation, the cyclist is traveling ahead of the motor vehicle however the following vehicle speed is controlled by the bike speed. The bus driver is expected to catch up to the cyclist easily, however as the SBBL is in a downtown environment, the short block length may not provide enough room for the bus to accelerate. During methodology discussions, it was noted that cyclists may be nervous to travel ahead of the bus because the can be run over by a distracted bus driver.

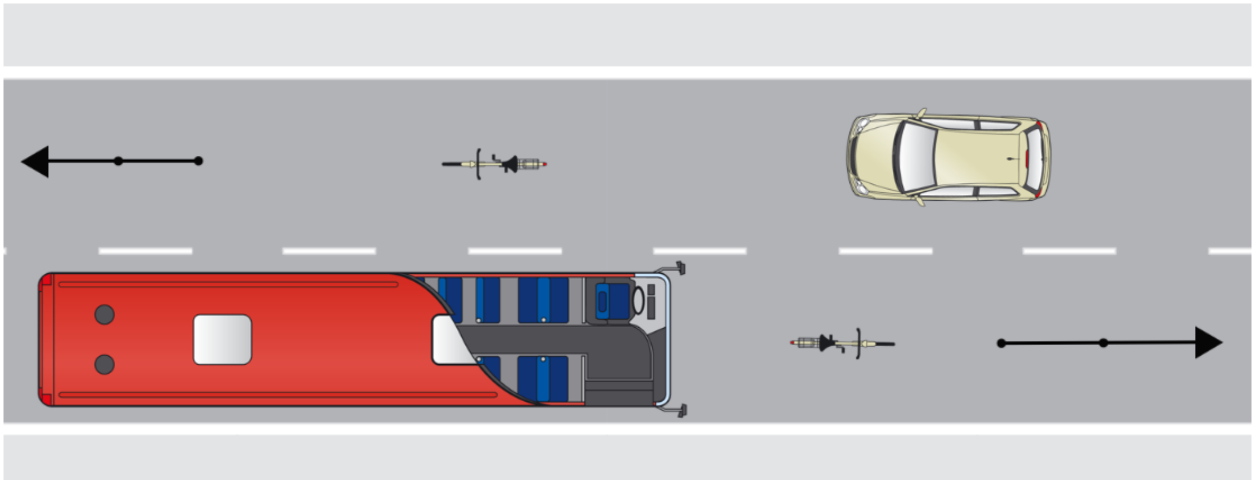


Figure 6: Cyclist ahead Vehicle

3.3.1.3 Cyclist in between vehicles

The final conflict collected noted all counts in which neither of the first two categories could be defined adamantly. As the opposing general lane had an additional parking for most of its extension, overtakes done by vehicles could happen in which case the same cyclist could be both ahead and behind the same vehicle and for that those instances are noted in this conflict category. It is expected that cyclists in these situations will deal with the disadvantages of both prior conflicts.

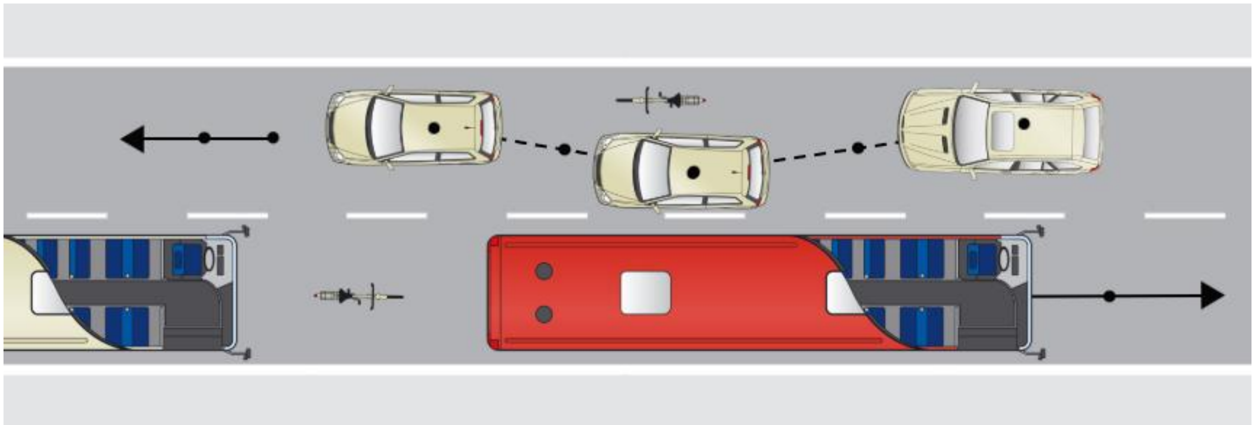


Figure 7: Cyclist in between Vehicles

3.3.2 Types of Issues (or Unexpected cyclist's maneuvers)

The Conflicts' categories between cyclists and motor vehicles presented above would provide quality information on the safety levels of the analyzed Contra-flow and could be used for future infrastructure analysis by itself. However, to enrich and corroborate the analysis and consequent results, the author decided to collect additional data during the analysis phase. We decided to review cyclists' movements as we expected that the conflicts mentioned above could serve as spark for dangerous movement, in special cyclists overtake, mentioned early on Section 3.3.1. However, we expected that overtake would not be the single cyclists' movement that could be generated by the SBBL and cyclists' discomfort with the infrastructure.

Like the previous "Conflicts" categories noted in the previous section, there is also a problem with the nomenclature for this data type and once again the selection of this name for the data was done interest of understandability and to be easier to reference later on. The name "Issues" may give the reader the feeling that this data type noted all types of issues but actually the data registered by the researcher catalogized can be referenced as decisions and/or maneuvers made by cyclists. Four out of the seven categories are maneuvers by the cyclists and the other are decisions made by the cyclists but all seven may at some point determined as undesirable or even unlawful.

With that in mind, the following seven categories are developed to note cyclist's decision that could either put themselves and/or others at risk or simply noting a possible discomfort with the SBBL. The first four are considered of high-risk as they can results in a crash between cyclist and motor vehicle. The fourth one is considered of relative risk as it may result in a collision between cyclist and pedestrian and the last two only not unusual movements that may or may not be related to the cyclist discomfort with the SBBL. This risk characterization will be important in the data analysis section as cyclists may perform two or more problematic maneuvers. This will be touched in more detail at the Data Analysis section.

3.3.2.1 Overtaking/Leapfrog

The major example of cyclists' movements that are discouraged while using the SBBL is overtaking. While passing is prohibited in the Smithfield SBBL, it was decided to create a category to gather overtaking attempts as being prohibited does not mean they will not happen. This category will be able to tell if there are any problems with the no-passing enforcement and/or any user is putting themselves and others in risk.

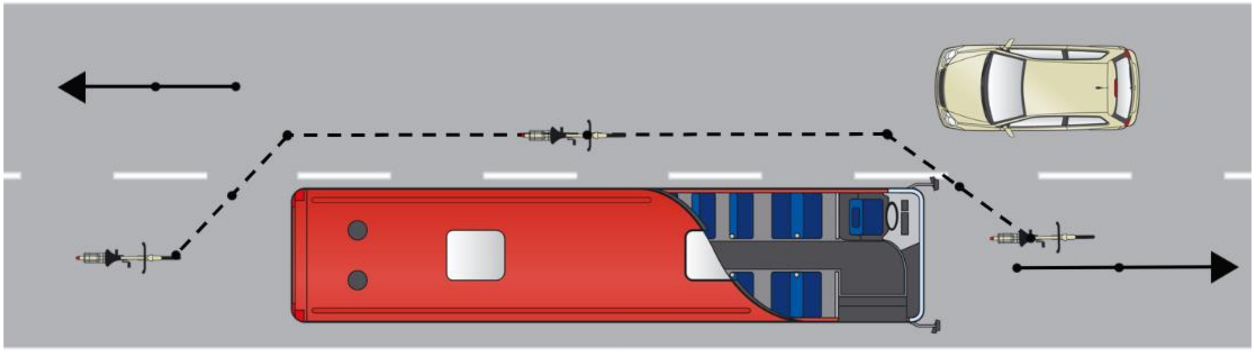


Figure 8: Cyclists performing Overtake/Leapfrog

3.3.2.2 Wrong lane

The wrong lane category encompasses bikers in two scenarios. First, those that may not feel comfortable traveling in their appropriate lane and decide to use the contra-flow lane for an extended period, even after completing a passing movement. A second scenario within this category is cyclists that note the contra-flow lane clear of traffic compared to their lane and decide to use that clean lane.

Figure 9: Cyclist travelling in the Wrong lane

3.3.2.3 Cut through opposite lane

Like the first two categories, this category deals with cyclists invading the contra-flow lane. However, the result for the first normally ends on the cyclist going back to their original lane, this one finish with the cyclist going for the side street using the opposing lane approach instead of turning at the intersection. Another group in this category is cyclists that crossed the contra-flow to reach and travel at the opposite sidewalk, perhaps uncomfortably with their original travel lane.

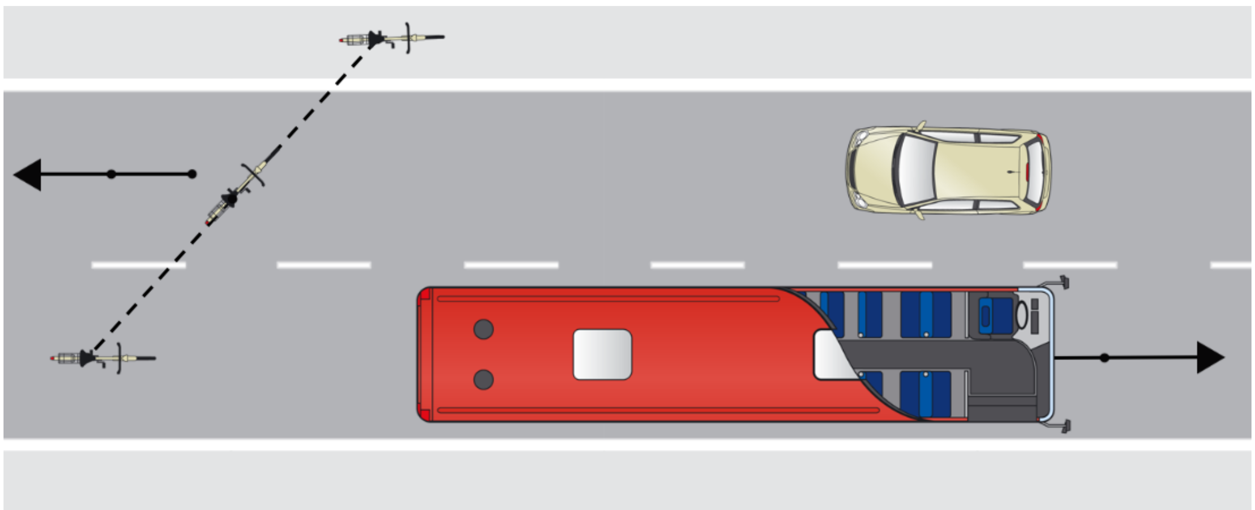


Figure 10: Cyclist cutting through opposing lane

3.3.2.4 Right-Side Overtake

This category is for cyclists that try to work their way past the stopped vehicle by going into the curb and squeezing between the little space given by the stopped vehicle. This movement is normally noted in the bike-bus interaction literature as especially risky for bus passengers getting on and off the bus.

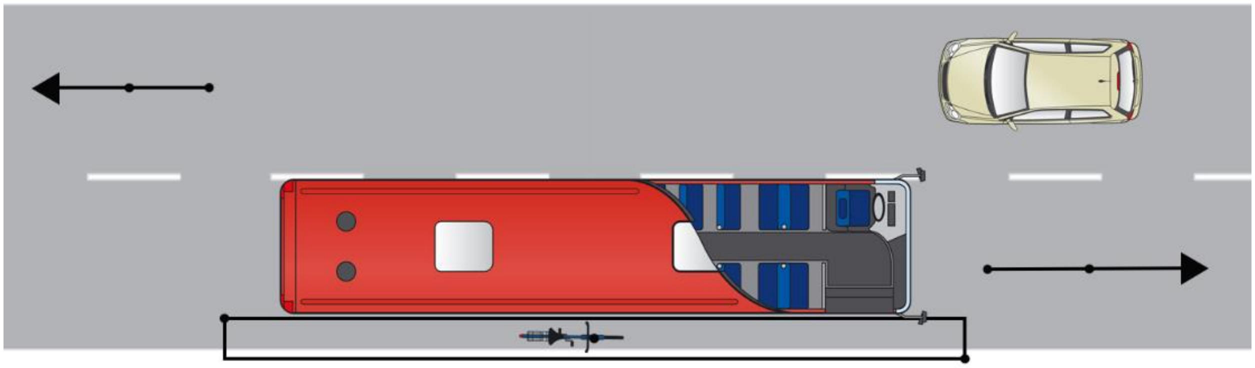


Figure 11: Cyclist performing right-side overtake

These top four categories are perceived as the most dangerous situation for the cyclist, in which the first three may result in a head-on collision and the fourth may ended with a sideswipe collusion with a bus in the SBBL. Outside of these dangerous movements for the cyclists, other movements can be noted for either putting bikers and others at relative risk or for highlighting that cyclists may not being felling comfortable with road conditions. Three categories could be noted as such.

3.3.2.5 Sidewalk cyclists

As the name implies, these are cyclists that do not feel safe with the corridor conditions and decide to travel in the sidewalk instead. In Pennsylvania, bicycles are considered vehicles and, while can ride on sidewalks in some localities, they are not recommended to do so in Business districts.

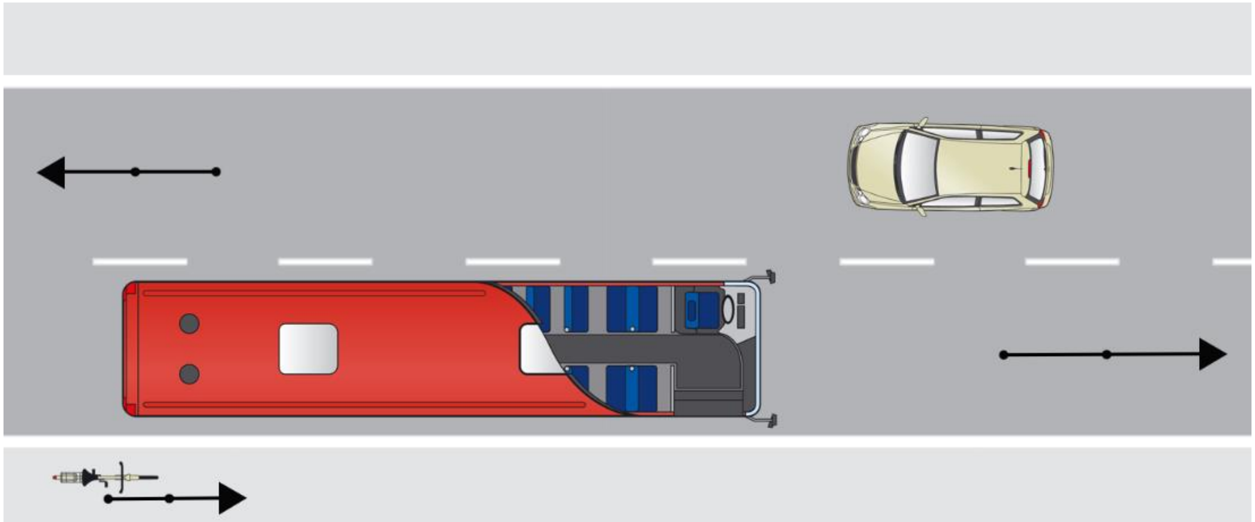


Figure 12: Cyclist travelling in the sidewalk

3.3.2.6 Embarking and Disembarking

This category notes cyclists that, while having a bike at their disposal, preferred to use the bus to complete all or part of their Smithfield trip in the bus than riding their bike.

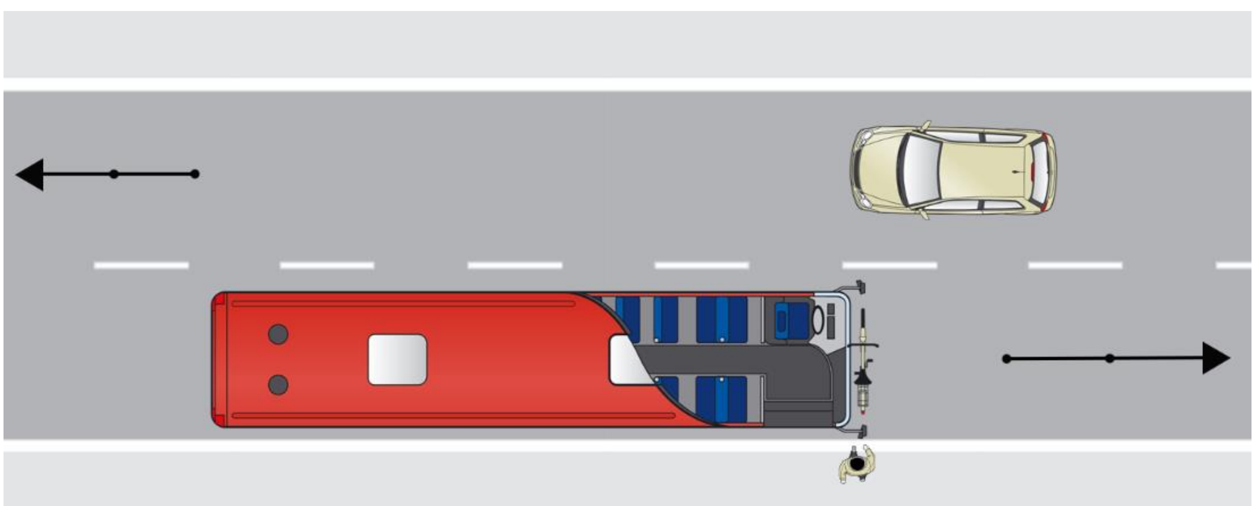


Figure 13: Cyclist embarking/disembarking the bus

3.3.2.7 Pedestrian

Like “Embarking and Disembarking” category, this class is for people that have a bike at their disposal but preferred to complete part of the trip by carrying their bike in the sidewalk along other pedestrians than actually riding it.

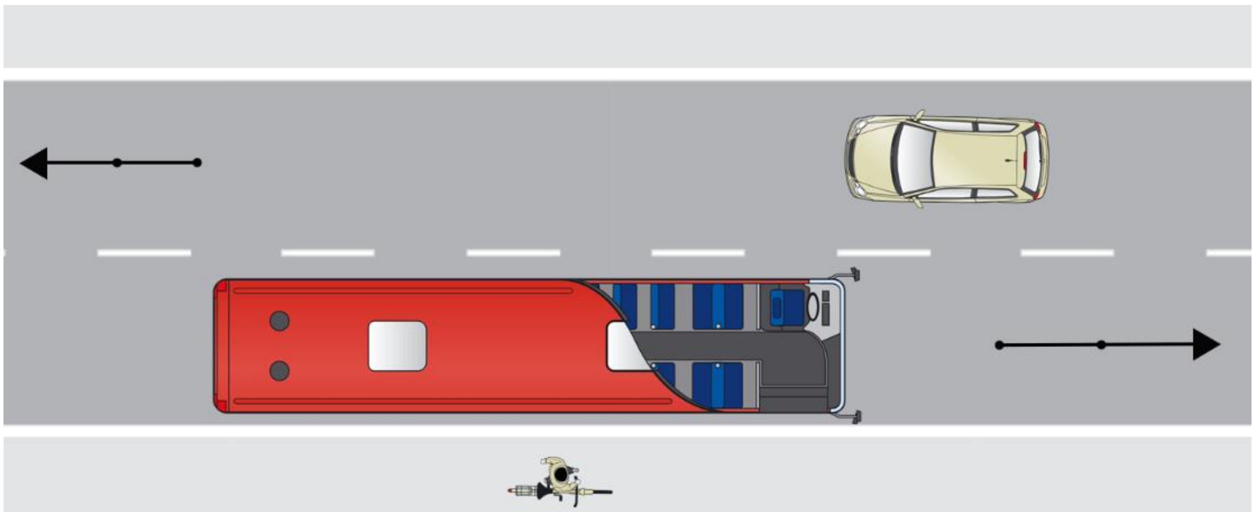


Figure 14: Cyclist carrying bike in the sidewalk

3.3.3 Summary of Method of Analysis

The two sections above provide the reader a better understand of the data types and data categories that the researcher compiled during the data collection phase. All ten noted data categories (Three “Conflicts” and Seven “Issues”). Again, the three “Conflicts” categories are situations that may lead into possible avoidance maneuvers for the following vehicles while the seven “Issues” categories split between maneuvers and decisions made by the cyclists that can be qualified as unexpected or even unlawful.

3.4 Area of Study: Downtown Pittsburgh Pennsylvania

With the data, collection and analysis methodology set, it was necessary to selected which intersections the cameras would be placed for the data collection. The following section explain the surroundings of the analyzed SBBL and discuss the particularities of each chosen intersection.

3.4.1 Surrounding Area

Smithfield Street is one of the major east-west corridors in Downtown Pittsburgh, even with its mostly two-way, two lane configurations. Unsurprisingly, the majority of the buildings occupied are for commercial and service use. There are 12 intersections on Smithfield counting from Liberty Avenue to Fort Pitt Boulevard. The total length is 2,650 ft with blocks of 260 ft. Smithfield Street is highlighted in blue in the Figure 15 below.

