CHESTNUT STREET
BIKE LANE EVALUATION

Project Overview

This study aims to illustrate an innovated technique toward evaluating bicycle infrastructure safety, using a mix of methodology and data. Most notably, this study features eye-tracking glasses and data analysis to form data-driven assessments of the facility and its features.
The following study was conducted as part of CPLN650: Transportation Methods (Fall 2017).

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Acknowledgments

The research team extends its thanks to the Children's Hospital of Philadelphia Center for Injury Research and Prevention; this project would not have been possible without their willingess to share the eye tracking equipment and provide guidance throughout the semester.
To the PennDesign faculty and students willing to participate in our study - many thanks!

Partners

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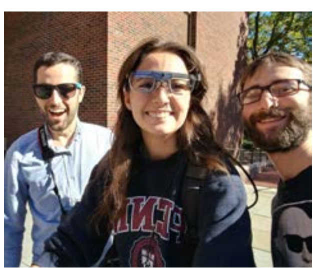
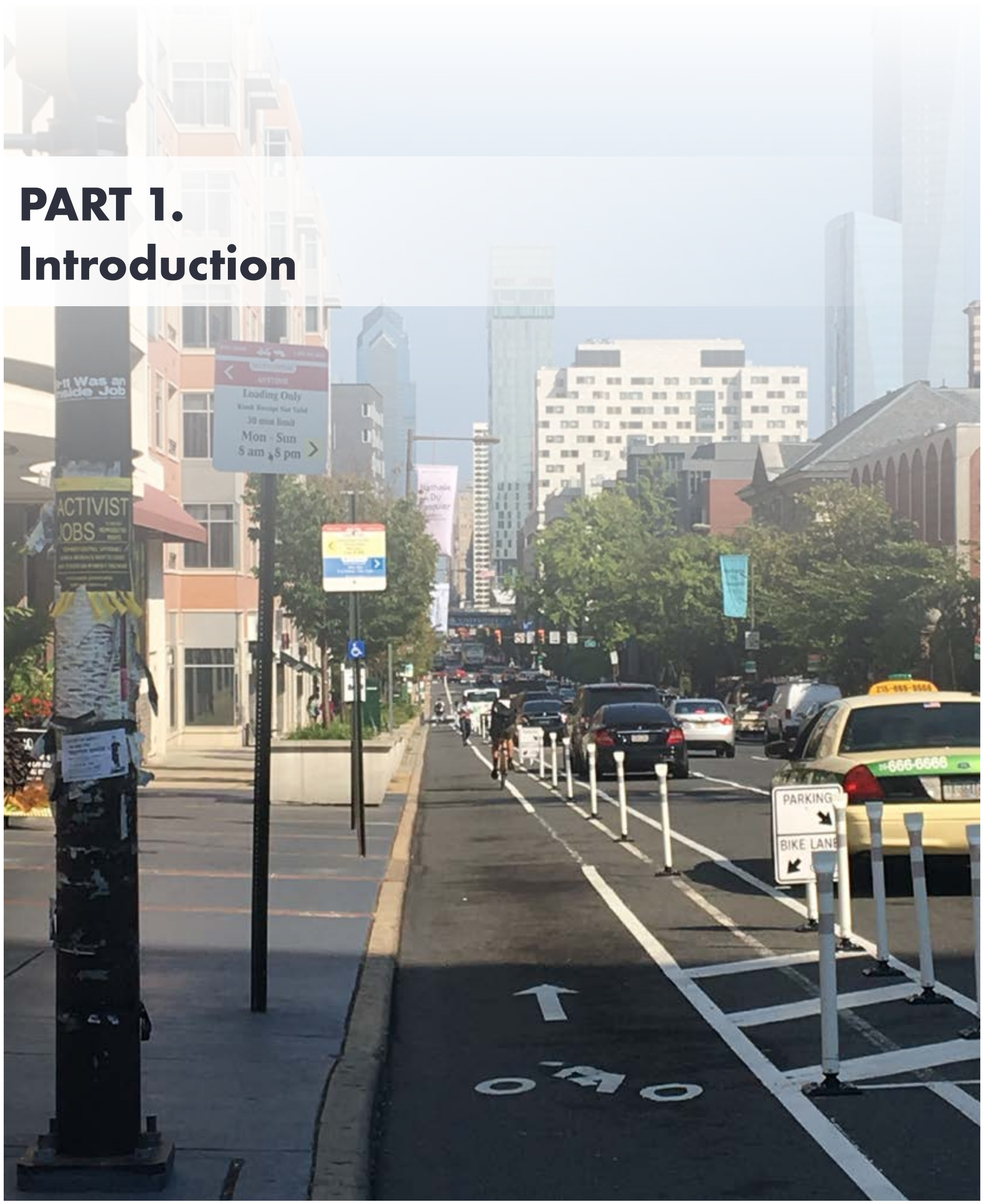



PART 1. Introduction



In 2015 Mayor Kenney pledged to build 30 miles of protected bike lanes by the end of his term. After installing the first protected bike lane in Philadelphia last year—a two way protected lane on Ryan Ave in Northeast Philadelphia—the City installed a mile-long protected bike lane on Chestnut Street, from 45th Street to 33rd Street. This new lane is an important link in the network as it connects West Philadelphia to University City and Center City and to other bike lanes in the bike network, including 40th, 38th, and 34th streets.

Implementation of this lane took nearly six years of work and coordination between the Office of Transportation and Infrastructure Systems (OTIS), other city agencies, and both public and private stakeholders. This particular segment was selected for this treatment because of its important connections, the width of the street providing feasible installation, and its designation as a high crash corridor due to high speeds. This portion of

Chestnut Street previously saw three times the number of crashes per mile compared to other Philadelphia streets (OTIS, 2015). Reducing crashes and improving overall safety in this segment of Chestnut Street was one of the key objectives of this lane's creation.

Report Overview

This report attemps to measure the safety and efficacy of this new infrastructure in two ways. First, we sought to simply evaluate the design of the protected bike lane, primarily in regard to how it was being used by bicyclists and how other modes on Chestnut Street interacted with the lane and with cyclists using it. Protected bike lanes are an unfamiliar piece of infrastructure in Philadelphia, and the Chestnut Street lane offered an opportunity to observe users who have perhaps never interacted with similar infrastructure prior to August. This section also incorporates a discussion of the lane's strengths and opportunities.

The second component of this analysis features a new and data-driven methodology for evaluating safety. We had the opportunity to use eye tracking equipment courtesy of the Children's Hospital of Philadelphia Center for Injury Research and Prevention. This equipment, when worn by participants as they traverse the Chestnut Street lane, allows us to record where bicyclists are looking while riding and outputs data that can be further analyzed, enabling us to garner some information about a bicyclist's perceived level of safety and comfort in the protected bike lane. This study collected and analyzed data on two types of bicycle lanes in order to accommodate comparisons of the protected versus a non-protected bike lane.

The following report is sectioned into four parts. Part 2 details our findings from the infrastructure analysis and observations of Chestnut Street. The next section, Part 3, introduces the concept behind the eye tracking component of the research, reviews our methodology, and summarizes findings. Based on the findings outlined in Parts 2 and 3, Part 4 provides a series of recommendations toward improvement of the Chestnut Street protected bike lane and for consideration on future protected bike lanes. The report closes with a conclusion section, highlighting our findings, limitations, and next steps for future research and for the City.

PART 2.
Infrastructure Analysis

We developed an understanding of the infrastructure through both quantitative and qualitative analyses. Methodology applied included counts, behavioral observations, and a review of specific features of the infrastructure.

Rather than assess the entire 1.1 mile stretch of this bike lane, we focused on specific areas for analysis because they were either unique elements of design that varied from other portions of the segment, points of potential conflict, or provided the greatest benefit to road users.