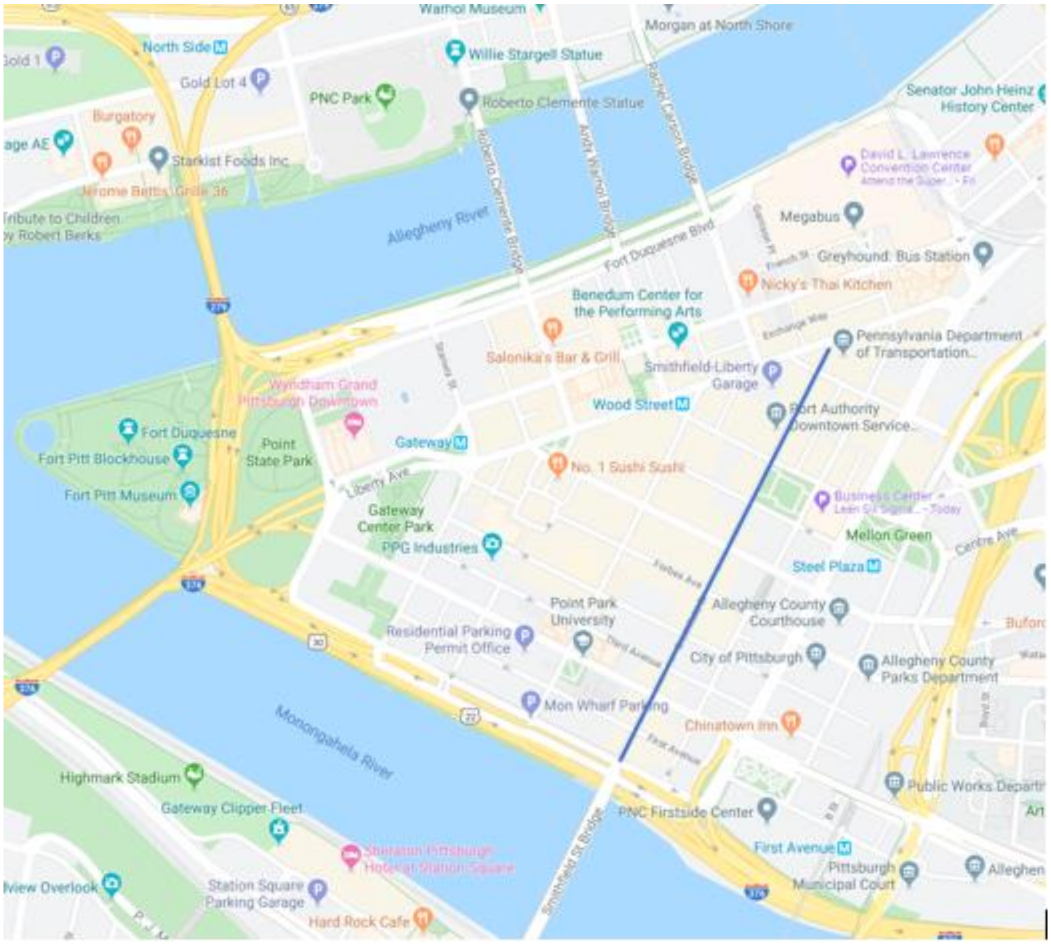


Figure 15: Downtown Pittsburgh.

For the bus routes that go through Smithfield, Port Authority was able to provide for this research a multitude of information. According the data provided, a total of 20 bus routes travel at some point in the corridor but only 6 routes travel all the way. The average headway is approximately 1 minute and a half for both the weekday peak hour for the weekday off-peak (Exception being the stop at Smithfield Street at Sixth Avenue with over 3 minutes of headway during off-peak hours). The headways presented for the weekends as also 1 minute and a half, with the stop at Sixth Avenue having over 8 minutes of headway between buses. Relative to the speed that buses achieve in the SBBL, Port Authority noted as the highest average speed as 17 mph between the stops at intersections in Third Avenue and Fort Pitt Boulevard during the weekends.

During peak hours between Liberty and Sixth noted less than 5 mph on average and approximately 11 mph between Third Avenue and Fort Pitt Boulevard, based on their GPS tracking of buses. More information on the Smithfield buses information is presented at the Appendix B.

An important note is that during the summer of 2019, when the data was collected a street parallel to Smithfield Street, Grant Street, was under construction for revitalization. Because of this work, Port Authority had to reroute bus routes that traveled on Grant to Smithfield. The possible impact of increased bus volume on the conclusions of this research was discussed between researchers and the Pittsburgh's DOMI officials and it was decided that said impact would be non-significant, because the total amount of buses that would be added was low in comparison to the usual traffic.

3.4.2 Selected Intersection

For the study, a total of four intersections are selected as representatives of the SBBL operation on Smithfield Street. The selections were made based on discussions with the Department of Mobility and Infrastructure and Port Authority authorities together with researchers. These are the intersections selected, accompanied by their respective reasoning.

3.4.2.1 Smithfield Street at Liberty Avenue

The intersection between Smithfield and Liberty Avenue was selected primarily for entrance to the SBBL. Other reasons for their inclusion in the data analysis are that the intersection is close to the most utilized bike-riding infrastructure in Downtown, the two-way protected bike lane on Penn Avenue, and the was confirmed by the density map available on Strava's website showed that this intersection receives a considerable amount of cyclist activity compared to other nearby streets. Below, Figure 16 shows the Strava's heat map for the intersection while Figure 17 shows the research cameras' locations, represented by red dots.

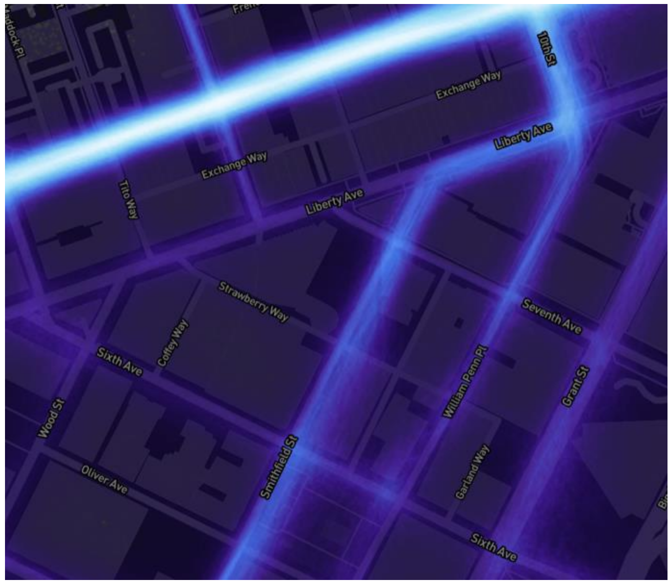


Figure 16: Liberty at Smithfield cycling heat map

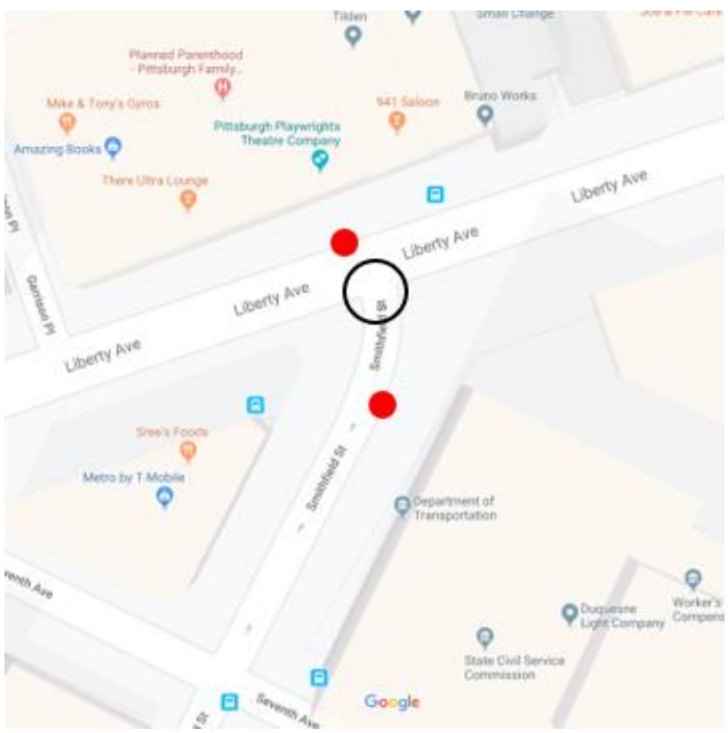


Figure 17: Surrounds of Liberty at Smithfield Intersection

3.4.2.2 Smithfield Street at Sixth Avenue

The intersection between Smithfield Street and Sixth Avenue was selected after discussions on what is the busiest intersections within the SBBL between researchers and City of Pittsburgh officials. The presence of a major bus stop in the intersection was noted as a great opportunity to study how the relationship between buses and bikes was happening when the headways between buses are shorter making conflicts more frequent. Below, Figure 18 shows the Strava's heat map for the intersection while Figure 19 shows the research cameras' locations, represented by red dots.

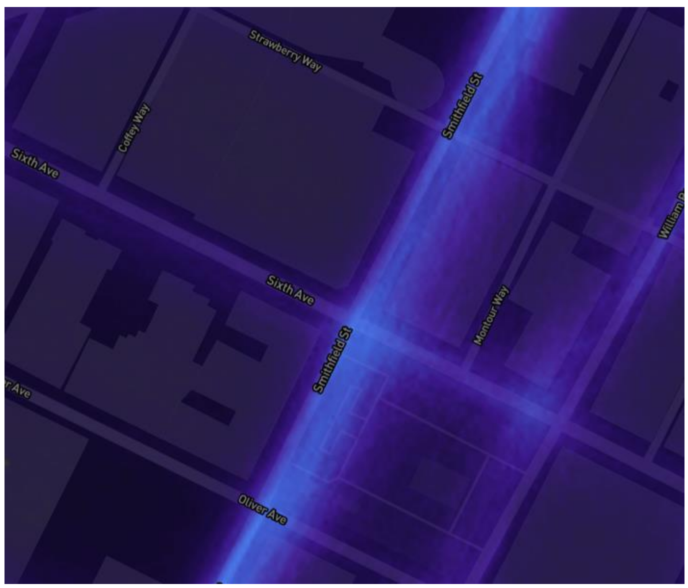


Figure 18: Sixth at Smithfield cycling heat map

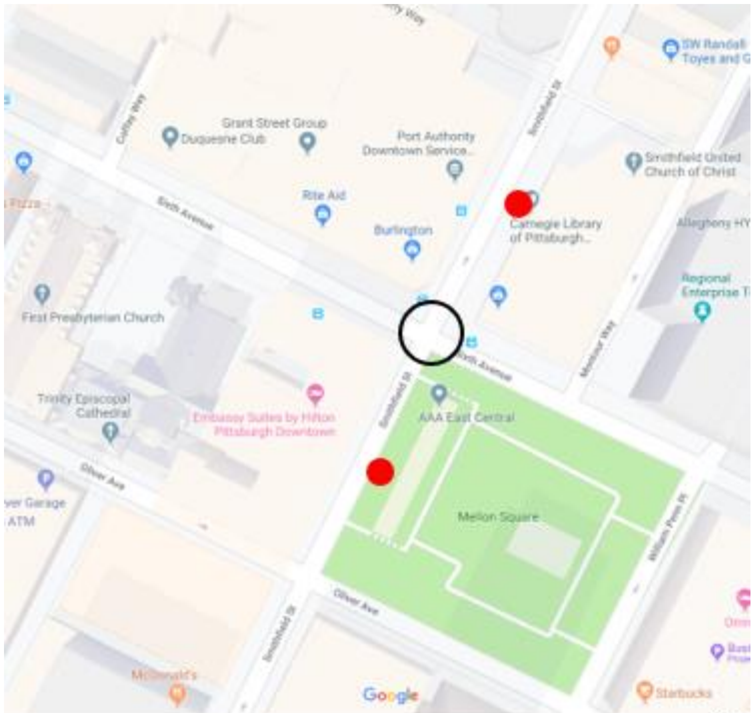


Figure 19: Surrounds of Sixth at Smithfield Intersection

3.4.2.3 Smithfield Street at Boulevard of the Allies

The decision to include the intersection between Smithfield and Boulevard of the Allies was made based in two major topics. Firstly, the Strava heat map noted many cyclists traveling along the Boulevard, which as identified during the discussions that cyclists traveling along Smithfield could very well decide to continue or not on Smithfield based on their perspectives on the Boulevard traffic and vice versa. A second reason for the selection was how different the intersection was from other intersections within the SBBL, the Boulevard had six traveling lanes, making cyclists cross 60ft before arriving to the new block. Below, Figure 20 shows the Strava's heat map for the intersection while Figure 21 shows the research cameras' locations, represented by red dots.

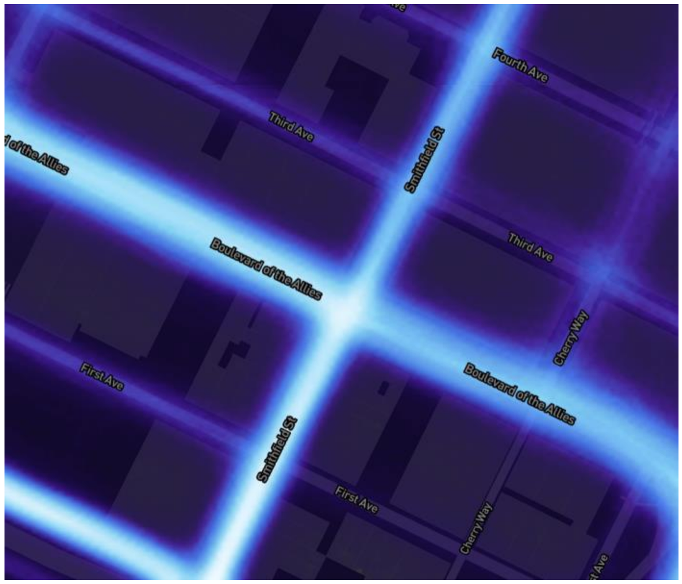


Figure 20: Boulevard of the Allies at Smithfield cycling heat map

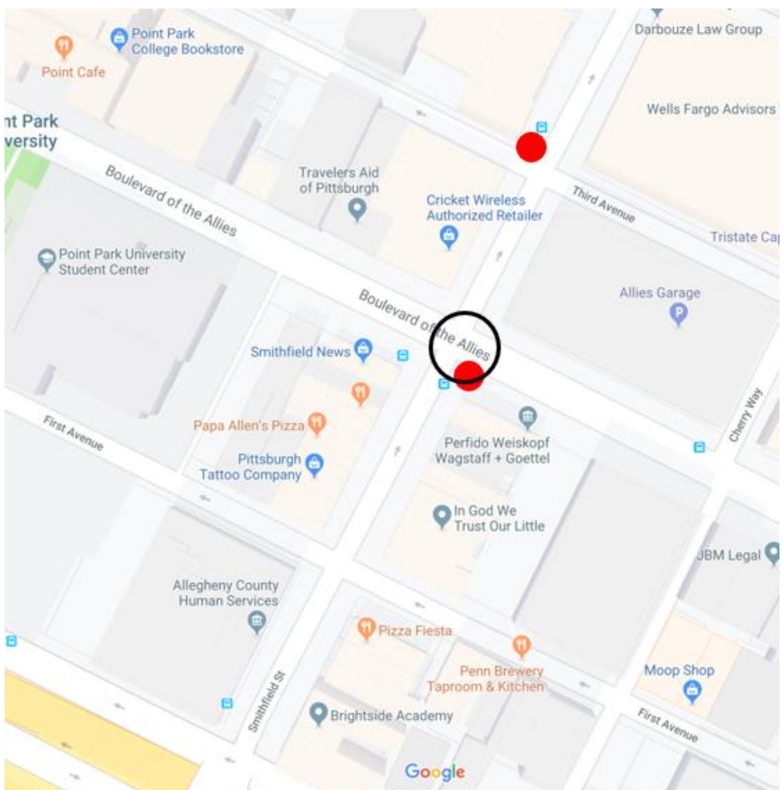


Figure 21: Surrounds of Boulevard of the Allies at Smithfield Intersection

3.4.2.4 Smithfield Street at Fort Pitt Boulevard

Finally, the last intersection selected for the data analysis was the intersection between Smithfield and Fort Pitt Boulevard. Much like the intersection between Smithfield and Liberty, this intersection was selected for being the end point of the SBBL and is also close to a more complete cycling infrastructure. Through shared sidewalks and crosswalks, the Smithfield Street is connected to the Allegheny River Trail. Cyclists that reach this intersection either by the SBBL or the trail can also take another SBBL that goes down Fort Pitt Boulevard to the SBBL in Wood Street. Below, Figure 22 shows the Strava's heat map for the intersection while Figure 23 shows the research cameras' locations, represented by red dots.

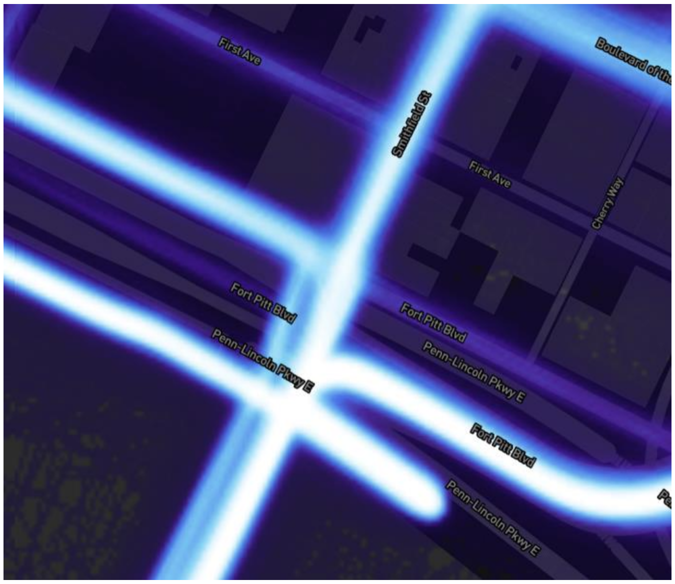


Figure 22: Fort Pitt at Smithfield cycling heat map

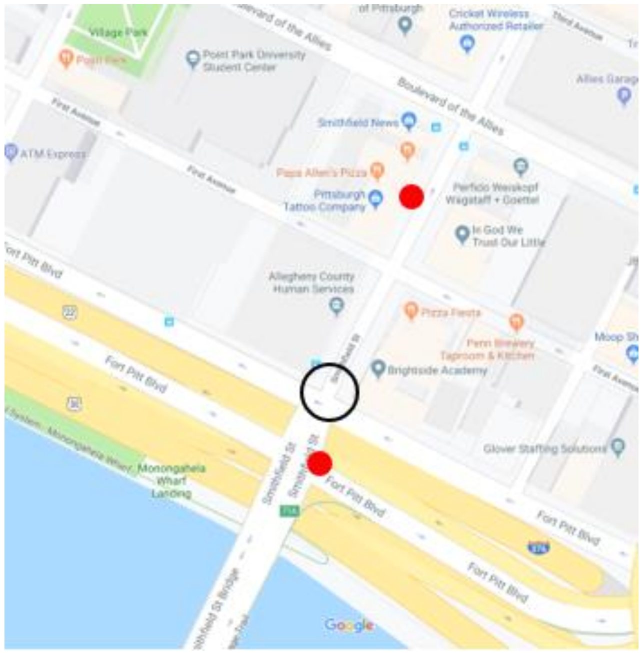


Figure 23: Surrounds of Boulevard of the Allies at Smithfield Intersection

3.5 Summary of Methodology

In summary, this research decided to analyze the safety aspects of the SBBL implementation in the Smithfield Street through the lens of interactions and conflicts between the modes due the lack of consistent bicycle crash report data and the newness of the SBBL. Other data were also collected such as traffic volume and roadway inventory, however those will be used for contextualization of the surrounding environment.

To observe the conflicts, two cameras were placed at each intersection, one facing the Smithfield SBBL traffic while the second one observed the movement in the SBBL before the intersection and the traffic coming from the opposite lane. Each intersection was recorded twice, once during the middle of the week and once more during the weekend, in order to recognize any differences in the type of day behaviors, which was not the case outside of reduced volumes. Each video record was expected to be a little over two days of observations.

Two types of data will be collected and analyzed in the next section: **Conflicts**, which will encompass all occasions that a cyclist has to interact with a motor vehicle (Buses on SBBL and vehicles in the opposing general lane), which is divided into three possible categories depending on the positioning of the cyclist and the vehicle which said cyclist is interacting with; and **Issues**, which embody both unlawful movements and simply undesirable movements. Those are divided into seven categories. The four intersections selected for the recordings were picked primarily for being either connected to a major corridor or being an attractive destination for cyclists in the downtown area.

4.0 Data Collection and Analysis

The following section present the data collection and its results. The section is introduced by a subsection with the days in which data was collected, the methodology to assemble the final video and the validation of those days by comparing ridership from established bike counter near Smithfield Street After validation, the data totals are presented with complementary analysis. First for the Smithfield corridor and after for each analyzed intersection to better understand the operation of the SBBL and point out outliers.

4.1 Collection and Validation of Data

With a well-defined methodology selected the data collection took place between the 2nd to 22th of July 2019. Within this interval, the researchers were able to record complete sets of 24 hours of video for two Wednesdays and two Saturdays. The collection date for each intersection is noted in the table below.

Table 2: Data collection Dates

Date	Intersection (Smithfield at)	Type of day
07/03/2019	Fort Pitt Boulevard	Weekday
07/03/2019	Boulevard of the Allies	Weekday
07/10/2019	Sixth Avenue	Weekday
07/10/2019	Liberty Avenue	Weekday
07/13/2019	Sixth Avenue	Weekend
07/13/2019	Liberty Avenue	Weekend
07/20/2019	Fort Pitt Boulevard	Weekend
07/20/2019	Boulevard of the Allies	Weekend

The cameras were mounted at the top of street poles located within Smithfield street with a 6-foot ladder and three members per crew. Each camera took approximately 30 minutes to be installed and 15 minutes to be removed from the pole. The cameras used for this research are indoor cameras modified for outdoor use. More detail on the mount and modifications can be found on the respective Appendix.

Figure 24: Jordan, Mateus and Yanbin finishing mounting the cameras

Cameras that recorded weekdays activity at Smithfield are installed at Tuesday mornings, around 9 AM while weekend cameras are installed at the end of Fridays, around 5 PM. Each camera was left at the pole for 3 to 4 days depending on the weather and availability of the crew. However, due to limitations of the capacity of the portable battery's attached to the camera, the maximum number of hours that the cameras could record was around 50 hours. The cameras were turned on immediately after being mounted.