Strengths

Before delving into specific target areas, it is important to recognize how valuable and important this infrastructure is for the community and for Philadelphia. This protected bike lane is a huge improvement over other forms of bicycle facilities such as traditional and buffered bike lanes or streets with painted sharrows. As the second protected bike lane in Philadelphia and the first one-way segment, the Chestnut Street lane serves as an example of infrastructure possible on Philadelphia streets. Lessons learned through the process of outreach, planning, and construction provide a road map for future lane creation. Since its installation, the City has committed to installing a protected bike lane on South Street, east of the South Street Bridge.

Beyond demonstrating the possibilities for Philadelphia streets, the Chestnut Street bike lane has specific strengths and opportunities. The overall cost of this lane reflects a comparatively low-cost intervention. Case studies of peer cities indicate that costs can range from $15 to $60 per foot for a parking-protected bike lane (Wilkes, 2014). In comparison, OTIS was able to construct this lane at an average cost of $8 to $9 per foot.

Mayor Kenney, with OTIS staff, opens the Chestnut Street protected bike lane on August 29th, 2017.
source: twitter.com (@JimKenney)

When the topic of new bike lanes is introduced, a common concern is the potential loss of parking and impacts on vehicular travel time. The Chestnut Street bike lane managed to design this lane without inciting negative impacts on vehicular access and throughput, including a minimal loss of parking and loading zones. The design did remove one travel lane from the street, but without exacerbating congestion or delay. This reduction in lane illustrates another strength of this lane, which is its function as a traffic-calming device (i.e. road diet).

Finally, an important benefit of the lane is the ways in which it has enhanced the pedestrian experience on Chestnut Street. The bike lane and parking allow for greater separation between the sidewalk and moving traffic, improving the perception of safety. The design of the bike lane also resulted in new pedestrian refuge islands, as seen on the intersection of 36th street and Chestnut Street. These refuge islands provide a safe space for pedestrians to wait for the walk signal, and shorten the crossing distance. These benefits are useful for all users of Chestnut Street.

The following section zooms in on four specific areas of the Chestnut Street lane to provide an evaluation of the infrastructure.

FOCUS AREAS

The focus areas of this analysis are primarily located on the eastern section of the bike lane, and include the following topics:

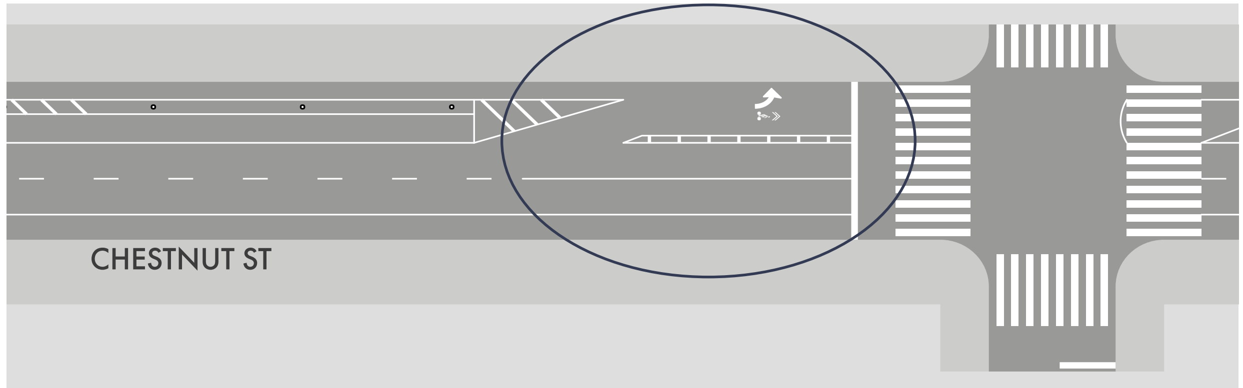
- Mixing zones;
- Pedestrian refuge islands;
- Intersection at 34th Street; and,
- Transition at 33rd Street.