The camera used for this study records continuous video through separate one-minute clips and stores such clips in a MicroSD card that can be removed. After each video collection, the researchers cleaned up the data by removing the video recorded before and after the established 24-hour period. After cleaning, the one-minute clips are joined together to form a single 24-hour video, using free software available. A considerable number of clips through all recordings lost some data, ranging between 1 to 10 seconds, mostly at the end of the minute. At the end, the most complete records lost less than 3 minutes and the most problematics lost around 14 minutes total. After analysis of the video, it was decided that the loss of individual seconds between 1440 clips was not significant to warrant a new data collection.

After joining the individual clips into single 24-hour video, the researcher merged the two videos for the same intersection at the same day from different perspectives into single side-by-side video as exemplified below. The decision was made to facilitate review of conflicts between cyclists and vehicles. The loss of seconds in clips was a problem, making the videos unsynchronized, but once again this issue could be bypassed.

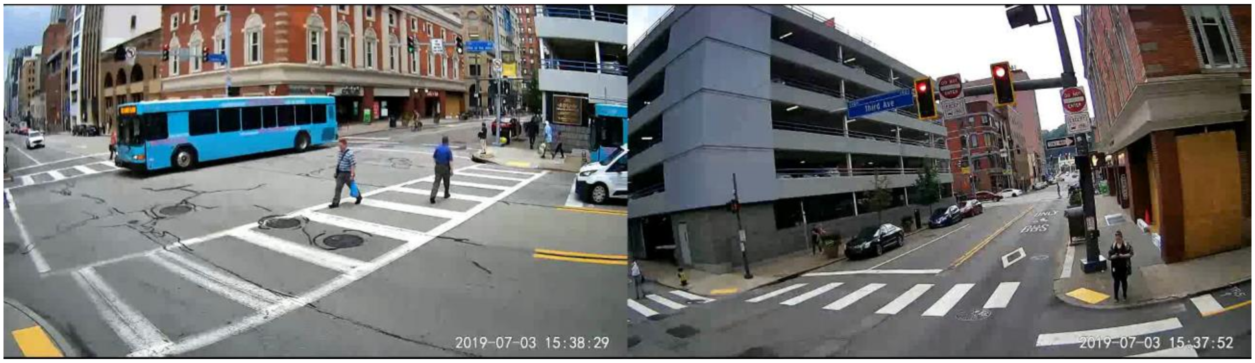


Figure 25: Example of the final video

Issues regarding cycling ridership during the days of the data collection did arise because of concerns of the impacts that weather could have to impact the data collected. Another issue was collecting data in the eve of the 4th of July, not a typical weekday due the holiday. To validate or adjust the data collected on the ridership, we observed the bike counts collected by the Pittsburgh Downtown Partnership (PDP) in Penn Avenue. Penn Avenue possess a protected bidirectional bike lane that connects Downtown Pittsburgh to the Strip District and continuously collects data. To evaluate the ridership on the days in which the data was collected, the researcher compared the respective days ridership' in the three locations where PDP counts bikes to the two types of days before and after this study data was collected.

Table 3: Ridership in Penn Ave during collection dates and two week margins

Weekday Bike Ridership in Penn Avenue Bike Lane			
Date	1200 Penn Avenue (# of bikes)	900 Penn Avenue (# of bikes)	600 Penn Avenue (# of bikes)
6/19/2019	570	381	295
6/26/2019	824	700	407
7/3/2019	705	348	20
7/10/2019	750	623	391
7/17/2019	527	391	296
7/24/2019	924	560	571
Weekend Bike Ridership in Penn Avenue Bike Lane			
Date	1200 Penn Avenue (# of bikes)	900 Penn Avenue (# of bikes)	600 Penn Avenue (# of bikes)
6/29/2019	552	26	337
7/6/2019	598	702	4
7/13/2019	653	650	533
7/20/2019	499	533	425
7/27/2019	829	797	626
8/3/2019	733	800	655

Source: Pittsburgh Downtown Partnership (PDP)

At the table above, we can say that for most part, the bike counts collected by PDP at the same time our research was collecting data, the bike ridership in Downtown maintained within the range of the established 6-week period, which draws the conclusion that the data collected is valid.

The researcher was the only individual to watch all eight 24-hour videos and identify conflicts and issues. The decision was made to maintain a consistent observation judgment on what configurates a conflict between modes and which Issue category should be prioritized in our collection as multiples could be detected in the same count. All videos are watched in 8x speed to save time and slowed back if needed for review purposes.

4.2 Data Analysis

The following analysis are done using the recorded data from the four days of records. Data from weekdays and weekends as put together to account all conflicts and issues recorded. Weekdays and weekend had similar datasets patterns, with the expected decrease in volume from weekday, making this assembling a non-issue. The analysis looked at the conflicts that cyclists had with buses and vehicles to determine if the hypothesis that the SBBL provide a safer environment for cyclists than a general lane is accurate. To complement this resolution, the unlawful movements by cyclists was also counted to note if the SBBL was leading cyclists to dangerous situation.

4.2.1 Data Totals

The data collected totaled 1,762 instances that a cyclist was caught on camera during the four days of footage. To make it clear, by no means this was a count of different cyclists or buses conflicting with each other once in the corridor but may include multiple instances of the same cyclists and/or bus have a conflict. All video records were viewed at the selected intersections in the same corridor, which makes it highly likely that the same cyclist or bus was recorded twice in the same trip for different conflicts. However, since the goal was to assess safety issues this should not be an issue relative to the absolute number of conflicts however it could be an issue when conflict rates were determined by on the volume of cyclist or buses. This issue also means that conflicts and issues that are not resolved in the first intersection could have been carried to next one and be counted twice on the data totals. It was decided that each conflict or issues should be studied as single, individual case and those, documented twice, would influence more in this analysis, for not being resolved.

Figure 26 below notes that the volume of cyclists on Smithfield Street carried a total of 1,762 cyclists during the time period recorded, with 1055 in the shared lane and 707 in the SBBL. The difference between the volumes of cyclists per directions most likely relates to the travel patterns in the central business district for bicycles.

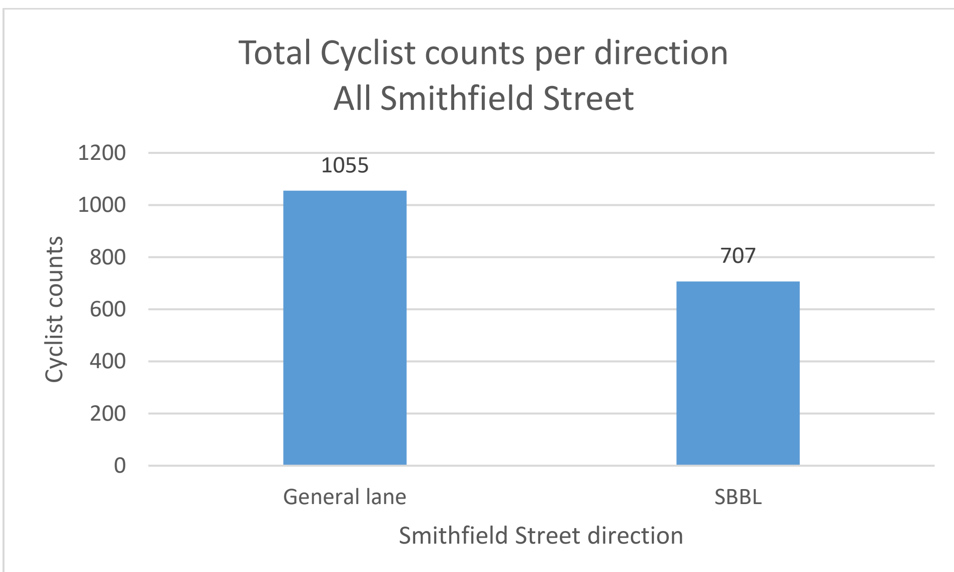


Figure 26: Smithfield Street Cyclist total counts

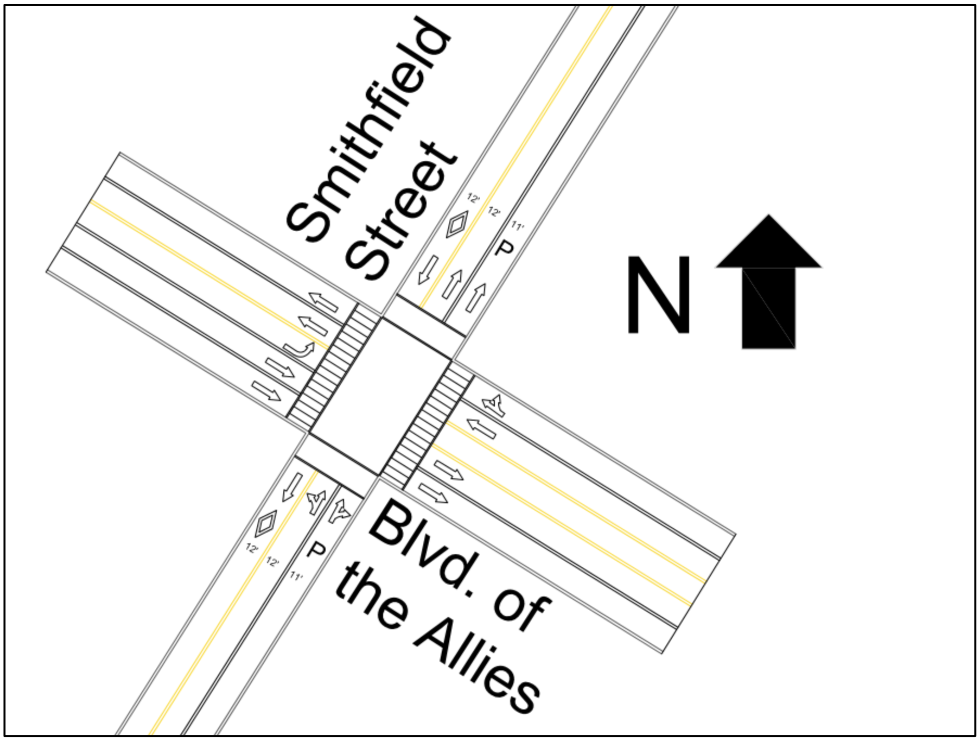


Figure 27: Schematic of intersection between Smithfield and Boulevard of the Allies

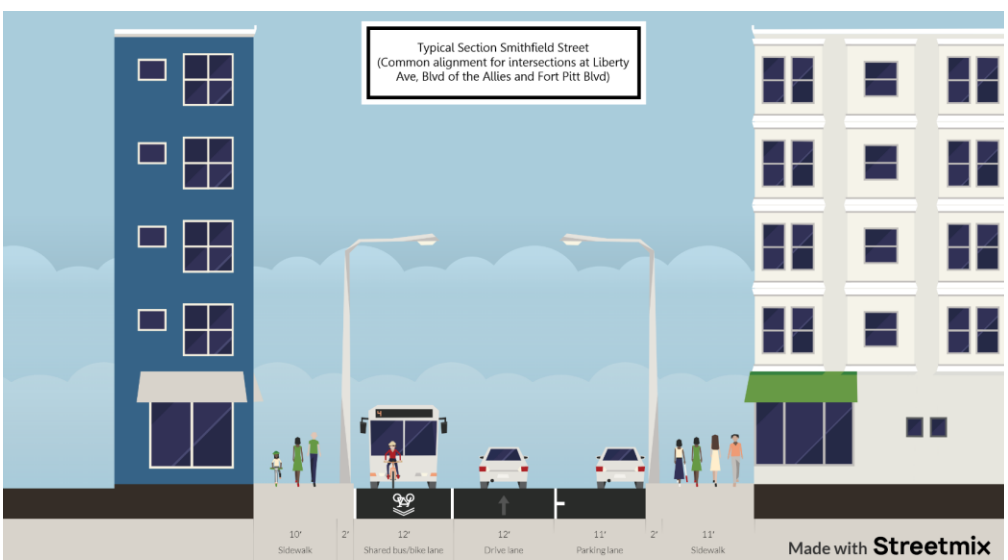


Figure 28: Typical section for majority of Smithfield Street

Looking at Figure 29 and the total collected cyclists' counts for each analyzed intersection reinforces the argument of different travel patterns. We can see a pattern in which the Southbound cyclists (Noted in red, with count values in red box near intersection) joins the SBBL as it gets closer to Fort Pitt, where they could take a bike trail near the intersection. Similar argument can be made for Northbound cyclists (Noted in blue) as the number decreases as it moves away from the trail and gets near Liberty Avenue.

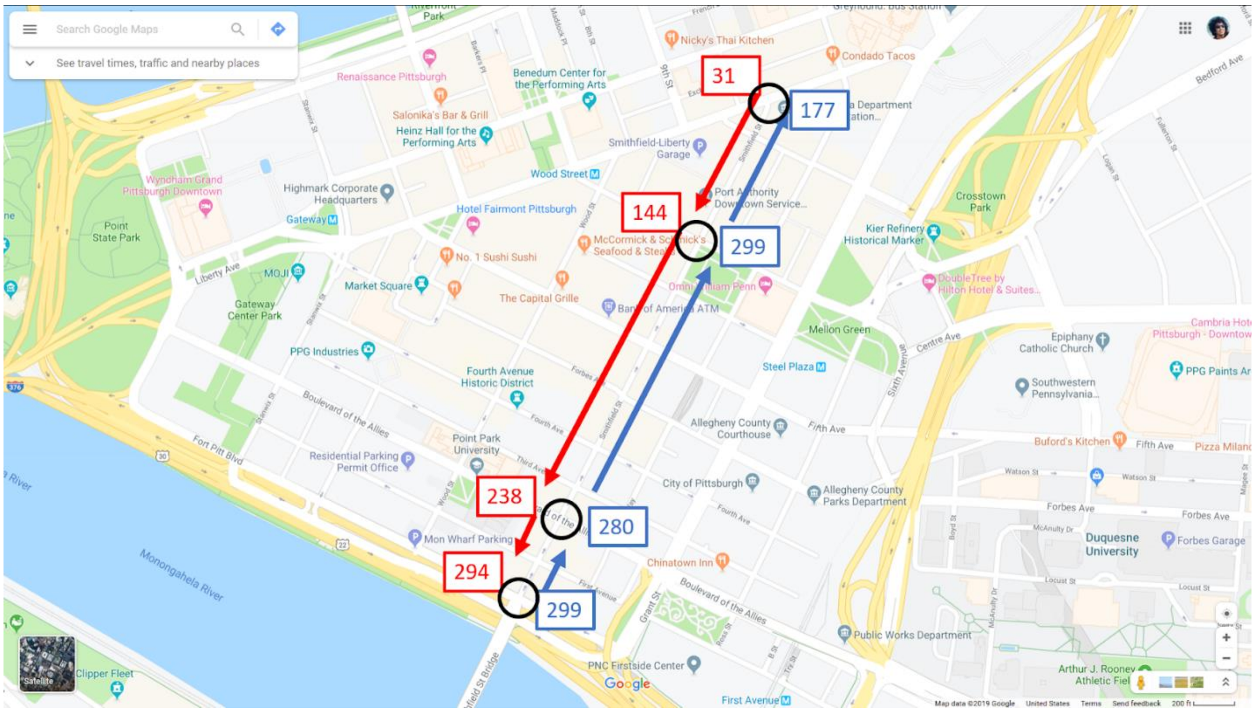


Figure 29: Recorded bicycle counts per direction

Regarding conflicts, Figure 30 and Figure 31 notes three categories that were determined to better explain all possible conflicts that cyclists may encounter while traveling within the Smithfield Street corridor. The categories used were: Behind vehicle, Ahead vehicle, In between vehicles. Behind and after vehicle conflict are noted at the methodology with its respective downsides each. In between vehicles category was created during data analysis to conglomerate the conflicts in which the cyclist found themselves between vehicles. The latter situation only applies to general conflicts as no bus overtake was recorded.

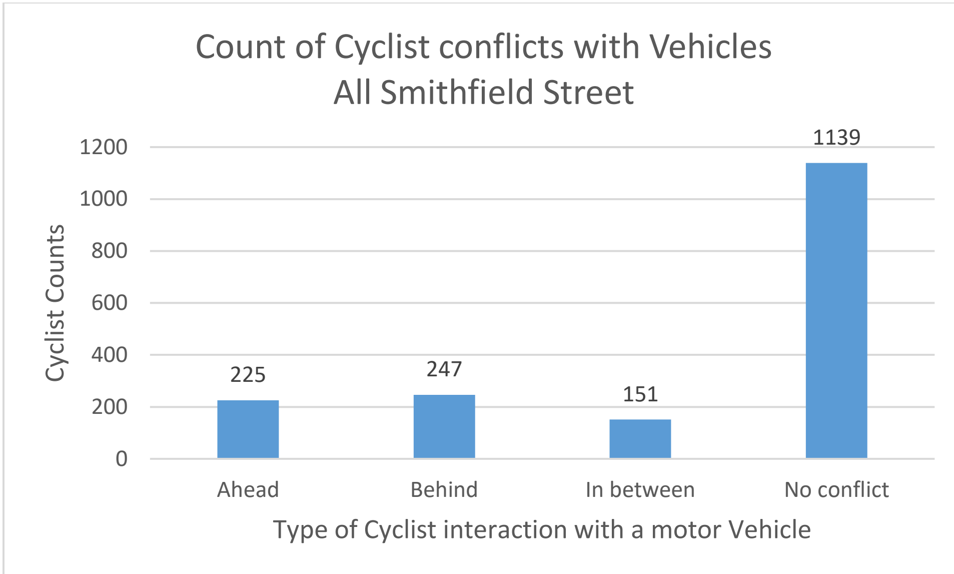


Figure 30: Smithfield Street Cyclist conflicts

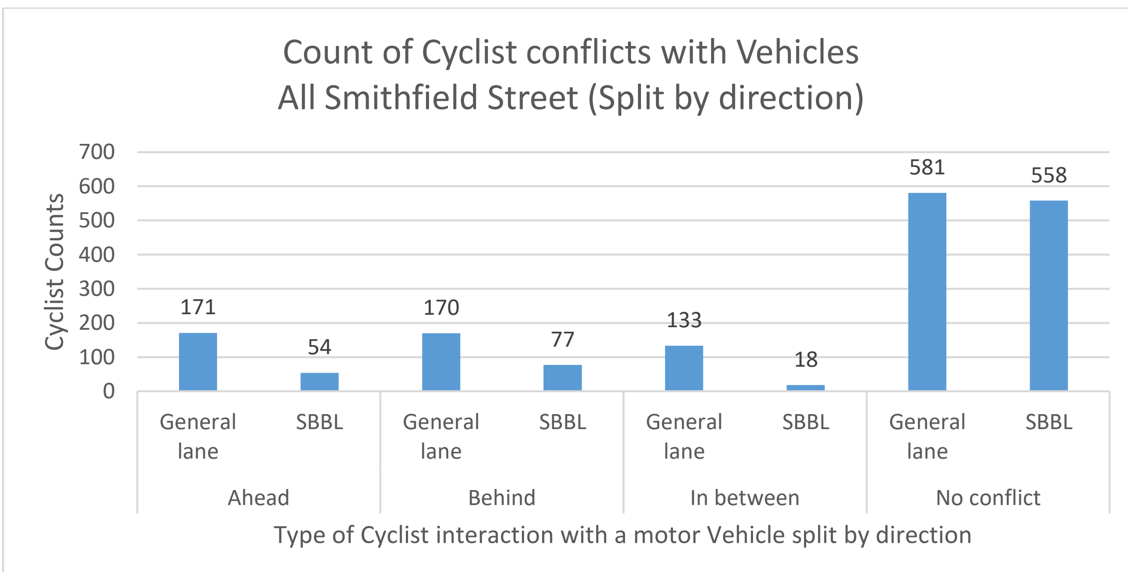


Figure 31: Smithfield Street Cyclist conflicts per direction

Figure 31 notes that conflicts are approximately three times less frequent in the SBBL than in the general lanes, reducing the odds of conflicts that could deteriorate into crashes and that the configurating the SBBL as a safer lane than a general traffic lane. However, issues were identified during the analysis that may have skewed specifically the SBBL data to draw the conclusion of less conflicts.

Outside the previous conflicts identified in the methodology, other concerns arise during analysis. Specifically, a considerable number of cyclists were identified as making unexpected decisions and even committing traffic infractions. For such, it was also decided to collect data on said issues. Those issues are separated in 7 individual categories accompanied by a “No issue” category. The following figures and tables present the issues noted both in total (Figure 32) and by direction (Figure 33 and Table 4).