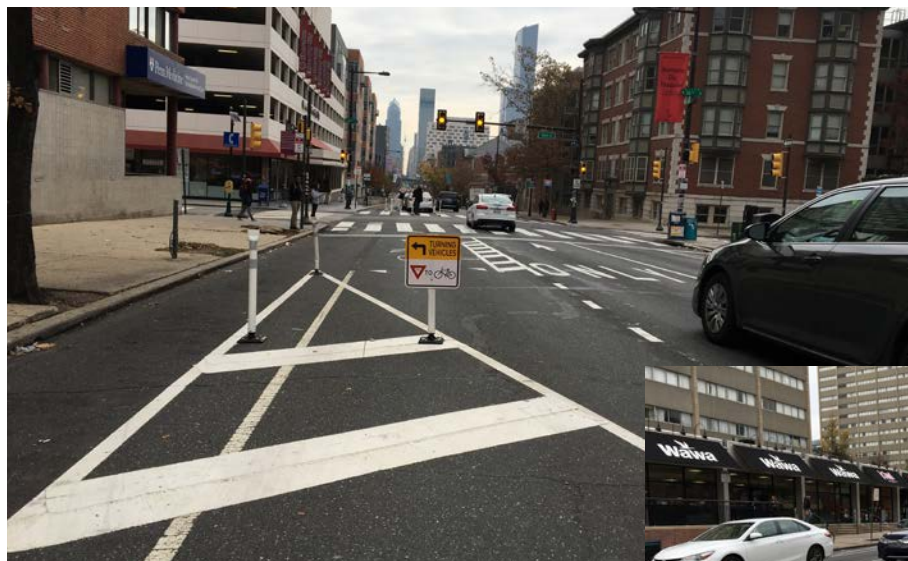
Mixing Zones

Protected bike lanes are popular and effective because they physically separate bicyclists from motor vehicle traffic, yet these modes still must interact at intersections. Since the Chestnut Street protected bike lane is on the left side of the street, any areas allowing left turns (of which there are six on this segment) would require a mixing zone where vehicles and bicyclists are forced to interact.

At these mixing zones, the bike lane temporarily ends and bicyclists share a lane with left-turning vehicles. These mixing zones are problematic because there is limited space to prepare motorists and bicyclists for this interaction and the limited signage that exists, as shown in *Figure 1*, is often not visible due to their small size and low height.

Figure 1. Mixing zone, depicted through street diagram and photos



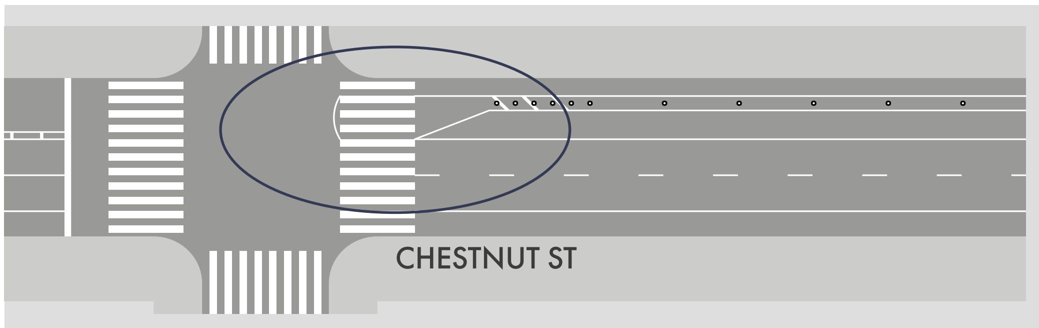


Mixing zone at the intersection of 36th Street, viewed looking east (above) and west (right).

Pedestrian Refuge Islands

A large benefit of protected bike lanes is that they add safety benefits for all road users, not just bicyclists. This shared benefit this was one of the goals of the Chestnut Street bike lane, as this segment was a high crash corridor for all modes, not just bicyclists. Protected bike lanes often calm traffic and provide shorter crossing distances for pedestrians through pedestrian refuge islands. This is space provided near the intersection (in front of the parking lane) between the bike lane and the motor vehicle travel lanes. *Figure 2* provides a diagram of a pedestrian refuge island.

Figure 2. Pedestrian refuge island



Pedestrians make use of the refuge island at the interssection of Chestnut Street and 36th Street.

Pedestrians can first cross the bike lane, wait in the refuge island until motor vehicle traffic has stopped and the light cycle shifts, then continue across the street, thus dividing their crossing into two shorter segments. Any intersection on this segment without a left turn lane has a pedestrian refuge island on both the western and eastern end of the intersection. Intersections with a left turn lane have a pedestrian refuge island only on the eastern end.

Pedestrians on Chestnut Street were quick to utilize the refuge islands provided. While conducting a bicycle count from 8:15AM to 8:45AM on a cold Wednesday morning, we observed 37 pedestrians using this pedestrian refuge island at the intersection of 40th Street and Chestnut Street. This figure was actually greater than the number of bicyclists using the bike lane at this intersection in the same timeframe.

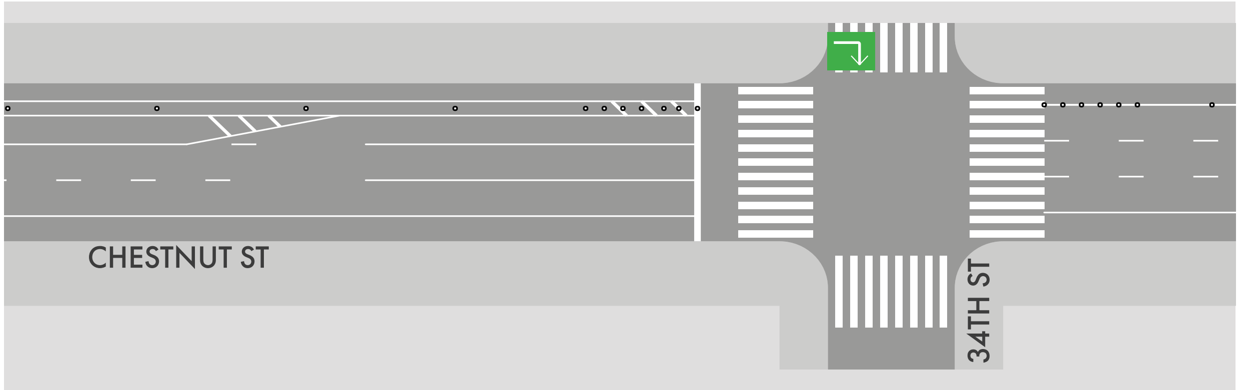
Intersection at 34th Street

34th Street is an important intersection for this lane, as this is where the bike lane ceases to be a parking protected bike lane and shifts to a traditional lane simply protected by bollards, with no buffer between motor vehicle traffic and the bike lane. Chestnut Street also sees the reintroduction of a third motor vehicle travel lane, prior to the intersection, despite the fact that there is no left turn on to 34th Street.

There is the option for making a right turn, however, and 34th Street has a bike lane heading south. Therefore, there is a bike box for bicyclists turning right onto 34th Street from Chestnut Street. This is important as many bicyclists turn right onto 34th from Chestnut in order to reach Penn's campus or the South Street Bridge. These elements are depicted in *Figure 3*, at right.

The reintroduction of the third travel lane is an interesting component of this focus area, as we rarely observed vehicles entering the space. In fact, the space was often used as an informal loading zone for people visiting the nearby Starbucks store. One such loading example is shown in the picture at right.