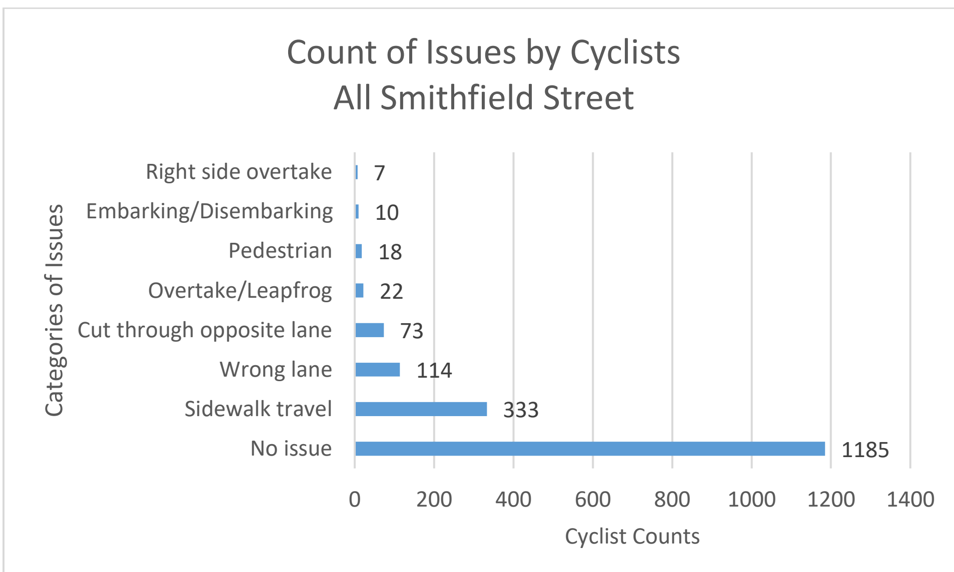


Figure 32: Smithfield Street Cyclist Total Issues

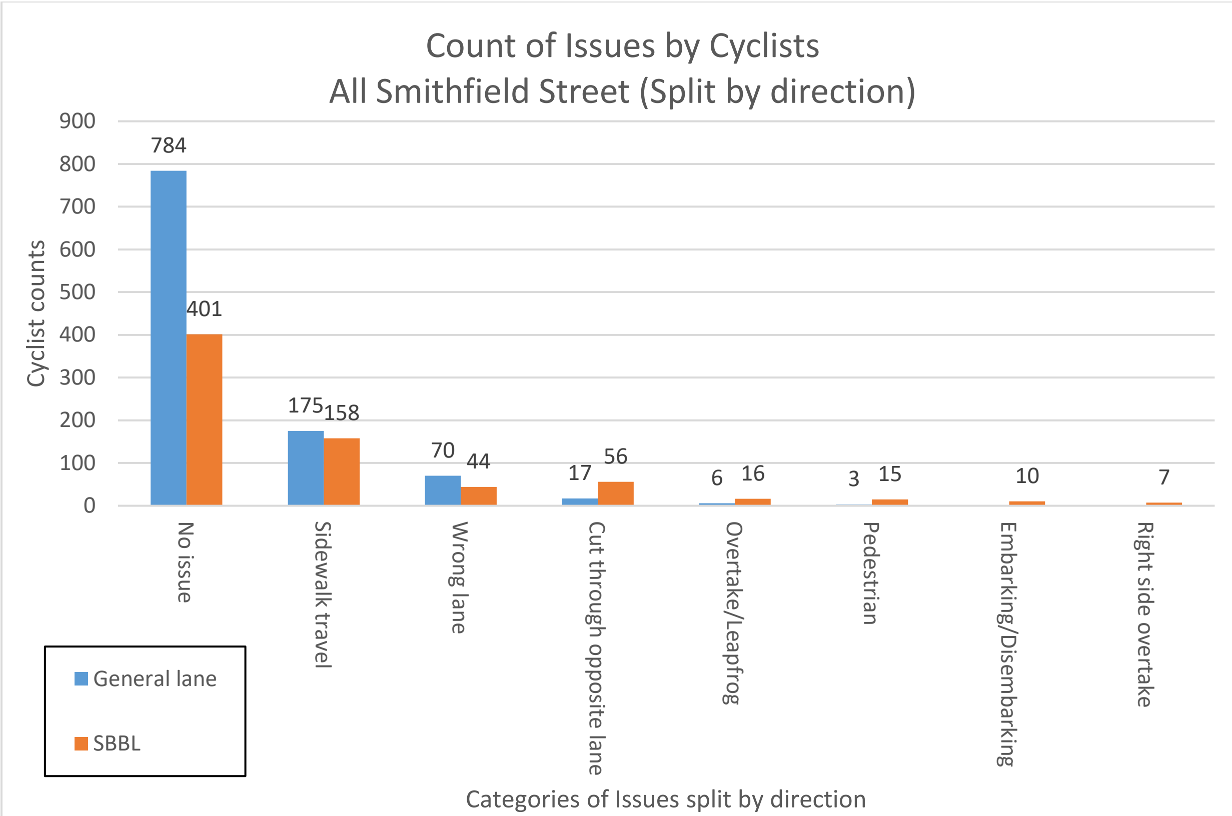


Figure 33: Smithfield Street Cyclist Total Issues per direction

Table 4: Issues noted during analysis and its respective counts

Issues	Direction	Count of Issues
No issue	General lane	784
No issue	SBBL	401
Sidewalk travel	General lane	175
Sidewalk travel	SBBL	158
Wrong lane	General lane	70
Wrong lane	SBBL	44
Cut through opposite lane	General lane	17
Cut through opposite lane	SBBL	56
Overtake/Leapfrog	General lane	6
Overtake/Leapfrog	SBBL	16
Pedestrian	General lane	3
Pedestrian	SBBL	15
Embarking/Disembarking	SBBL	10
Right side overtake	SBBL	7

First, a quick glance to Figure 32 highlights that two thirds of the cyclists that traveled through Smithfield Street corridor did so without a noticeable issue, which speaks to mainly to confidence of those cyclists and/or their efforts of comply to traffic laws.

"Sidewalk travel" and "Pedestrian" are categories that can be qualified by cyclists that are warier of the road and either decided to ride the bicycle in the sidewalk or dismount the bike and walk along Smithfield. "Sidewalk travel" can also have confident cyclists that decided to travel in the sidewalk to get closer to the next section (Such will be discussed in more detail in the Smithfield Street at Fort Pitt Boulevard analysis).

In the other hand, over-confident cyclists seemed to commit infractions which configurates into four other categories. "Overtaking/Leapfrog" are passing maneuvers in which the cyclist used the opposite flow lane, which is prohibited for those traveling in the SBBL. "Right side overtake" are cyclists that either used the last space possible near the curb or used the sidewalk to get in front of the vehicle. "Cut through opposing lane" notes cyclist that inadvertently went to the opposite lane during a mid-section briefly to either reach the sidewalk or get ahead in the turning movement. These issues could result into crashes between cyclists and turning vehicles. "Wrong lane" encompasses cyclists that traveled in the opposite lane for a considerable length. This category highlights how the lack of traffic in the SBBL may attract contra-flow cyclists. Finally, "Embarking/Disembarking" notes cyclists that used both modes in the same trip.

It is important to note that the same cyclists may have multiple issues during the same trip. For example, a cyclist near Fort Pitt Boulevard traveling along the SBBL could decide to cut through the general lane, which is contra-flow, in order to reach the opposite sidewalk, where they would ride to the near trail. This would configurate two issues "Cut through opposite lane" and "Sidewalk travel". It was decided to maintain only a single major issue to preserve an equal number of counts and issues. For that it was necessary to create a priority rank between issues. Said ranking is presented in Table 5 below and its positioning was decided mainly on the risks to the cyclists. The top four categories can be considered of high risk to the cyclist with the next adding risk to pedestrian experiences and the bottom two are simply noted for being unusual movements. The ranking between high-risk maneuvers was done looking at how difficult would be for the cyclist to avoid a collision if the encounter a vehicle during each maneuver.

Table 5: Ranking of identified Issues by danger to cyclist

Ranking	Type of Risk	Issue
1	High Risk	Overtake/Leapfrog
2	High Risk	Wrong Lane
3	High Risk	Cut through opposite lane
4	High Risk	Right side overtake
5	Relevant Risk	Sidewalk travel
6	No Risk/Unusual movement	Embarking/Disembarking
7	No Risk/Unusual movement	Pedestrian

We can see in Figure 33 with the breakdown between lanes that sidewalk cyclists are more frequent found in the SBBL than in the General lane. Most cyclists that are counted for "Sidewalk travel" are also counted for "No conflict" with vehicle which could skewed. For such reason, it was decided to present another figure for conflicts without sidewalk travel cases (Figure 34).

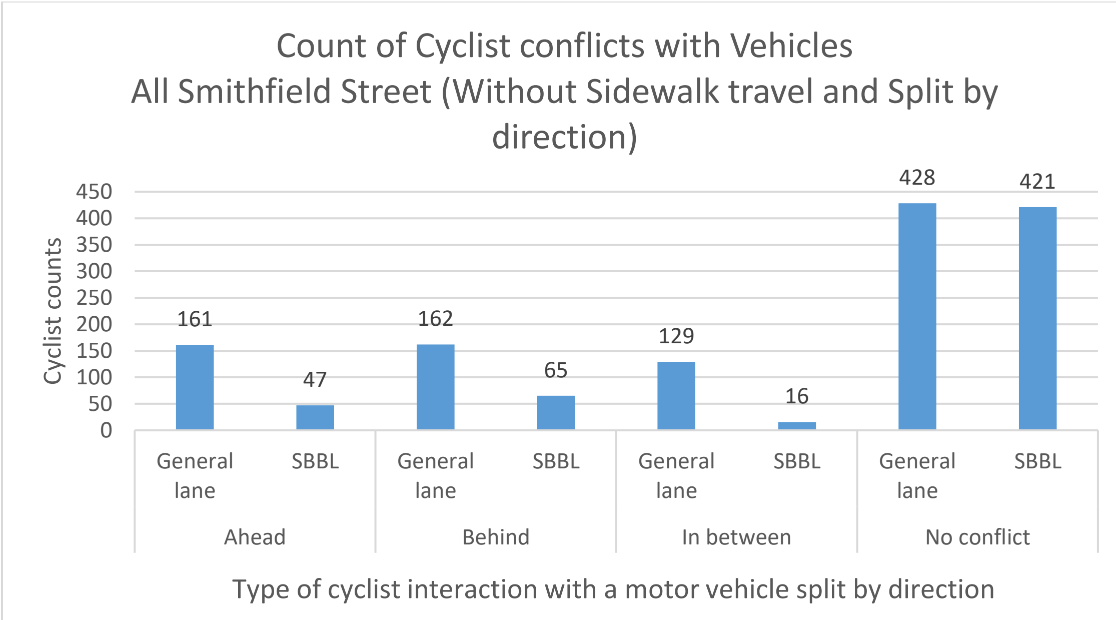


Figure 34: Smithfield Street Cyclist total conflicts without sidewalk Cyclists

Comparing the results from Figure 31 with sidewalk cyclist against Figure 34 without, no clear pattern can be noted. As expected, "No conflict" had biggest loss but across the board the loss of counts was fairly even, which could be concluded that sidewalk cyclists did not skew that conflict data and that cyclists traveling along the SBBL will have to deal with far less encounters.

Reviewing the numbers provided by Figure 31, counting the sidewalk cyclists, for every two cyclists traveling in the general lane is likely that one will have to interact with a vehicle. For the Shared Bus-Bike Lane, the number of cyclists traveling in the lane goes up to four before one has interact with a bus. This result reinforces the hypothesis of this study that a SBBL are a safe infrastructure for cycling as cyclists in the SBBL will enjoy their ride with less conflicts to worry about, similarly to a bike exclusive infrastructure.

The researcher wanted to look not only at the Contra-flow SBBL performance in comparison to the opposing general lane but also at the selected intersections, thus it is important to present similar rates of conflicts by total amount of cyclists to the four intersections. Those ratios are presented at Table 6 below. Unsurprisingly, all four had similar results in which SBBL cyclists always had less conflicts than the cyclists in the general lane, most intersections presenting SBBL cyclists having half of conflicts.

Table 6: Ratio of cyclists' conflicts with motor vehicles to the total of cyclists

Location	General Lane Conflict $\left(\frac{Cyclist\ with\ conflicts}{Total\ cyclists}\%\right)$	SBBL Conflict $\left(\frac{Cyclist\ with\ conflicts}{Total\ cyclists}\%\right)$
Sum of all Smithfield	42.84	18.10
At Liberty Avenue	28.81	9.68
At Sixth Avenue	48.16	25.69
At Blvd of the Allies	54.64	21.43
At Fort Pitt Boulevard	32.76	19.73

A similar ratio of the high-risk issues was calculated and presented at Table 7 below. Au contraire to the ratios at Table 6, the high-risk ratio did not follow a visible pattern. Looking at the whole Smithfield Street, cyclists in the SBBL performed high-risk maneuvers twice as much than their general lane counterparts, which could mean that cyclists would find discomfort in the SBBL and are willing to take risks of crashes, going against our study hypothesis. However, the discomfort assumption is not carried for most analyzed intersections, where SBBL cyclists performed similarly to the general lane cyclists, with the exception of the intersection in Smithfield Street at Fort Pitt Boulevard, with a high-risk rate almost three times higher for SBBL cyclists than general lane cyclists.

Table 7: Ratio of cyclists in high risk situations to the total of cyclists

Location	General Lane High Risk $(\frac{Cyclist\ with\ high-risk\ maneuvers}{Total\ cyclists}\%)$	SBBL High Risk $(\frac{Cyclist\ with\ high-risk\ maneuvers}{Total\ cyclists}\%)$
Sum of all Smithfield	8.82	17.40
At Liberty Avenue	3.95	9.68
At Sixth Avenue	13.38	9.72
At Blvd of the Allies	6.43	9.66
At Fort Pitt Boulevard	9.36	27.55

As the intersections in the Smithfield Street are also being analyzed for safety regarding the SBBL operation, it is important to reinforce that analyzed length for each intersection was not the same due to field conditions and each intersection has a different ADT due to land use. For that reason, it was important to find a way to standardize all four intersections to better identify and understand outlier in our data among the selected intersections. For that, the Equation 4-1 below was developed to standardize the conflict data collected based on the ADT and the analyzed length.

$$\text{Confict Rate or Cr} = \frac{\sum \ (Conflicts)}{((Bus\ ADT + Bicycle\ ADT) * \frac{Observed\ Length\ (ft)}{1000\ ft})} \qquad (4\text{-}1)$$

The observed length used in the equation was the distance between the cameras used. Two ADT are used: The SBBL recorded weekday bicycle ADT in this study and an estimation of the SBBL bus ADT based on the headways given at Appendix B (Estimating four hours of peak and sixteen off-peak hours). The bus ADT used for each intersection was based on the nearest bus stop: Smithfield at Sixth for both Sixth and Liberty intersections and Smithfield at Fort Pitt for both Fort Pitt and Boulevard of the Allies intersections. The values are presented at Table 8 below.

Table 8: Conflict rate (Cr) ratio for each intersection

Location	SBBL Conflicts counts (Weekday)	SBBL Estimated Weekday Bus ADT	SBBL Recorded Weekday Bicycle ADT	Observed Length (ft)	Cr (Conflicts/ADT)
At Liberty	2	408	16	100 ft	0.05
At Sixth	28	408	86	230 ft	0.25
At Boulevard of the Allies	34	472	110	200 ft	0.29
At Fort Pitt	41	472	137	300 ft	0.22

A similar rate could be calculated for all the high-risk acknowledged during the analysis using the Equation 4-2 below, followed by Table 9 with the results.

$$\text{High} - \text{Risk Rate or HRr} = \frac{\sum \ (\text{High} - \text{Risk Rate })}{((Bus\ ADT + Bicycle\ ADT) * \frac{Observed\ Length\ (ft)}{1000\ ft})} \quad \text{(4-2)}$$

Table 9: High Risk rate (HRr) ratio for each intersection

Location	SBBL High Risk Issues Counts (Weekday)	SBBL Estimated Weekday Bus ADT	SBBL Recorded Weekday Bicycle ADT	Observed Length (ft)	HRr (Issues/ADT)
At Liberty	1	408	16	100 ft	0.02
At Sixth	13	408	86	230 ft	0.11
At Boulevard of the Allies	10	472	110	200 ft	0.09
At Fort Pitt	58	472	137	300 ft	0.32

Looking at the results in Table 8 and Table 9, two things can be inferred: First, Liberty Avenue intersection presents itself as a safer environment in both the conflict and high-risk issue perspective but that could due to the low bike volume compared to the other intersections. Boulevard of the Allies led the conflict rates while Fort Pitt Boulevard rose in the High-Risk rate, which could build up the argument that conflicts with buses does not force bikers into dangerous situations.

However, no group of intersections maintained a pattern, which warrants an intimate analysis for each intersection, which is presented in the following subsections with each intersection peculiarities.

4.2.2 Smithfield Street at Liberty Avenue

The data was collected for Smithfield Street at Liberty Avenue in the days 07/10/2019 (Weekday) and 07/13/2019 (Weekend). Both cameras were placed in poles near the analyzed intersection within a 50 feet radius (Example of the cameras POV is presented at Figure 35, below). The intersection design is a three-way intersection with an angled connection between Liberty and Smithfield. More detail on the intersection design is presented at the Appendix C. Conflicts for exiting cyclists in the general lane may be reduced thanks to the reduced length provided by the angle.

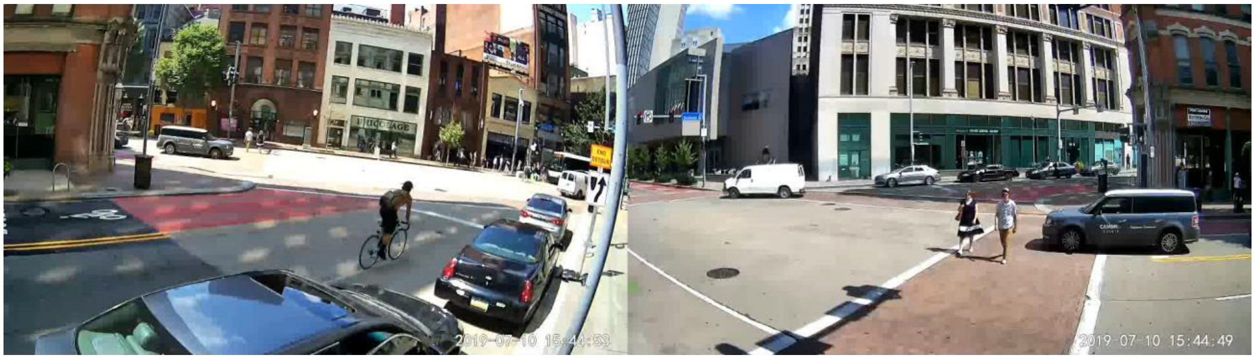


Figure 35: POV of the two cameras in the Smithfield at Liberty intersection

The total data collected noted a total of 208 cyclists traveling along the intersection during the two days, the lowest number of all four-intersection analyzed, present on the Figure 36 below. The results from SBBL count is quite surprising. Only 31 cyclists are found traveling along the intersection. As this research was focused on analyzing solely the Smithfield street, no official count was made of cyclists traveling along Liberty Avenue in the direction of the SBBL, however, said phenomenon was noticeable. Coupled with growing number of cyclists that the SBBL had in the subsequent intersections, this phenom could warrant a future analysis.

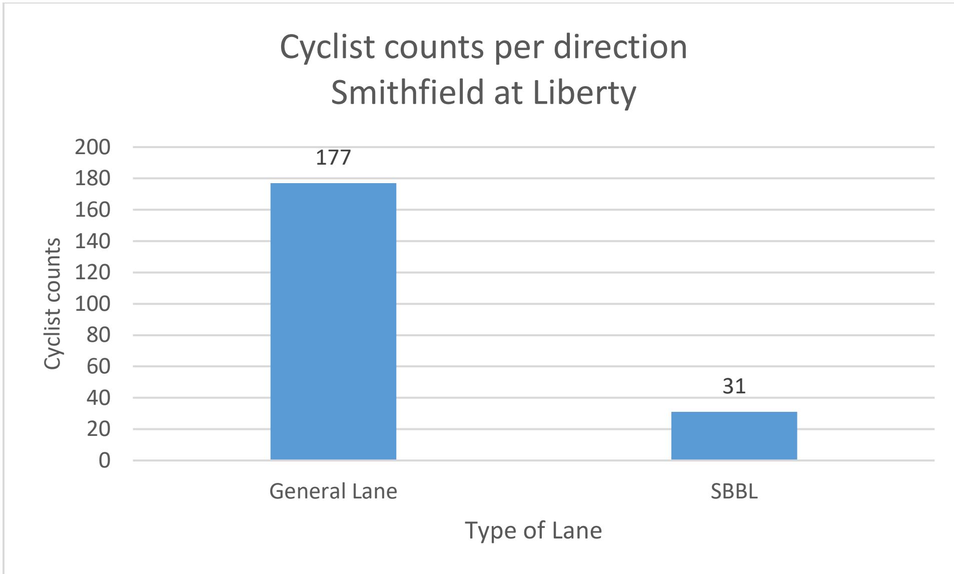


Figure 36: Smithfield at Liberty Cyclist counts

The counts of conflicts were noted in Figures 37 (Total Numbers) and 38 (Divided by direction). Well over half of the cyclists traveled without having to deal with sharing the road with a vehicle. The general lane was where these conflicts occurred primarily. 96% of all conflicts occurred in the general lane, affecting 45% of general lane cyclists.

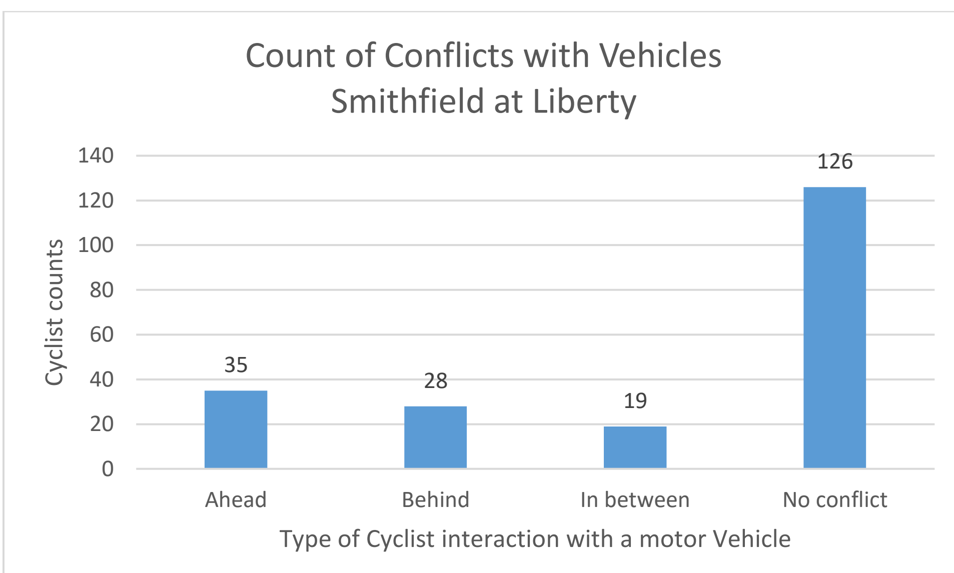


Figure 37: Smithfield at Liberty Cyclist conflicts counts

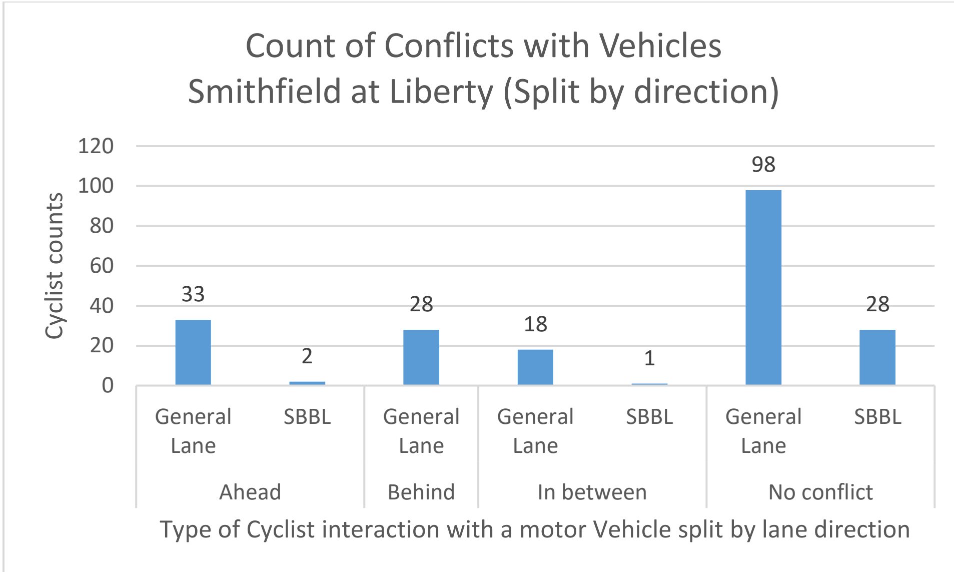


Figure 38: Smithfield at Liberty Cyclist conflicts counts per direction

Regarding "Issues", 18% of all cyclists performed an unusual action. Sidewalk travel was the most noticeable action with 12% of total counts. When looking at the lanes separated, the percentage of sidewalk travelers in SBBL (26%) shows less comfort between those cyclists in comparison to the ones traveling in the general lane direction (10% traveled in the sidewalk).