Figure 3. Intersection at 34th Street, depicted through street diagram and photos



Transition at 33rd Street

The stretch of the bike lane immediate preceding and following the intersection at 33rd Street is perhaps the most important point of the segment in the study area, as this is where the new infrastructure ends. At this point, the bike infrastructure on Chestnut Street transitions from a protected bike facility to an unprotected bike facility.

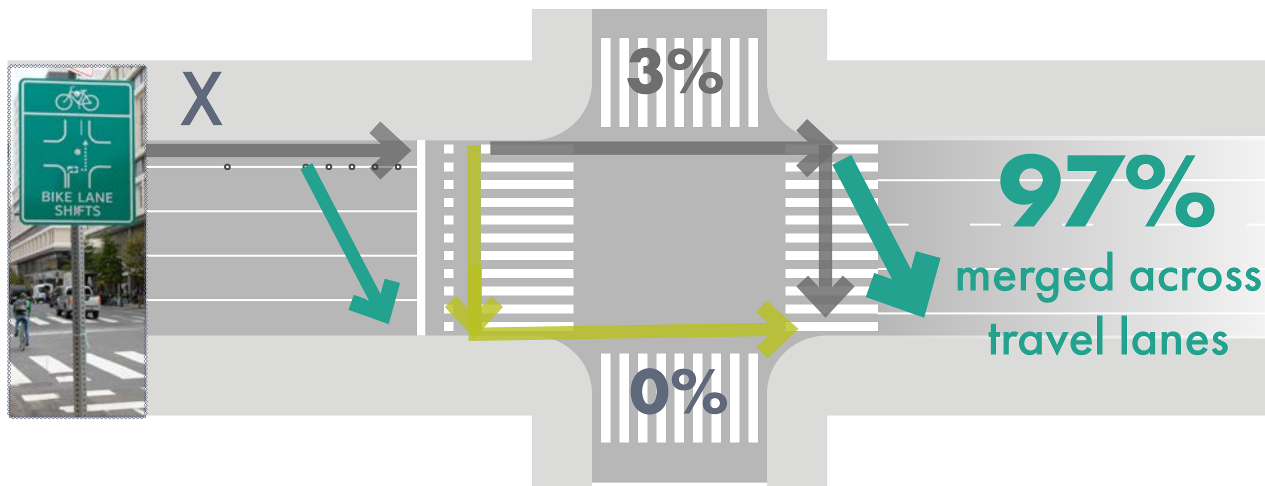
After the intersection, there is a shift in the bike lane from the left side of the street to the right side, where there was already an existing traditional bike lane. The City ended the treatment at 33rd Street, because PennDOT was scheduled to reconstruct Chestnut Street east of 33rd Street around the same time, as Chestnut Street is a state road. A report from OTIS (2015) suggests that this reconstruction project may incorporate a redesigned bike lane from 34th Street to 22nd Street, and this redesign would place the bike lane on the left side of the street. As such, this would have extended the protected bike lane, continuing into Center City without making a shift to the other side of the street.

The City strategically timed their installation to be in line with PennDOT's, but unfortunately PennDOT's installation process was delayed. The outcome of this misalignment of schedules is the resulting problematic intersection where bicyclists are forced to cross three lanes of motor vehicle traffic in order to remain in the bike lane. While there is signage instructing bicyclists on how to maneuver the shift, it often goes unnoticed.

From 8:15AM to 8:45AM on a weekday morning, we observed a total of 30 bicyclists at this intersection. Of those 30, not a single bicyclist navigated the intersection as the sign instructs them to do. The green line on *Figure 4* shows the recommended route for bicyclists according to the street signage.

All but one bicyclist (97 percent) crossed three lanes of moving traffic in order to move from the bike lane on the left side of the street to the lane on the right side of the street (noted in teal on the graphic below). Using the eye tracking equipment discussed in the following section, we also observed that no bicyclists saw the sign at this intersection instructing them on how to navigate the intersection.