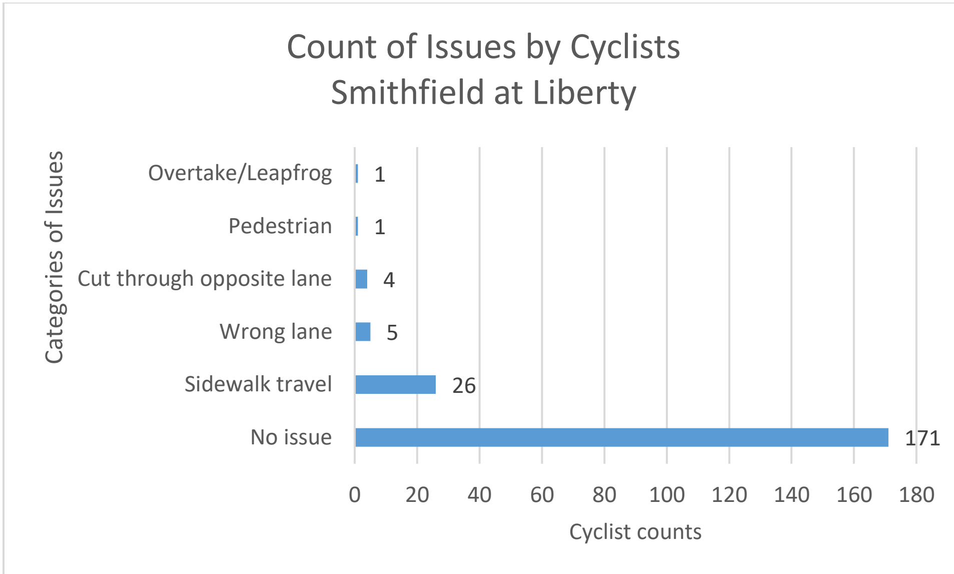


Figure 39: Smithfield at Liberty Cyclist Issues counts

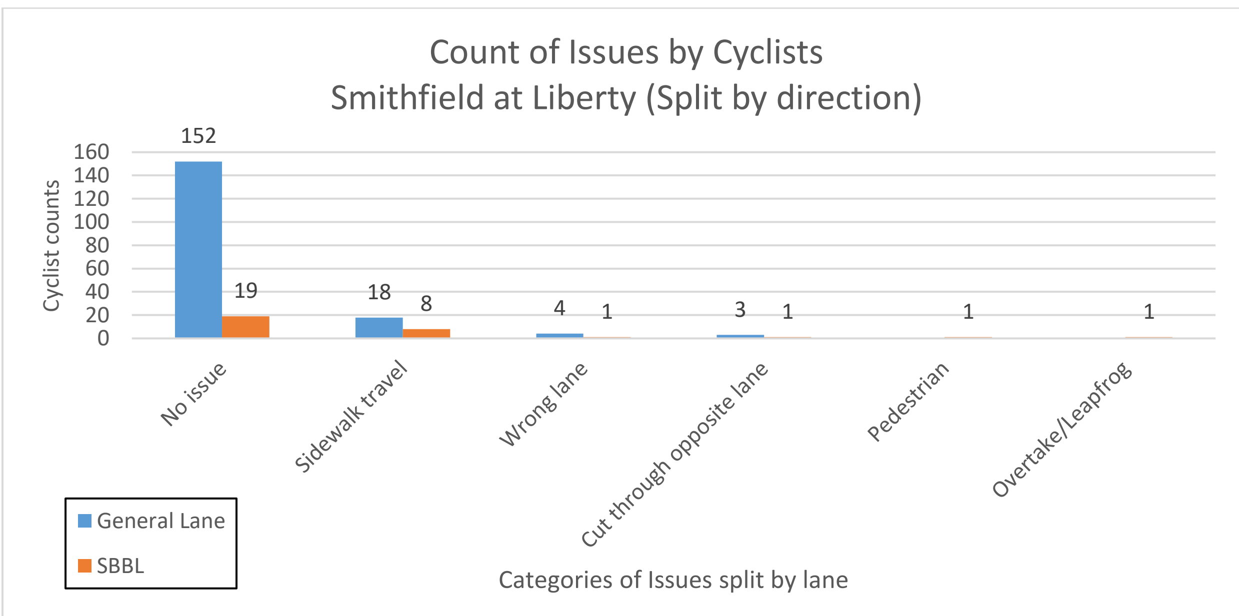


Figure 40: Smithfield at Liberty Cyclist Issues counts per direction

4.2.3 Smithfield Street at Sixth Avenue

The data was collected for Smithfield Street at Sixth Avenue in the days 07/10/2019 (Weekday) and 07/13/2019 (Weekend). Both cameras were placed in poles near the analyzed intersection within a 150 feet radius (Example of the cameras POV is presented at Figure 41, below). The intersection design is a four-way intersection where vehicles in Smithfield travel in flat surface while vehicles coming from Grant Avenue are going downhill. From Seventh Street to Sixth Avenue, Smithfield has its SBBL going southbound and a general lane and parking lane going northbound. Between Sixth and Oliver Way, the design changes as the parking is moved to the Southbound direction, adjacent to the SBBL, while the general lane is the north lane going north. Another important characteristic is that before the intersection, the SBBL has a sizeable Bus Stop, which has 13 bus routes. More detail on the intersection design is presented at the Appendix C.

Figure 41: POV of the two cameras in the Smithfield at Sixth intersection

The total counts of cyclists in the Sixth Avenue intersection noted a total 443 cyclists in the footage, accounting both the 10^{th} and the 13^{th}. The general lane had the advantage over the SBBL for over 100% of the totals in the SBBL. Still, the ground gained by the SBBL is considerable and could mean that the SBBL may pick up bikers along the corridor and not solely at its designed entry point (Figure 42).

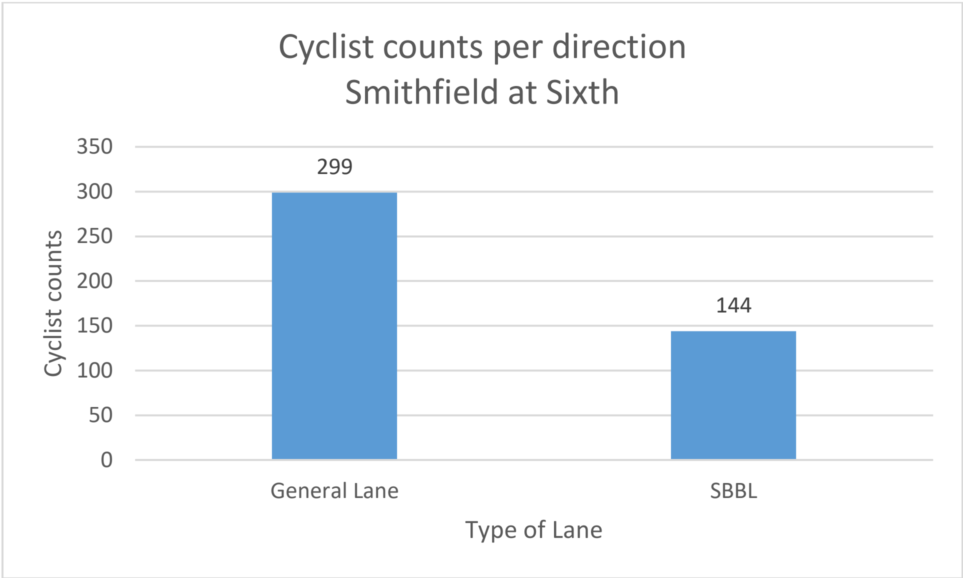


Figure 42: Smithfield at Sixth Cyclist counts

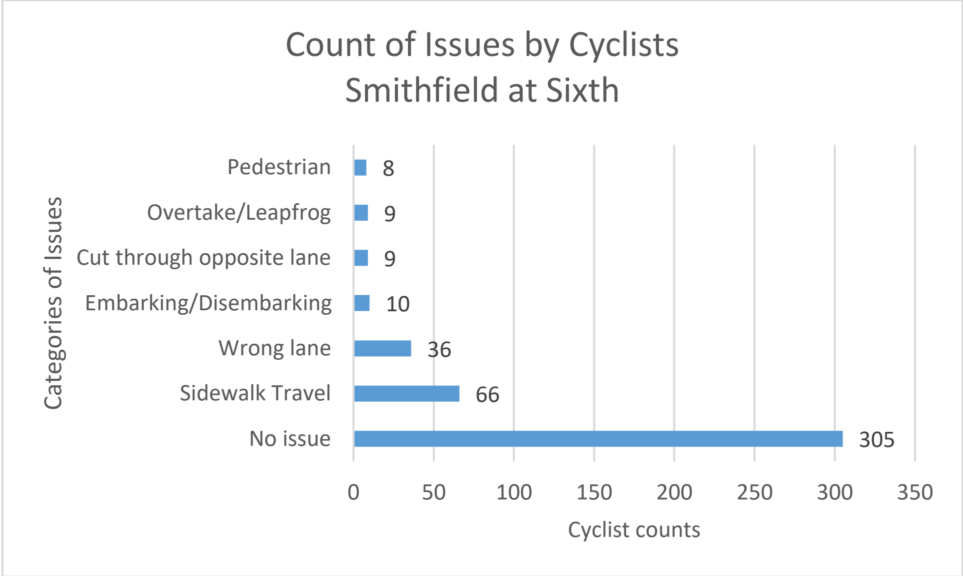


Figure 43: Smithfield at Sixth Cyclist Issues counts

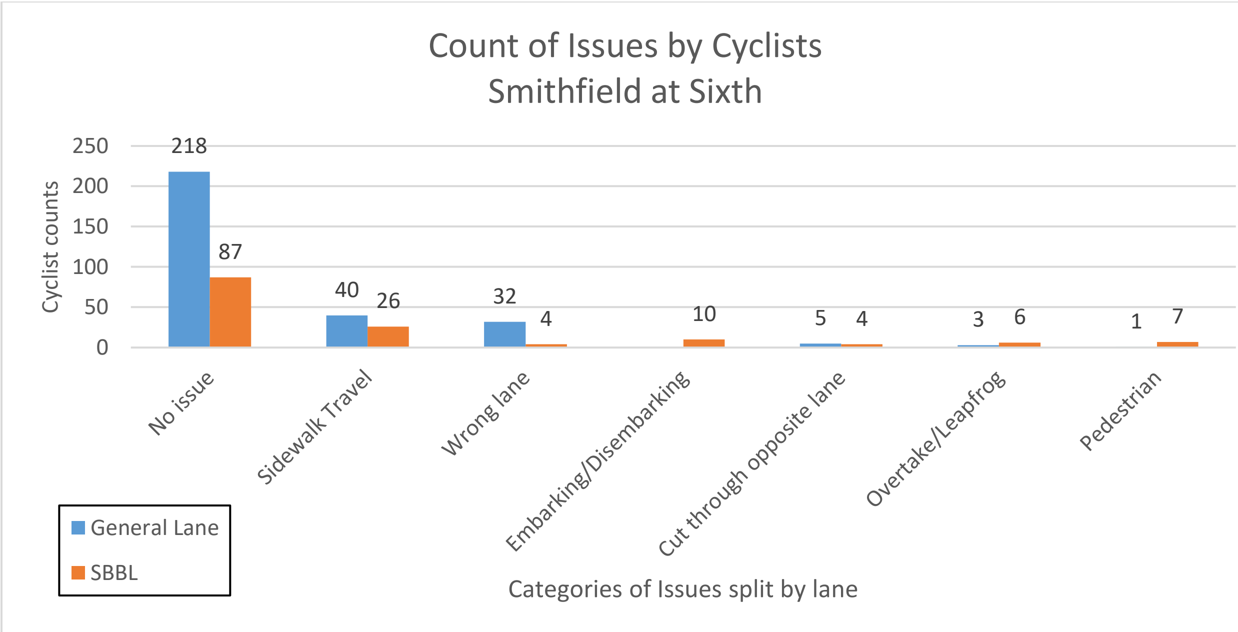


Figure 44: Smithfield at Sixth Cyclist Issues counts per direction

Figures 43 and 44, both above, notes the counts for the issues recognized in the footage. 305 of the cyclists did not do anything unusual. Sidewalk travel was the action that most cyclists carried out, followed by traveling in the wrong lane. Other issues had lower rates less but warrant some discussion. Embarking and disembarking bus passengers with bicycle appeared 10 times in the footage, all those in the SBBL. Cutting lane cyclists and wrong lane cyclists are 18 total, 9 each. Finally, dismounted cyclists appeared 8 times in the footage. Individualizing per direction, we had similar rates of sidewalk cyclists between the general lane and the SBBL. However, the rate of cyclists that invaded the SBBL from the General lane was 10.70% while only 2.78% of uninvited cyclists from the shared lane.

Regarding conflicts with motor vehicles, cyclists ended up behind vehicles in a higher frequency than ahead but not by much (Figure 45). Dividing by direction on Figure 46, it’s clear that the general lane cyclist has to deal with traffic more often than SBBL cyclists. Having the bus stop near the intersection had relative effect on conflicts by having significant numbers on both behind and after but neither of the categories had a substantial lead over the other.

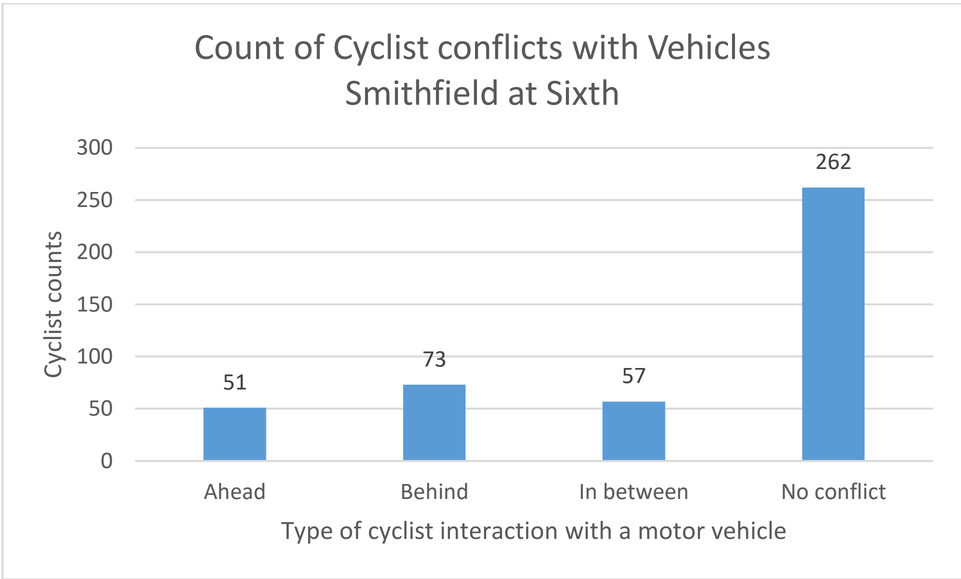


Figure 45: Smithfield at Sixth Cyclist conflicts counts

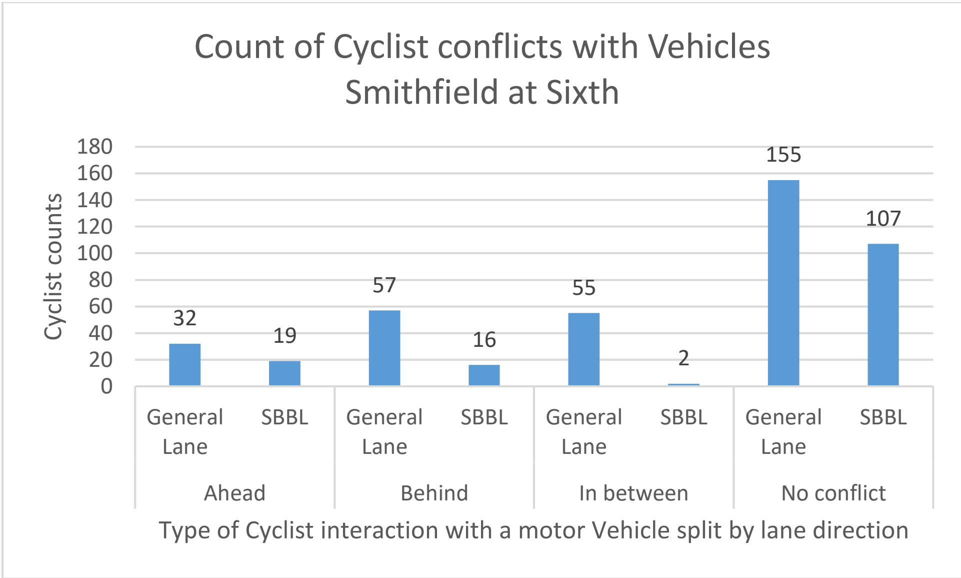


Figure 46: Smithfield at Sixth Cyclist conflicts counts per direction

4.2.4 Smithfield Street at Boulevard of the Allies

The data was collected for Smithfield Street at Boulevard of the Allies in the days 07/03/2019 (Weekday) and 07/20/2019 (Weekend). The camera looking at incoming SBBL traffic was placed in a pole at the intersection while the camera looking at incoming General Lane traffic was placed at a pole in the intersection between Smithfield Street and Third Avenue The decision to place the camera at an intersection before was made in order to the researcher be able to see any conflict happening behind a bus, which would likely block the point of view of the intersection camera. The second camera was positioned approximately 180 ft of the intersection. POV of both cameras is presented below, at Figure 47. Both intersection approaches have a single SBBL going southbound and a general lane and a parking lane going north. Boulevard of the Allies has five traffic lanes, making it the longest intersection that users have to cross with 60 ft. More detail on the intersection design is presented at the Appendix C.

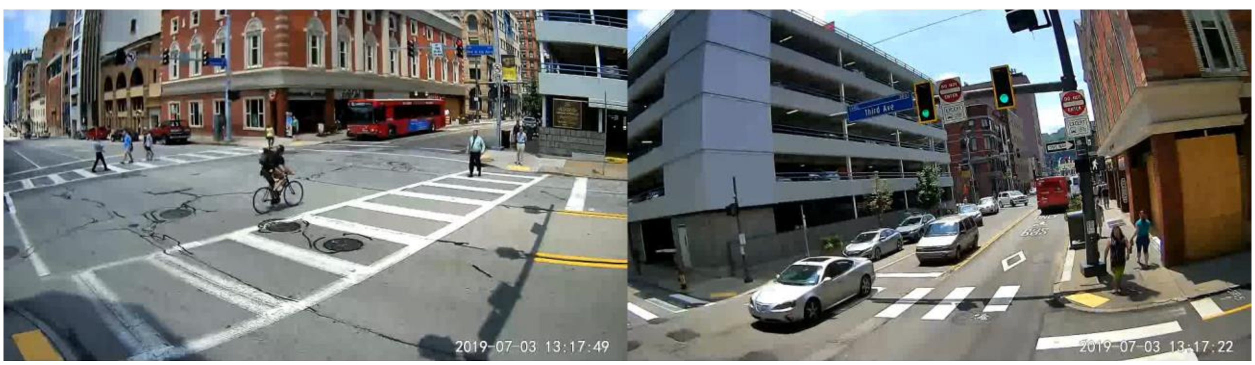


Figure 47: POV of the two cameras in the Smithfield at Boulevard of the Allies intersection

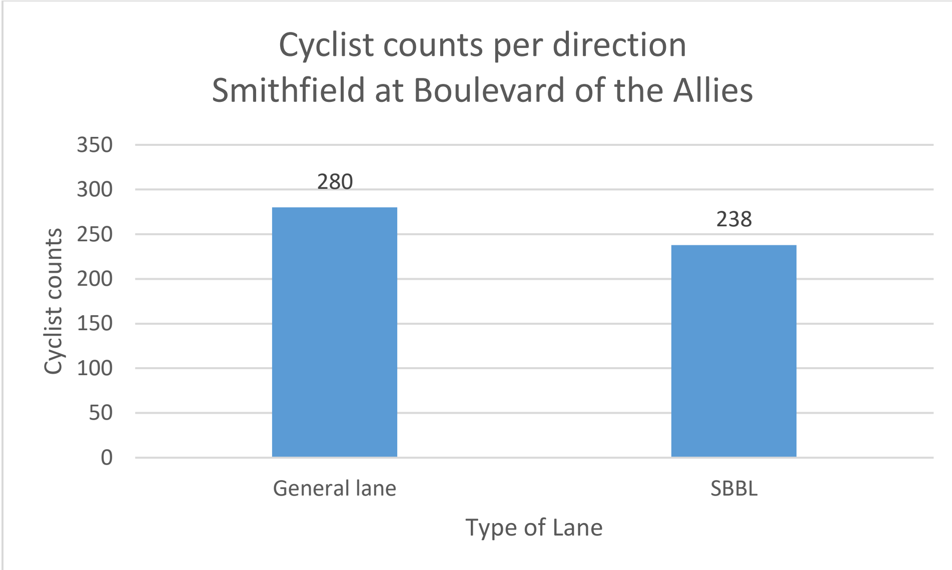


Figure 48: Smithfield at Boulevard of the Allies Cyclists counts

The counts on the third intersection maintained close to the geometric growth observed from the first to the second intersection however general lane counts had a drop in numbers. Not necessary a significant drop but both phenoms could flag that Smithfield cyclists in general may be avoiding the entry points and start to enter the street when near the end point.

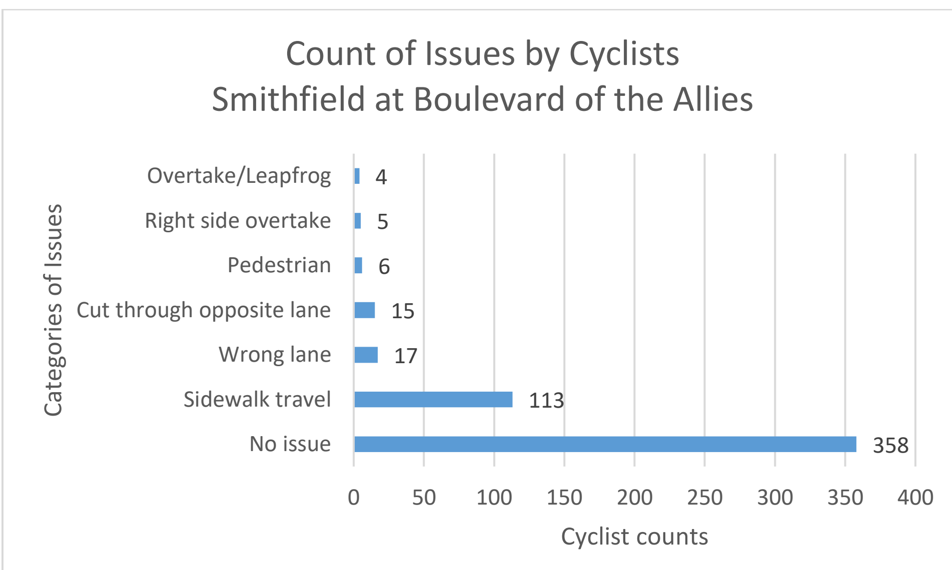


Figure 49: Smithfield at Boulevard of the Allies Cyclist Issues counts

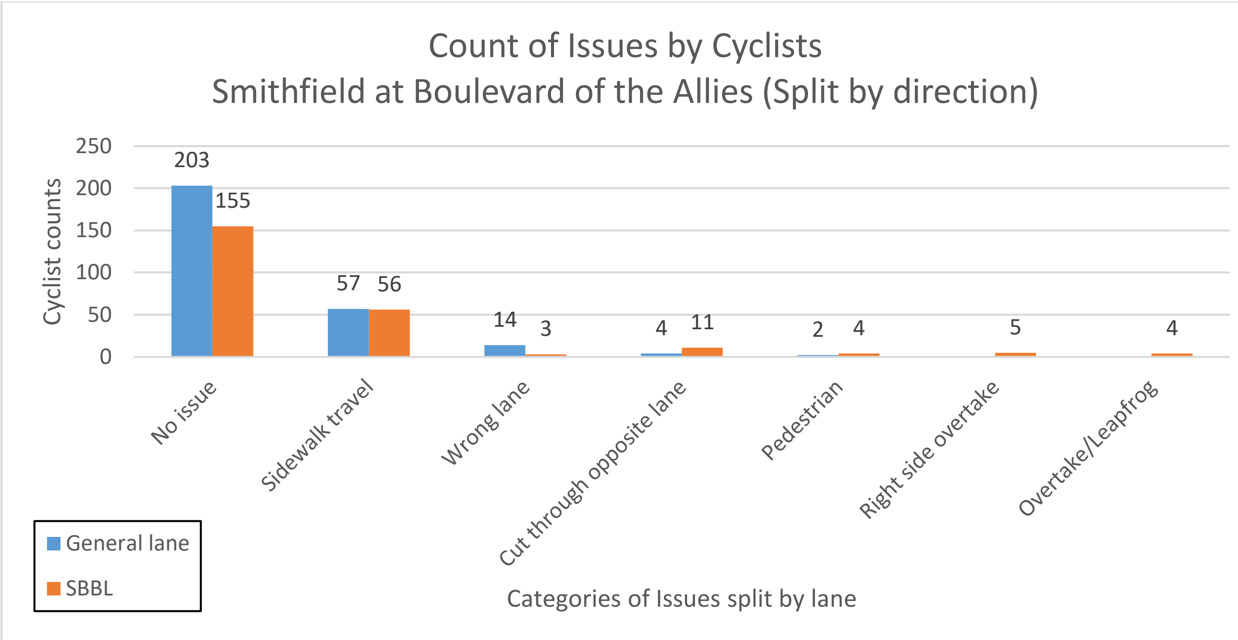


Figure 50: Smithfield at Boulevard of the Allies Cyclist Issues counts per direction

For the issues counts, 358 did not had issues, infractions or had unusual movements. Sidewalk travel was unsurprisingly the major issue once again, followed by wrong lane travel and cutting cyclists (Figure 49). In Figure 50, with counts divided by direction, sidewalk travelers are evenly split, however the following two categories had quite interesting result. General lane cyclists were the majority when invading and travelling the opposite flow lane, which could be reasoned by lack of traffic in the SBBL. The SBBL cyclists ended up quickly cutting through the opposite lane to reach either the sidewalk. Said movement could be explained by them wanting to reach their destination but it is also possible they are not feeling comfortable in the SBBL.

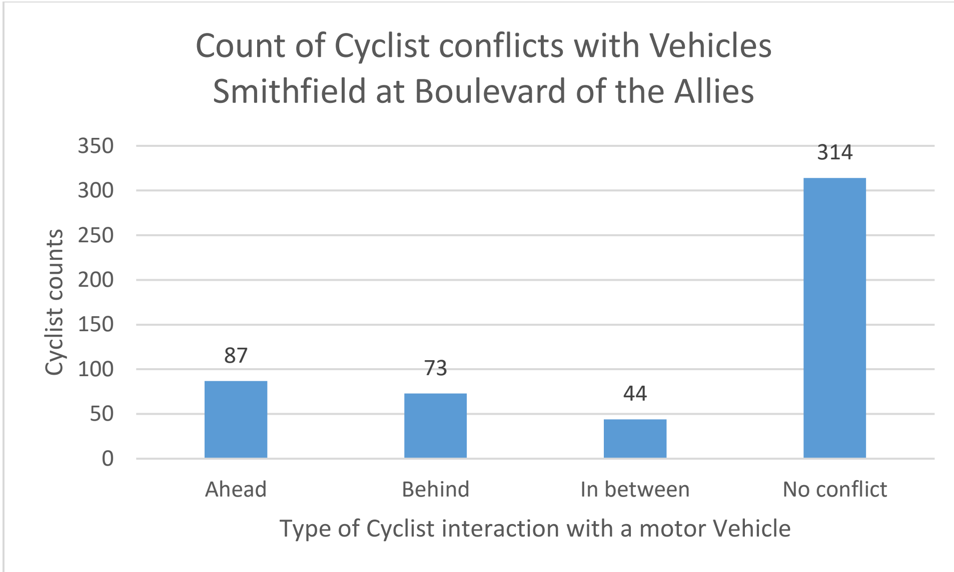


Figure 51: Smithfield at Boulevard of the Allies Cyclist conflicts counts

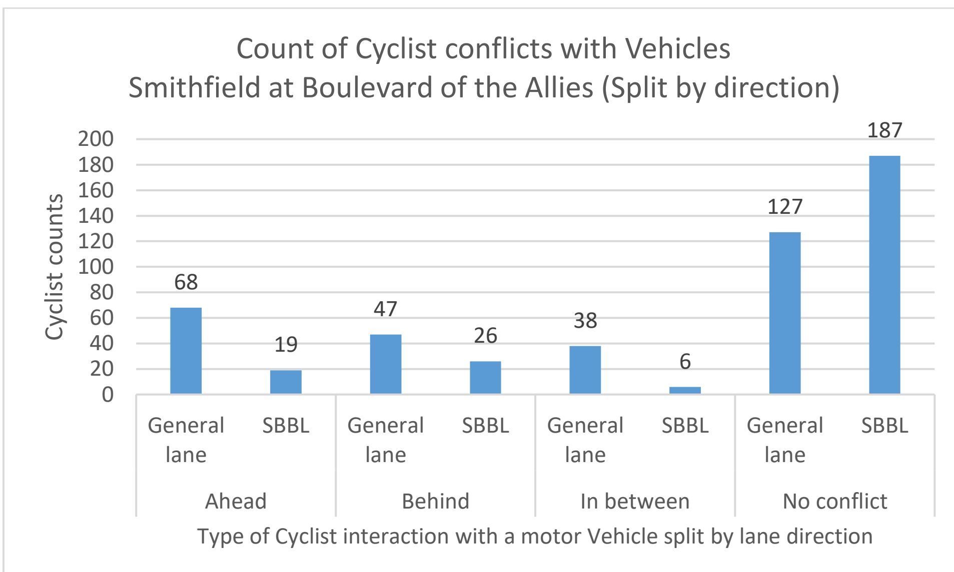


Figure 52: Smithfield at Boulevard of the Allies Cyclist conflicts counts per direction

Boulevard of the Allies presented the highest numbers in relation to conflicts counts. In the Figure 51, we can see "Ahead" and "Behind" categories leading, with "In Between" at last. Looking at Figure 52, is clear that majority of counted conflicts are in the general lane instead of the shared lane. For both "In between" category had the lowest count while the top swapped places between lanes.

Thanks to having a much longer intersection in comparison to the intersection at Sixth Avenue, it was decided to use the footage collected at Boulevard of the Allies to analyze and determine if there is an issue for the SBBL cyclists regarding arriving at the intersection at a red signal, and if so, deciding to unlawfully cross it in order to not interact with a coming vehicle. When looking at the total data (Figure 53), 149 crossed (Either on street or crosswalk) or turned at the intersection with a red signal, good for 29% of counts. Breaking down to direction (Figure 54), we noted that cyclists in the SBBL are susceptible to disregard for the red signal, however the percentage was only 32%, 3% above the total data. General lane cyclists crossed a red signal 26% of times. With these results, it can be pointed out that while SBBL cyclists put themselves more often at risks, but not necessary that can be attributed to the sharing nature of the lane.

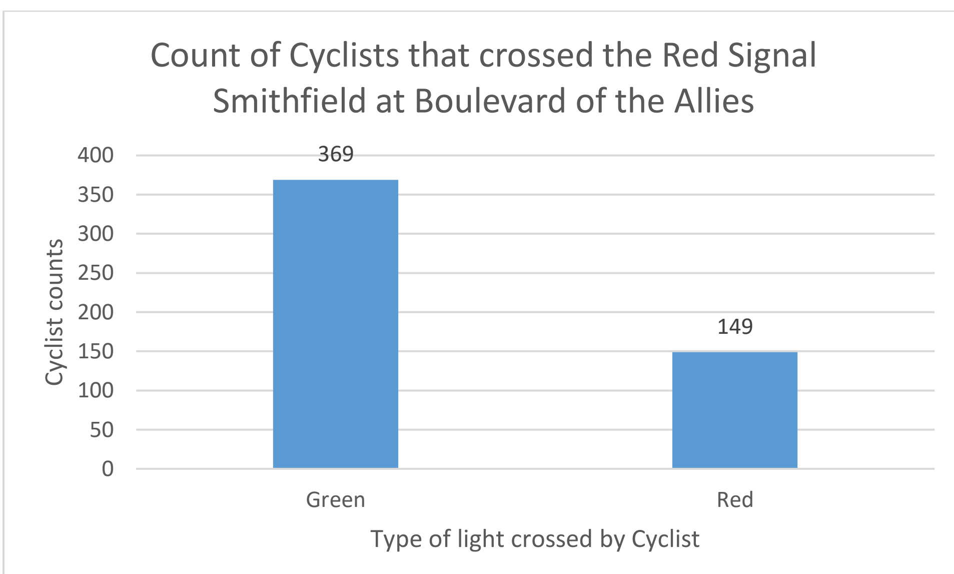


Figure 53: Smithfield at Boulevard of the Allies Cyclists' red signal crossings counts

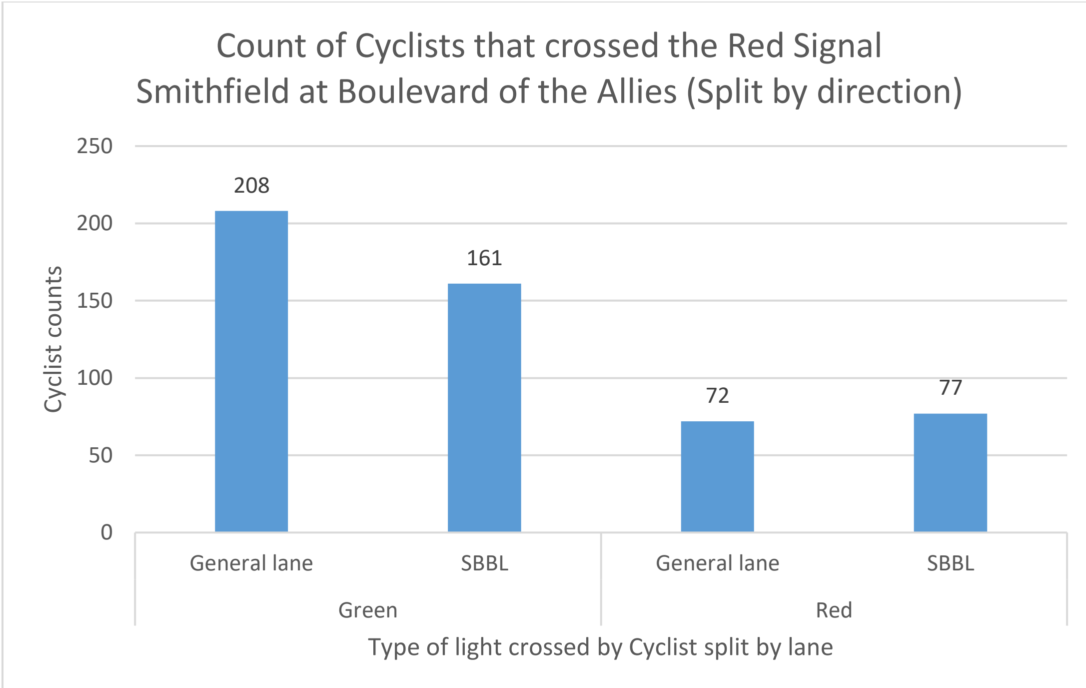


Figure 54: Smithfield at Boulevard of the Allies Cyclists' red signal crossings counts per direction

4.2.5 Smithfield Street at Fort Pitt Boulevard

The footage data was collected for Smithfield Street at Fort Pitt Boulevard in the days 07/03/2019 (Weekday) and 07/20/2019 (Weekend). The camera looking at incoming SBBL traffic was placed far after the studied intersection. The reasoning was that the poles near the intersection could not hold the camera in a safely manner also having the camera that far from the final intersection of the SBBL helps the researcher understand the possible destinations of the cyclists leaving the infrastructure. The second camera was positioned approximately 280 ft away from the studied intersection. The decision to place the camera that far away from the intersection was made for the lack of proper poles to install the cameras but also to give proper sight of the conflicts between cyclists and buses. More detail on the intersection design is presented at the Appendix C.

Figure 55: POV of the two cameras in the Smithfield at Fort Pitt intersection

The counts made through the footage pointed that the Fort Pitt Boulevard had the highest volume of cyclists of all intersection analyzed, with 593 bikers. At first, one could expect such high number thanks to the general lane cyclists coming into Smithfield from the bike trail, however the split between lanes notes almost a 50/50 share between both directions (Figure 56).

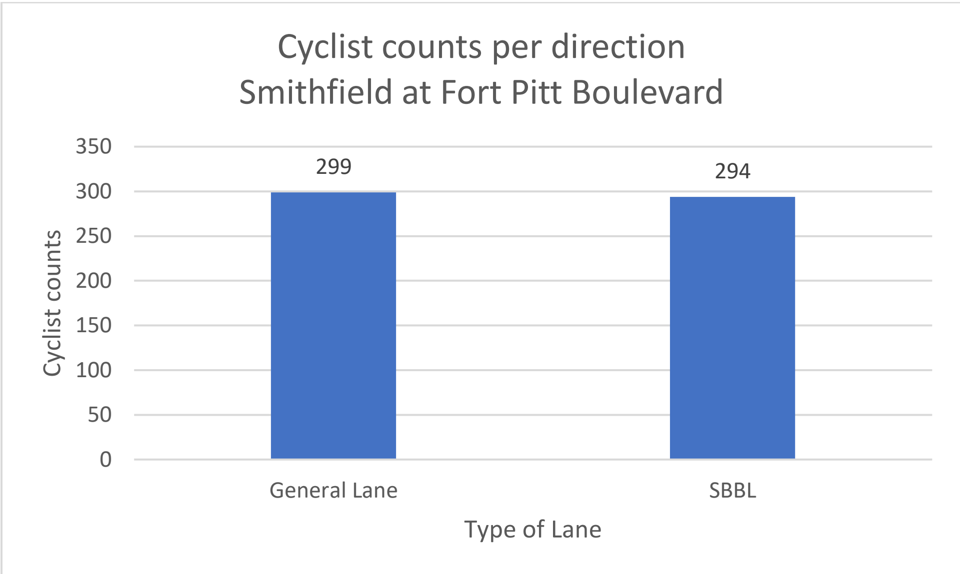


Figure 56: Smithfield at Fort Pitt Cyclist counts

Regarding cyclists' issues counts at Figure 57, once again sidewalk cyclists appeared at the top of issues (128 out of 593). For this intersection, the numbers for both cyclists that traveled in the wrong lane at some point or simple cut through the lane before the intersection have increased considerably. The number of offenders in Fort Pitt for traveling in the wrong lane was 56, good for 9.4% of all counts. The total of cutting cyclists was 45, accounting for 7.6% of the total. Looking at Figure 58, the split shows the SBBL cyclists are more susceptible to commit all three highlighted issues. While sidewalk travel was more evenly split directions, the preeminence of cutting cyclists and southbound cyclists traveling in the wrong lane reveal issues in the connection between the SBBL in Smithfield and the desired path to the bike trail near the Allegheny River.

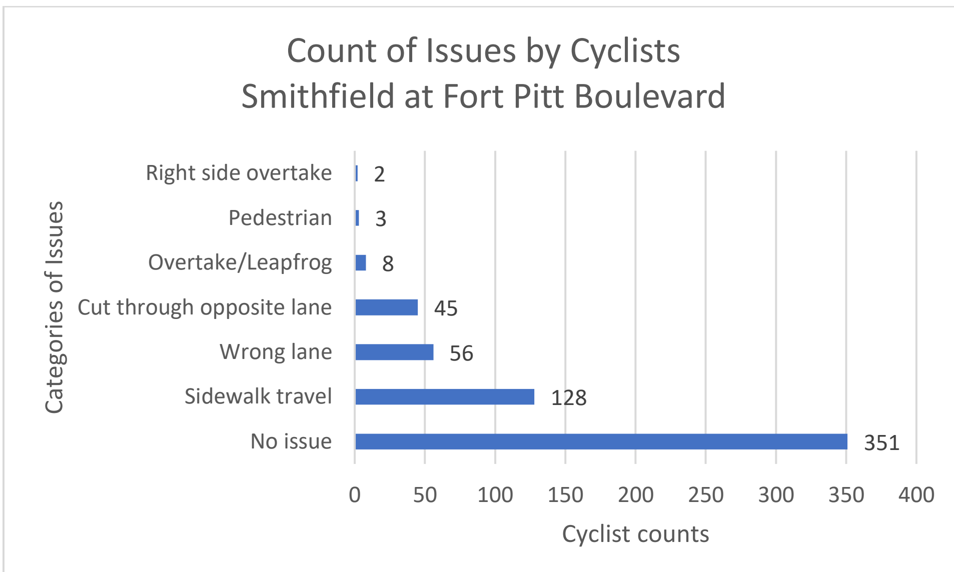


Figure 57: Smithfield at Fort Pitt Cyclist Issues counts

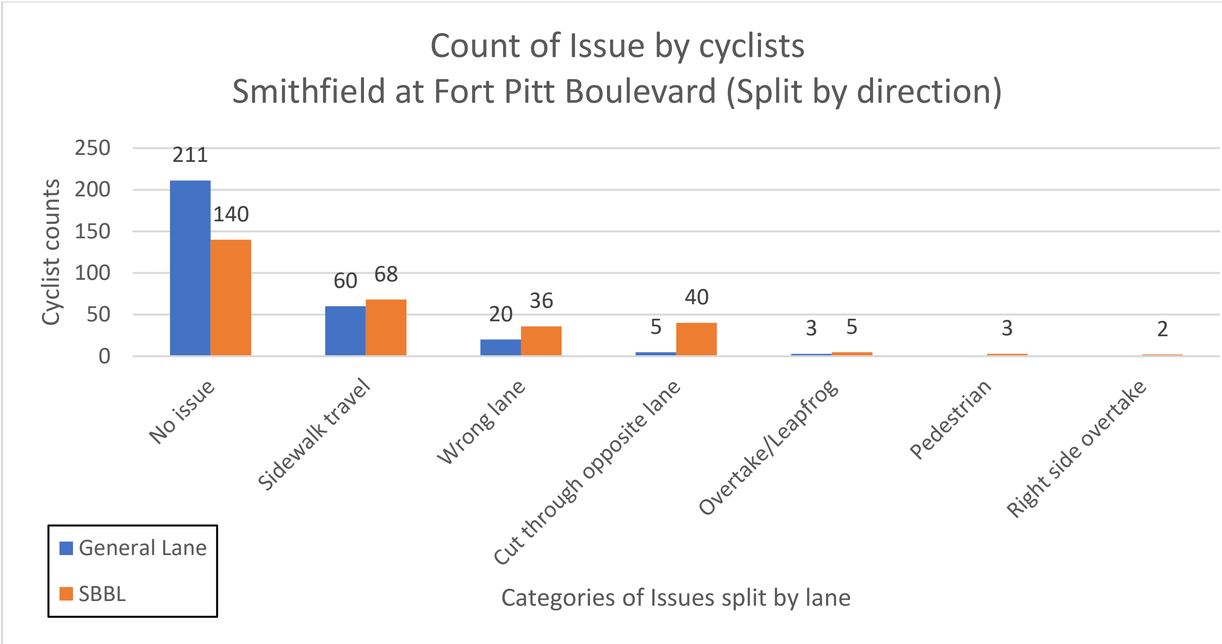


Figure 58: Smithfield at Fort Pitt Cyclist issues counts per direction

The conclusion drawn for the intersection between Smithfield and Fort Pitt Boulevard is that it’s current design and connectivity with the next section of bike path, the Three Rivers Heritage Trail, is the main reason for SBBL cyclists to enter or cross the contra-flow lane, putting themselves in a risky position and not the bus-sharing nature of the lane. The current design asks for the SBBL cyclist to stay in the lane right until the intersection, where they will find at their right side, a signalized shared crosswalk, followed by a pedestrian island where they will wait for another pedestrian phase to cross a second shared crosswalk for another pedestrian island. After waiting for a third pedestrian phase and crossing another crosswalk, they will finally reach the trail. This path is illustrated by the blue trail at Figure 59 below. However, a good number of cyclists in this intersection are going through the red trail at the figure below.