Figure 4. Observed cyclist behavior at Chestnut Street and 33rd Street



PART 3.
Eye Tracking Analysis

The second component of our analysis incorporates eye tracking data. At present, this study reflects the second-ever application of eye trackers on cyclists riding on city streets (i.e. not within a controlled or simulated space). As this is a novel approach to this type of data, a brief overview of eye tracking research and equipment is provided.

EYE TRACKING RESEARCH

In its capacity to capture a participant's vision or focus in response to different stimuli, eye tracking research is invaluable data for understanding a participant's experience. The field of eye tracking research was pioneered by psychologists, mostly in regard to reading-related hypotheses. Modern applications have focused on tracking how users interact with websites, advertisements, and other marketing material.

Driving Simulators

Eye trackers are a useful tool for evaluating driving scenarios and drivers' response. This is conducted using a driving simulator, as shown in *Figure 5.* Driving simulators provide an opportunity to collect eye tracking data in a controlled environment. The photos at right feature the driving simulator and a research session at the Children's Hospital of Philadelphia Center for Injury Research and Prevention (CIRP). This study had the opportunity to borrow the equipment CIRP uses in this lab for application in an outside environment.

2017 Bologna Study

Earlier this year, Mantuano, Bernardi and Rupi (2017) published the first study that used eye trackers on cyclists and did not rely on a controlled environment. Cyclists rode on streets in Bologna, Italy; data collected informed findings related to cyclist experience and interactions.

The current study is particularly interesting and differs from Mantuano et al. (2017) in that our eye tracking data is used as a means to an end—a way to assess perceived safety on various types of cycling infrastructure.

Equipment

The equipment borrowed from CIRP includes Tobii eye tracking glasses and the associated lenses and devices, as well as a Tobii-enabled laptop. *Figure 6* provides context to the type of equipment pieces utilized in this research. Of note: to collect data, the eye trackers were required to be connected to the laptop at all times.

Figure 5. Driving simulator; with participant wearing eye tracking glasses

sources, left to right: simcreator.com; penncurrent.upenn.edu

Figure 6. Eye tracking equipment in use with the current study

METHODOLOGY

This project aimed to use eye trackers in a dynamic, urban environment, which is a fairly novel use of the equipment. Several overarching questions served as the guide for the research:

- *How can eye trackers help us to understand the best infrastructure and signage design?*
- *Can we measure the safety, comfort, and stress of bikers when using protected and unprotected bike lanes?* And finally,
- *Can we create a methodology to inform future research related to pedestrian and bicycle infrastructure safety and design?*

These guiding questions framed the approach and methods employed to collect and analyze the eye tracking data. The following sections discuss the methodology associated with the eye trackers, including participants, study route, and limitations.

Participants

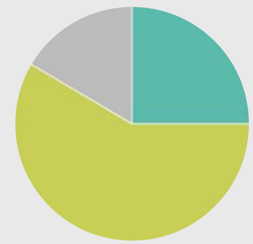
To attempt to answer these questions, data was collected from volunteer participants who biked and walked wearing the eye-tracking device.

Eleven individuals participated in this study (seven female, four male, median age=29). As a prerequisite, all individuals were recruited through the University of Pennsylvania system so as to meet liability coverage should any incidents occur with the eye tracking equipment. Of note: this exclusivity in sampling likely impacted the reliability of the study, in that participants from PennDesign are familiar with the transportation planning program and process, and may have been aware that Chestnut Street was the focus of our class project.

Recruitment was conducted via email in early October, with testing occurring over the following two months. Details about the confidence and cycling experience level of the study participants, as well as basic demographic data, was collected through an online survey, the findings of which are provided in *Figure 7*, at right. This sample pool includes participants that opted to conduct the test as pedestrians (N=4) as well as those who biked (N=7). Notably, our participants trended towards higher-than-average experience and comfort as cyclists, with nearly half biking to work or school on most days.

Figure 7. Participant cycling comfort

1. There is a fairly standard distribution of cycling comfort among participants, with most self-reporting that they are comfortable using bike lanes.