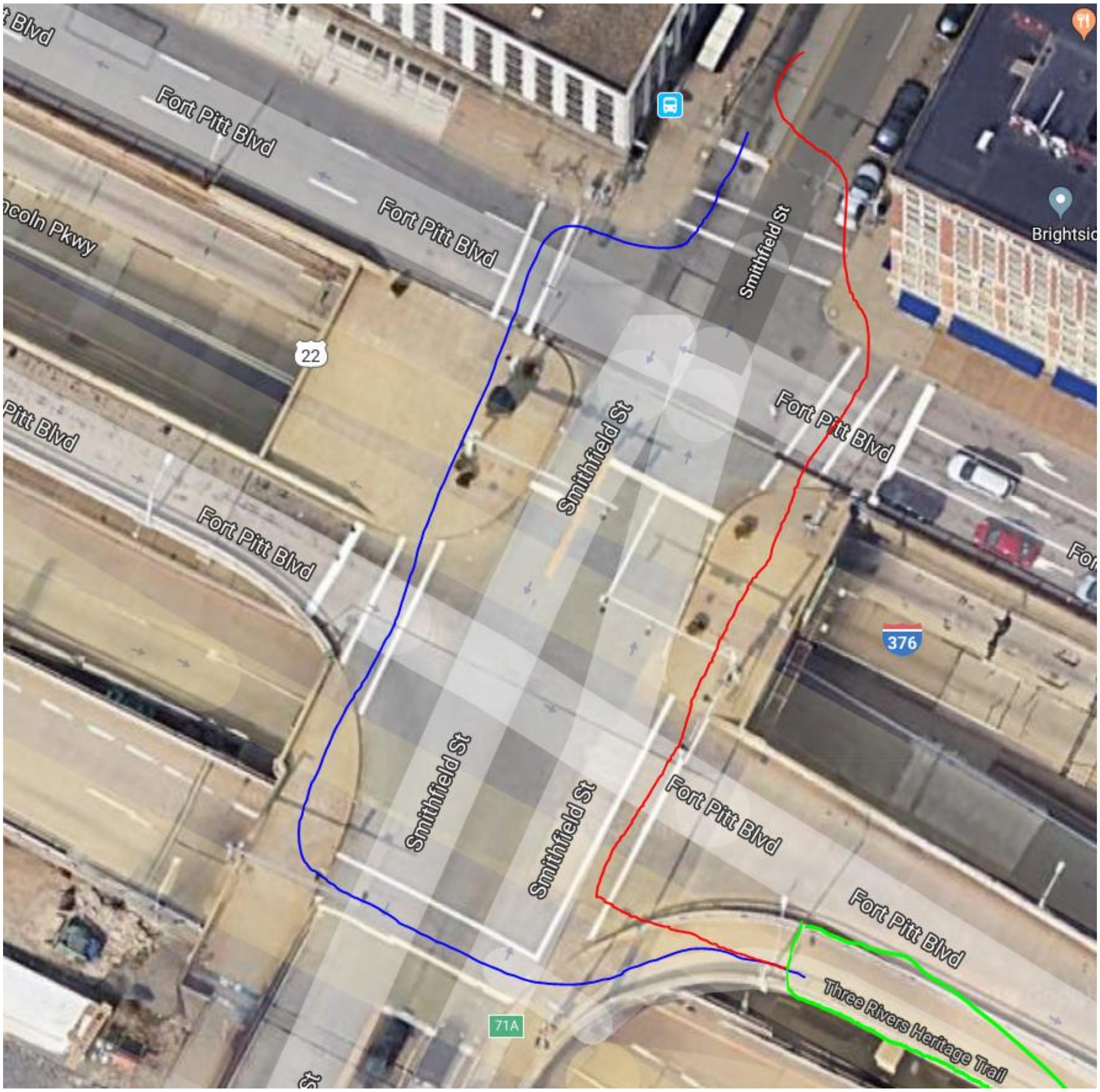


Figure 59: Possible Cyclists paths in Smithfield at Fort Pitt

It can be concluded that what the cyclists using or cutting through the contra-flow lane (This is also valid for some of the Sidewalk traveling cases) are actually doing is that they are trying to avoid a third signal phase and having to cross an extra crosswalk in order to save time and not because they are wary of the bus presence. Buts it is important to note that for cyclists that find themselves approaching the intersection behind a bus and may decide to save time by taking one of the three highlighted risky actions, the dimensions of the bus will increase the danger of a collision due to sight issues, as a bike coming from behind a bus into a contra-flow lane will be extremely hard for contra-flow drivers to see and react with any avoidance maneuver.

For conflicts, the results present at Figure 60 considerably lower numbers of conflicts in comparison to previous intersections. That improvement can be considered repercussion to having a bike exclusive infrastructure and well signalized surrounding (Painted crosswalk and signs) so close to the intersection that drivers are more aware and will maintain safe distance to cyclists. But the low numbers can very well simply be a consequence of the increased issues and infractions, especially sidewalk travelling.

Looking at Figure 61, the cyclists travelling in the SBBL had the roadway for themselves more frequently than northbound cyclists in the general lane (80.3% vs. 67.2% of unrestricted bikers). Breaking into types of conflicts, cyclists stuck behind motor vehicles lead for both directions with an even split. The difference makers for the general lane lead in conflicts were the "Ahead" and "In between" categories. The majority of those cyclists, coming from the bike trail, tried to get a head start on traffic but are caught by cars before leaving the second camera's sight.

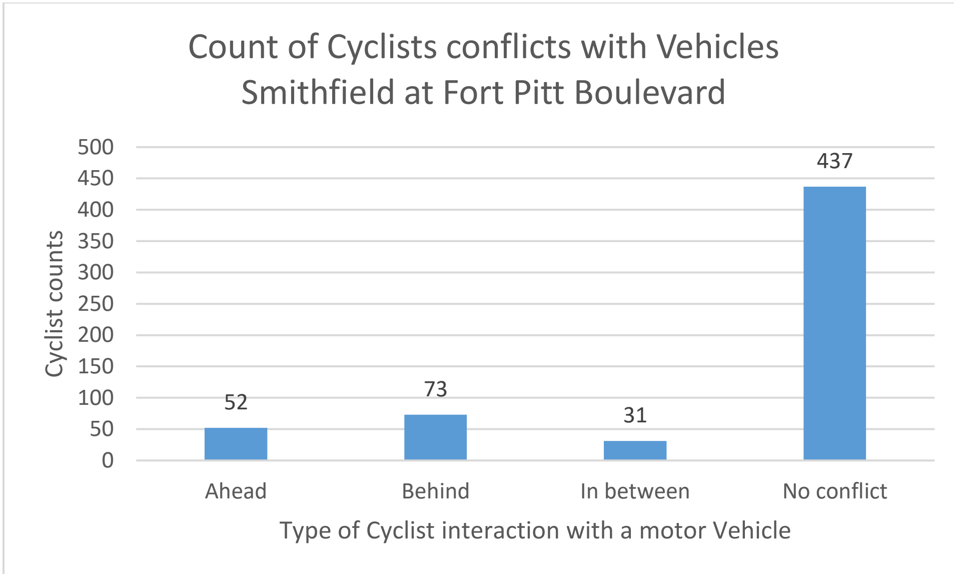


Figure 60: Smithfield at Fort Pitt Cyclist conflicts counts

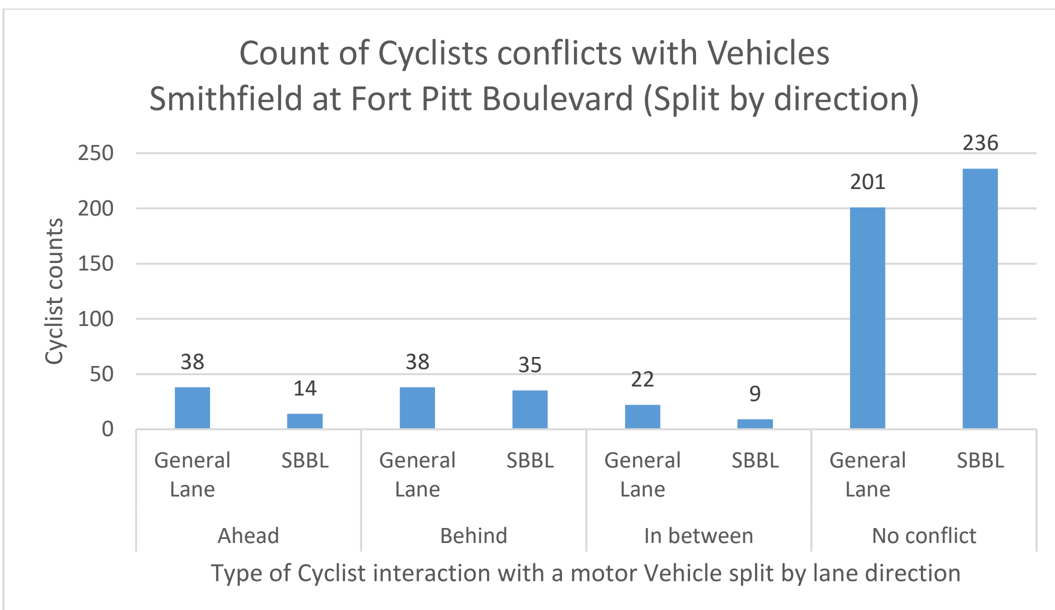


Figure 61: Smithfield at Fort Pitt Cyclist conflicts counts per direction

4.3 Summary of Data Collection and Analysis

Reviewing the data collection topic, no gross errors were present or essential information was missing. The data collection followed the methodology set previously to its best degree considering the field issues with pole placement, crew availability and weather. Ideally, all intersections would be counted in the same weekday and weekend in order to maintain consistency. The two types of data set in our methodology was collected in all four selected intersections, plus an additional type of data was collected in Boulevard of the Allies regarding the frequency in which cyclists in both the general lane and the SBBL crossed a red signal.

The data was validated using established bike counts near the SBBL, showing the cycling ridership was normal to all four days of collection. The Conflicts category was collected for situations in which was evident that either the cyclist or the vehicle had to be aware of the other presence in order to react any unnatural movement. The Issues category was collected for the decisions made by the cyclists that either put themselves at risk of a crash or simply decided to not use the road infrastructure. Various times in the recorded video, the same cyclist performed two maneuvers/decision within the Issues category (e.g. SBBL cyclist cut through opposing lane and ride in sidewalk). The researcher decides to collect the most dangerous issues, based on the ranking at Table 5, developed by the researcher.

Presenting the data and counts in total tallies for all Smithfield Street (Both SBBL and general lane) helps capture how the Smithfield Street has been operating for cyclists and drivers sharing the road and responds to this study's hypothesis that the SBBL is a safer cycling environment, compared to the general lane as the conflicts were cut in half compared to the general lane (42.84% of general lane cyclists interacted with vehicles the general lane while only 18.10% cyclists in SBBL had to interact with a bus). Collecting data for just four intersection even though the corridor has twelve was done because it was not feasible to collect data for every single intersection in the corridor. Still, the collective of intersections can paint the picture for the whole corridor, as the information collected in each intersection either reinforces or fill the blanks for the others. Also, presenting the individualized data by intersection helps to determine the peculiarities that intersection may have in comparison to the other ones. It was noted that Liberty Avenue had a much lower volume for SBBL cyclists that the other three intersections, which could be due to high volume of cars that travels in Liberty. Boulevard showed a slightly higher rate of Conflicts for SBBL cyclists to the total volume, which could make cyclists uneasy in the intersection but said rate did not translate in the Issues category, where Fort Pitt Boulevard lead far and away with SBBL committing a considerable number of high-risk maneuvers. These dangerous decisions are concluded not directly related to the SBBL but to connectivity issues between the SBBL in Smithfield and the following cycling infrastructure.

Overall the data analysis shows that the established hypothesis is correct in stating that SBBL are a safe cycling infrastructure and the problems found in our data analysis are strongly to other infrastructures surrounding the SBBL.

5.0 Conclusions

The main goal of this research was to answer the hypothesis that SBBL are a safe infrastructure for cycling. SBBLs are hardly used, which makes literature and guidelines rare for policy makers to base decisions. Also, the studied SBBL being recent infrastructure, no reliable crash data was found. In future years, with the observed SBBL already established in the Downtown Pittsburgh, crash data could be used to measure safety levels in the corridor. For that, an additional type of data was chosen in the form of conflicts to help understand the SBBL operation.

The results show that our hypothesis was corrected as cyclists traveling on the SBBL will have a safer experience than cyclists traveling in the general traffic lane. Bikers in the SBBL, having to share the lane with only the buses, will have less conflicts to worry about. It was expected that the reduced volume in the SBBL would provide less interactions, and the footage collected corroborated that reasoning significantly by showing that cyclists in the general lane had to worry about a vehicle twice as often than a SBBL cyclist (42.84% vs. 18.10%).

Conflict data could be easily collected in comparison to other secondary data options through video recordings of the corridor, making it more appealing due to time and resource restraints in the research.

Even as crash data was not the main data source for this study is important to note that during all 192 hours of recorded video and analyzed traffic conflicts not a single crash, reportable or not, was found.

But it is also necessary to note that there were moments recorded in video in the collected data that more than one accident was avoided thanks to the reflexes and awareness of the biker, driver or both. These moments did not have numerical relevance to be cataloged, but it is important to recognize them.

Percentagewise, cyclists in the SBBL appeared to be more susceptible to committing undesirable movements that could result into collisions with motor vehicles. The numbers showed that 8.82% of general lane bikers put themselves at high risk while for SBBL the numbers grow to 17.40%, almost doubling.

This could lead to the judgement that the Shared Bus-Bike Lane drives its cyclists to risky situations, however when looking closely at individual intersections, we can see that is three out of four intersection are operating in similar standards for both the general lane and the SBBL and actually the intersection of Smithfield Street at Fort Pitt Boulevard was the one driving the SBBL high-risk percentages numbers up due to its current design.

Questions regarding the entry and exit points of the Shared Bus-Bike Lane (High-Risk rate at Fort Pitt Boulevard and low volume at Liberty Avenue), but our results point the problems not the SBBL infrastructure but to the linking infrastructures.

The analysis of cyclists' red signal crossings in the Boulevard of the Allies, while the data showed a slight edge that SBBL cyclists crossed the red light more often but it was rendered inconclusive as the difference in percentage was not large enough to point out this behavior was due the buses presence.

Another point interpreted inconclusive was the cyclists' preference to stay ahead or behind the bus. The number of prohibited overtakes was relatively low to the total volume and the conflicts comparison show a small but still ambiguous difference between the bike being either ahead or behind the bus.

That was instances that the lack of bus traffic in the SBBL brought in uninvited general lane cyclists going in the opposite flow, even in situations where they could very well travel with the general lane without conflicts with others. Such scenarios appeared in relatively low numbers (6.6% of all counts) but it may need to be addressed nonetheless.

The final of the secondary conclusions from this research relates to the surprising high number of cyclists that decided to travel on the sidewalk instead of using the traffic lane. It is important to remember that traveling on the sidewalk was considered only the fifth most note-worthy category in the “Issues”, which means that is fair to assume that some amount of counts in the top four categories may also had traveled on the sidewalk at some point, especially the ones that only cut through the opposite lane. Having one to each five Smithfield cyclists in sidewalks have not only them but pedestrians at risk.

6.0 Future Research

The research methodology and results corroborated the conflict data could be used for safety evaluations even though it is only considered as a secondary data source. One of the reasons for such a gap between conflicts and traditional safety data sources is the lack of literature to make sure the data collected is not surrogated into a biased, desired outcome. Providing a comparison scenario such as the one done in this research (SBBL vs. General Lane) set a good precedent and should be looked and published in more detail to reference future researchers that decide to use conflict as a data source.

Majorities of the early difficulties in the research was due to the lack of literature on the Shared Bus-Bike lanes. It is understandable due to small numbers of similar infrastructures. However, as the current Smithfield SBBL is held in place, as does the ones in Wood Street and Fort Pitt Boulevard, it is highly recommended that an annual review should be done to measure cyclists get more or less confident and to grow the literature.

An evaluation method that was discussed early on in the project but was dismissed was the elaboration of a Crash Modification Factor (CMF) for the implementation of a Shared Bus-Bike Lane. Ideally, to produce those you would need either an extensive crash data for both before and after implementation or an in-depth study of similar periods. As no study was done before and there is no considerable crash data for the after, the CMF was impractical. But it can be done in the future with the SBBL settled for multiple years.

An approach that could enhance future works in this topic would be to expand the analysis of conflicts to include the total amounts of vehicles travelling in the lane. This works focused on study the effects on cyclists' safety and for that focused on cyclist's volume in each lane direction.

However, it is safe to assume that the Shared Bus-Bike Lane would have a lower volume, counting all types of vehicles, due to its restrictive nature. Idealistic, an ADT assumption similar to the ones presented at Tables 8 and 9 for the SBBL would be elaborated to give a fair comparison between the SBBL and the General Lane. Also would be interesting to use the same “Conflicts” definition developed in this study and analyze it from the motor vehicle driver’s perspective.

Another discussed opportunity with city officials that could not be a part of this final document was gathering of opinions from users: Bus operators and especially cyclists. It is one thing to deduce uncomfortable situations as a single researcher, however hearing the perspectives from daily users would provide a more insightful POV on these situations, which in turn could provide the right emphasis during data analysis. The recommendation would be to formulate surveys or focus groups with users on the conflicts and issues noted on this study for the perspective on the risks associated with each and with their inputs, new data could be collected and weighted accordingly.

One of the surprising results of this study was the high number of bikers on the sidewalk, which is not recommended in the State of Pennsylvania in Central Business District, putting not only cyclists but pedestrians are also at risk. Once again, if resources allow it, a survey should be running between cyclists to know what lead them into the sidewalk. Pedestrians could also be surveyed on their feelings towards sidewalk cyclists and if there would support policies to provide a safer environment for all.

While the current connection design between Fort Pitt Boulevard and the Three Rivers Heritage is well-intentioned and somewhat innovative with its use of shared crosswalks, there are still missing pieces to either make this linkage easier and/or quicker or refrain hurried cyclists to jump into the contra-flow lane. It is recommended for the City of Pittsburgh officials to further research and plan for alternatives for the intersection in order to avoid severe accidents.

Also recommended to the City of Pittsburgh officials for future studies is the analysis of the impacts that the SBBL implementation had in the bike ridership of Downtown Pittsburgh by providing another bike-friendly infrastructure. And considering the Three Rivers Heritage Trail as a main destination for bikers, it would be interesting to review the cycling travel times in the Smithfield SBBL versus the travel in the general traffic lanes at Grant Street and Wood Street, which are parallel streets.

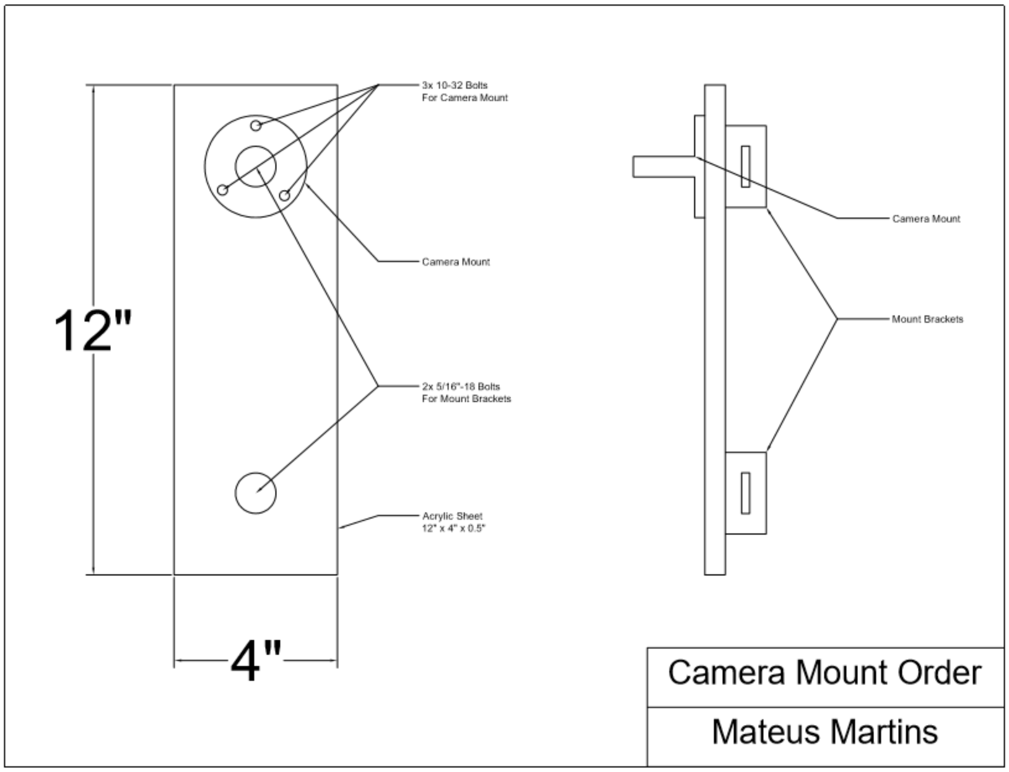
Due to resource and time constraints, the author did not move further into statically analysis of the correlation between conflicts between buses and bikes and high-risk issues outside of simple descriptive analysis. However, it is heavily suggested for future research that such an approach should be taken to advance the literature and understanding on Shared Bus-Bike Lanes.

Finally, for secondary research, the cameras used provided a good enough image quality that the author was able to different both cyclists that are either using helmets or not and cyclists that are using bikeshare bicycles or not. Both topics could either be researched alongside SBBL or generate their own research topic on their correlation with conflicts and high-risk issues.

Appendix A Camera Mount

Appendix Table 1: List of materials used for the camera mount

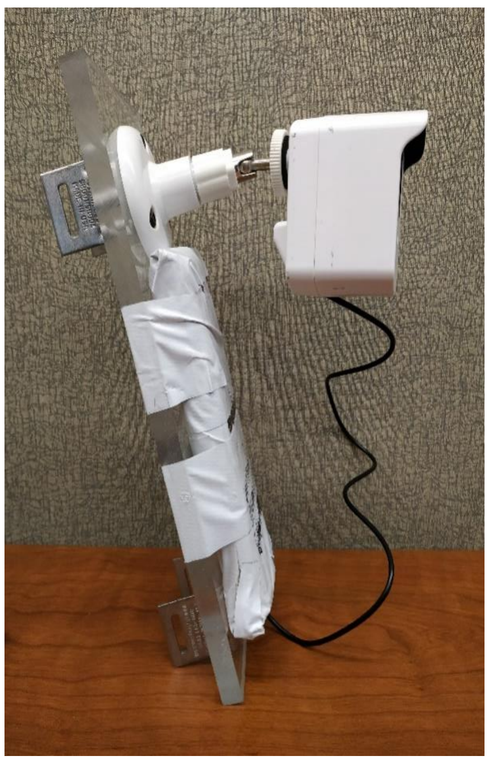
Material	Quantity	Reference or Model Number	Unit Price	Reasoning
Bought in Amazon or Another retailer				
Wyze Cam 1080p HD Indoor Wireless Smart Home Camera with Night Vision, 2-Way Audio, Person Detection, Works with Alexa & the Google Assistant	4	WYZEC2	$25.98	Camera
Wyze Cam Wall Mount Bracket, Protective Cover with Security Wall Mount for Wyze Cam V2 V1 and Ismart Spot Camera Indoor Outdoor Use, **(White 3 Pack)**	2	wyzemount_wh_3	$25.99	Camera housing to protect from weather
SanDisk 32GB Ultra microSDHC UHS-I Memory Card with Adapter - 98MB/s, C10, U1, Full HD, A1, Micro SD Card - SDSQUAR-032G-GN6MA	4	WYZEMSD32C10	$8.89	Storage for video records
ANKER PowerCore 26800 mAh External Battery with Dual Input Port and Double-Speed Recharging	4	A1277	$65.99	External Battery for the Camera
Boulder Twin Lock Bags, 40 bags	1	Not available	$1.99	Provide an extra layer of water protection to the external battery
Nashua All-Weather Duct Tape, 1.89 in x 60 yd	1	Not available	$8.50	Fix external battery to the acrylic board and provide a weather protective layer
Bought in McMaster-Carr				
Clear Scratch and UV Resistant Cast Acrylic Sheet, 12” x 12” x ½”	2	8560K265	$32.05	Provide stable basis for the camera mount
Provided by the University of Pittsburgh Engineering Machine Shop City of Pittsburgh				
10-32 Bolt	12	Not available	Provided by the Machine Shop	Fix Camera wall mount into Acrylic board
5/16"-18 Bolts	8	Not available	Provided by the Machine Shop	Fix Sign Mounting Brackets to Acrylic Board
Stainless Steel Bull’s Eye™ Sign Mounting Brackets. Straight Leg w/Stainless Steel Bolt & Washer	8	SB001	Provided by City of Pittsburgh	Provide stable basis between camera mount and street pole
Quick Release Worm-Drive Clamp	8	Not available	Provided by City of Pittsburgh	Fix the camera mount to the street



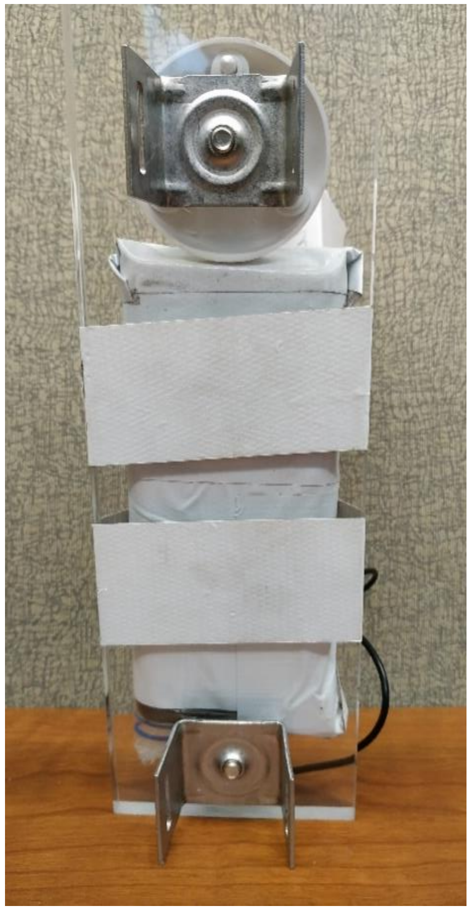
Appendix Figure 1: Schematic of Camera Mount

Appendix Figure 2: Early prototype of camera mount

Appendix Figure 3: Final version of camera mount, Front



Appendix Figure 4: Final version of camera mount, Side



Appendix Figure 5: Final version of camera mount, Back

Appendix B Port Authority Bus Information at Smithfield Street

Appendix Table 2: Smithfield Street Bus Route Data

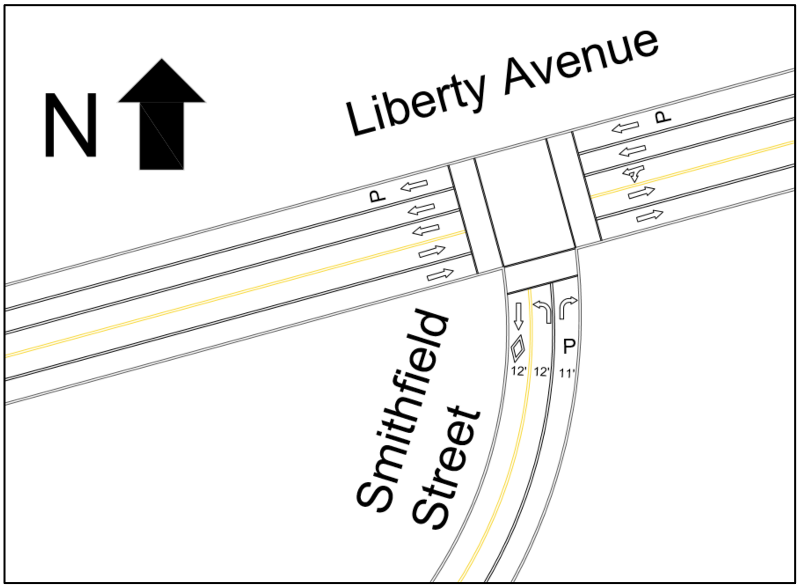
There are 4 stops on Smithfield:	Served by:
Smithfield at Sixth	Loops A + C
Smithfield at Forbes	Loops A + B
Smithfield at Third	Loops A + B
Smithfield at Fort Pitt	Loops A + B
All of these stops are **outbound** and there are 3 loops of buses:	
A	**39,40,44** (turn left onto Smithfield from Liberty Ave and travel the entire length of Smithfield until going over the bridge; this loop has all 4 stops on Smithfield)
B	**41,43,48,51,51L,Y1,Y45,Y46,Y47,Y49** (turn right onto Smithfield from Sixth Ave and travel the rest of Smithfield until going over the bridge; this loop has 3 stops on Smithfield)
C	**87, P1, P68, P71** (turn left onto Smithfield from Liberty Ave and turn left off Smithfield at Sixth Ave; this loop has just one stop on Smithfield)
	***Note: P2 is included in Loop C but only runs during the morning peak**
Note about headway:	Peak, off-Peak, and weekday headway data for Smithfield stops includes 3 non-PAAC regional bus carriers (Fayette, Mon Valley, Washington)
Routes included in headway data:	
Smithfield at Sixth:	39, 40, 44, P1, P68, P71, FACT, MMVTA, WCT
Smithfield at Forbes:	39, 40, 41, 43, 44, 48, 51, 51L, Y1, Y45, Y46, Y47, Y49, FACT, MMVTA, WCT
Smithfield at Third:	39, 40, 41, 43, 44, 48, 51, 51L, Y1, Y45, Y46, Y47, Y49, FACT, MMVTA, WCT
Smithfield at Fort Pitt:	39, 40, 41, 43, 44, 48, 51, 51L, Y1, Y45, Y46, Y47, Y49, FACT, MMVTA, WCT

Appendix Table 3: Smithfield Street Bus Operations Data

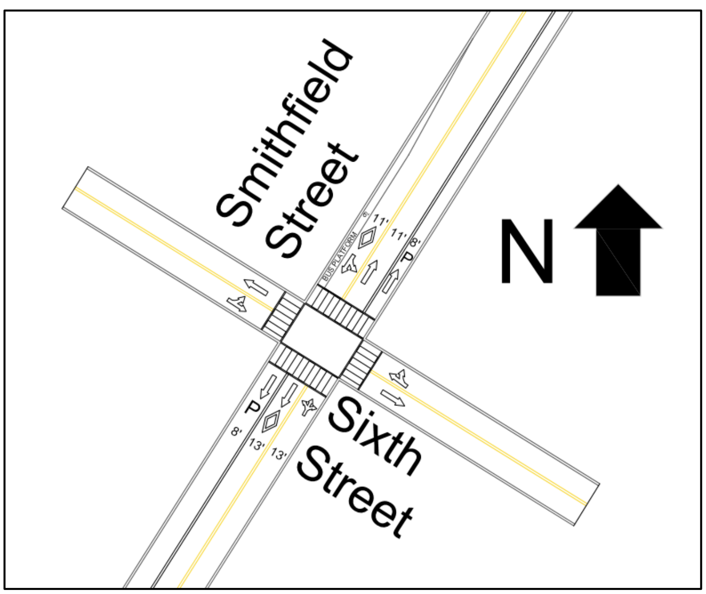
DATA BY STOP							
		Loops A + C	**Loops A + B**	**Loops A + B**	**Loops A + B**		
		Smithfield at Sixth (3090)	**Smithfield at Forbes (3145)**	**Smithfield at Third (3000)**	**Smithfield at Fort Pitt (3150)**	**Time**	**Timeframe for Average**
Peak	**Dwell Time (min)**	1.47	0.96	0.9	0.75	**4-6:30 PM**	1-year average
	Headway (min)	1.58	1.43	1.43	1.43	**4:00 PM**	March 2019 Alignment
	Ridership (ons)	1533	643	281	192	**4-6:30 PM**	April 2019 Average
	Riders/min	10.22	4.29	1.87	1.28	**4-6:30 PM**	April 2019 Average
Off-Peak	**Dwell Time (min)**	0.96	1	0.8	0.52	**11AM - 1 PM**	1-year average
	Headway (min)	3.75	1.43	1.43	1.43	**11:00 AM**	March 2019 Alignment
	Ridership (ons)	288.00	112.00	43.00	44.00	**11AM - 1 PM**	April 2019 Average
	Riders/min	2.40	0.93	0.36	0.37	**11AM - 1 PM**	April 2019 Average
Weekend	**Dwell Time (min)**	0.85	0.85	0.67	0.52	**11AM-1PM**	1-year average
	Headway (min)	8.57	1.43	1.43	1.43	**12:00 PM**	March 2019 Alignment
	Ridership (ons)	59.57	16.40	4.16	7.89	**11AM-1PM**	April 2019 Average
	Riders/min	0.50	0.14	0.03	0.07	**11AM-1PM**	April 2019 Average
SPEED BY SECTION							
		Liberty to Sixth	**Sixth to Forbes**	**Forbes to Third**	**Third to Fort Pitt**	**Time**	**Timeframe for Average**
	Peak	4.64	7.82	7.82	11.30	**4-6:30**	1-year average
	Off Peak	7.27	7.88	11.19	16.94	**11AM - 1 PM**	
	Weekend	8.10	7.26	12.14	17.04	**11AM-1PM**	

Appendix C Smithfield Street Drawings

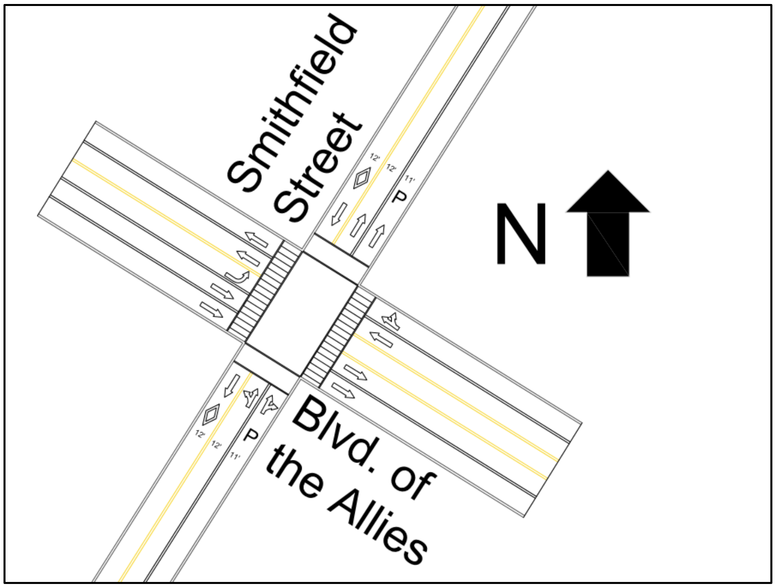
Appendix C.1 Lane configuration schematics



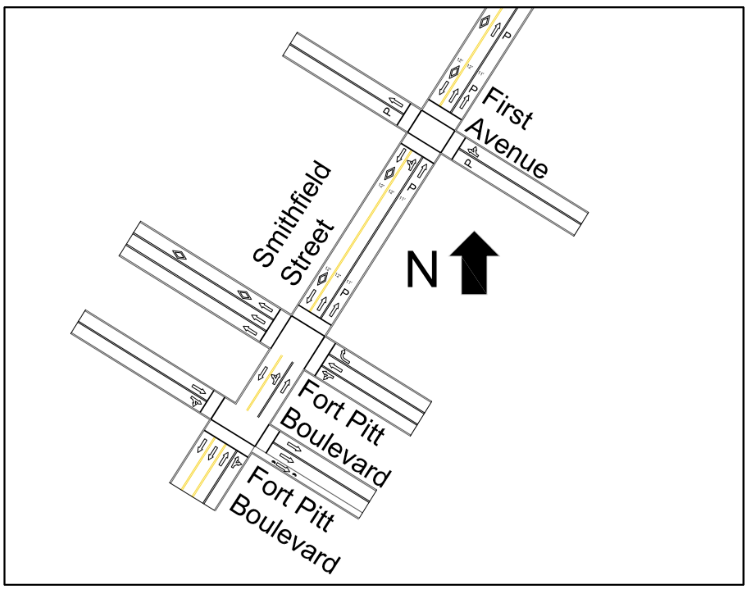
Appendix Figure 6: Schematic for Smithfield Street and Liberty Avenue



Appendix Figure 7: Schematic for Smithfield Street and Sixth Avenue

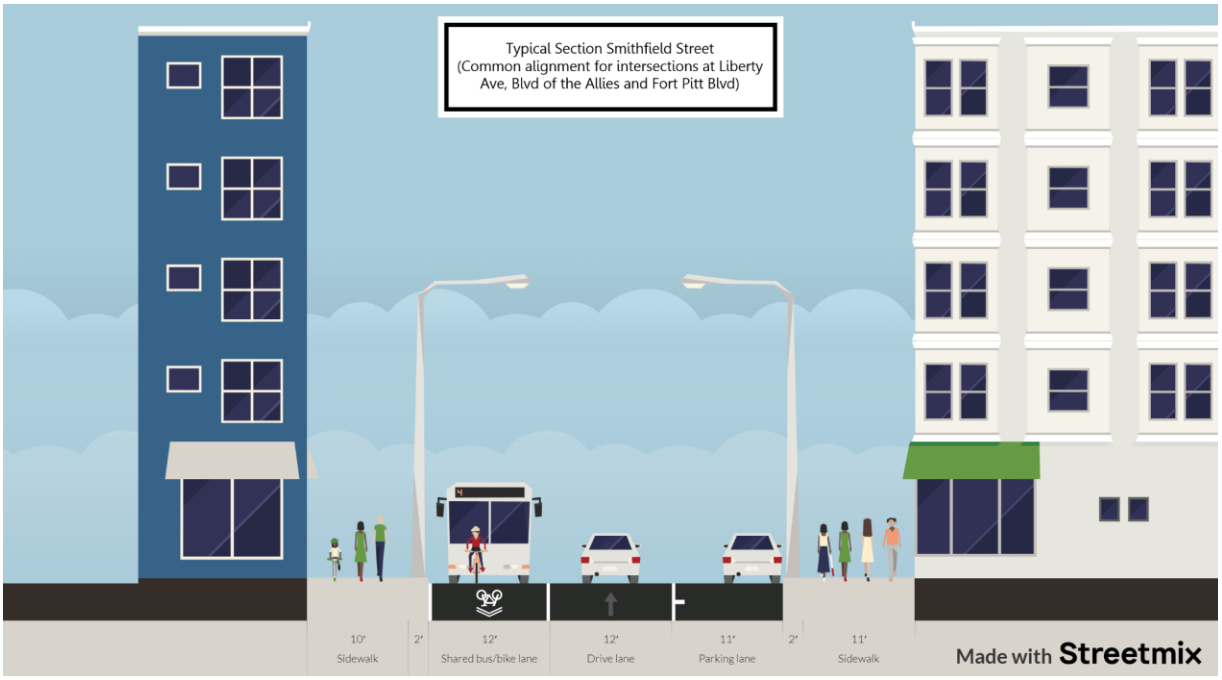


Appendix Figure 8: Schematic for Smithfield Street and Boulevard of the Allies

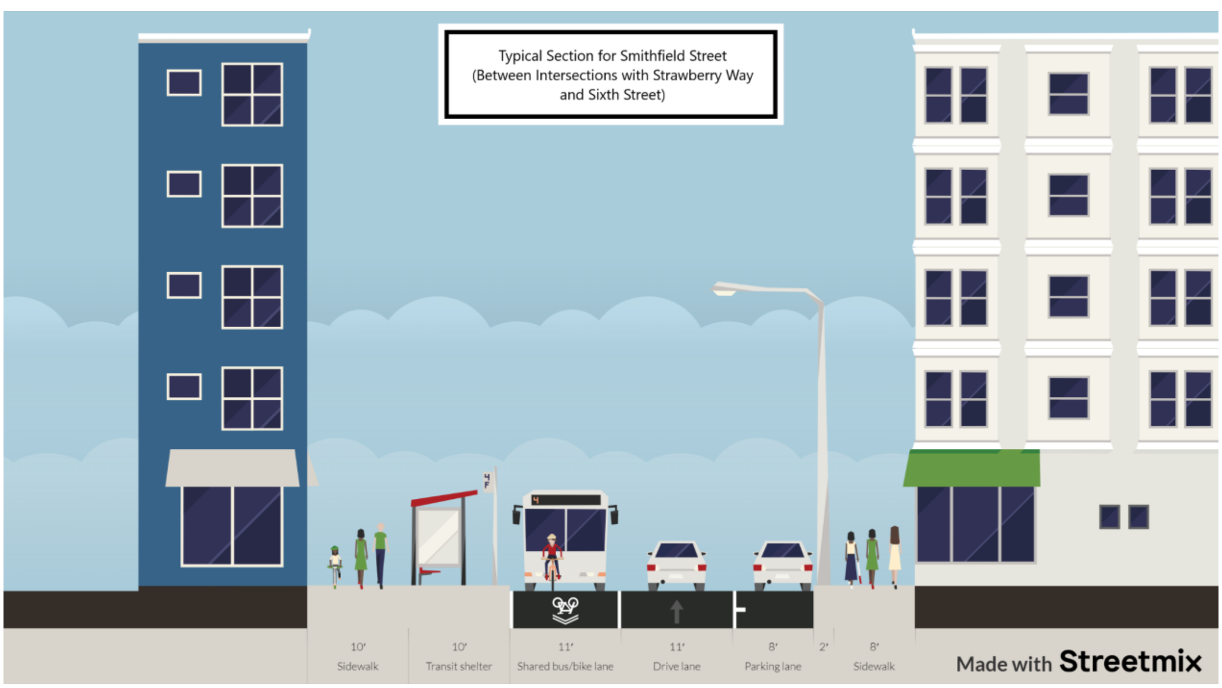


Appendix Figure 9: Schematic for Smithfield Street and Fort Pitt Boulevard

Appendix C.2 Typical section for Smithfield Street



Appendix Figure 10: Typical Section for majority of Smithfield Street corridor



Appendix Figure 11: Typical Section for Sixth Avenue approach (Southbound)

Appendix Figure 12: Typical Section for to Sixth Avenue approach (Northbound)

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