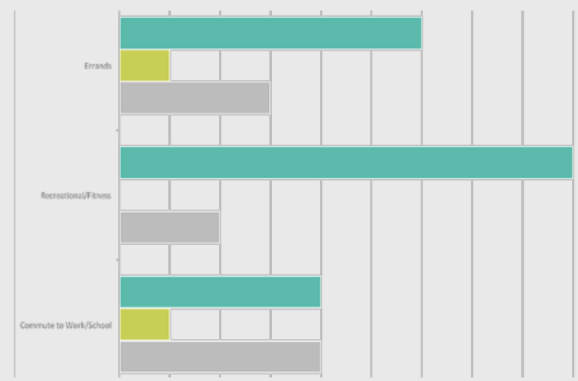
25%: I am comfortable sharing the road with vehicles, with or without a bike lane

58%: I am comfortable sharing the road with vehicles if there is a bike lane

16.7%: I will only bike if there is a trail or bike path; I am uncomfortable sharing the road with vehicles

2. Nearly half of participants commute by bike to work/school, many have more than three years of experience biking for commuting or errands.

3+ years experience cycling: errands (6), work/school (4), fitness (9)
1-3 years experience cycling: errands (1), work/school (1), fitness (0)
<1 year experience cycling: errands (3), work/school (4), fitness (2)



Study Route

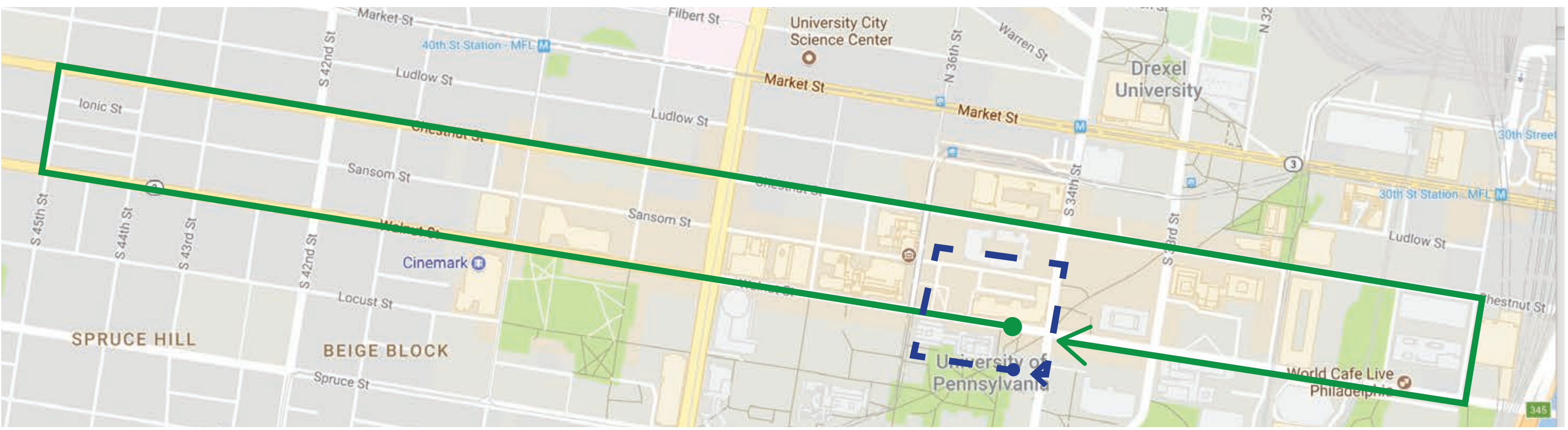
The route these participants took was in University City, Philadelphia, close to the University of Pennsylvania campus. *Figure 8* shows both the biking and walking routes. The biking route was chosen to include 15 blocks of travel on Walnut Street in a buffered, unprotected bike lane as well as 15 blocks of travel on Chestnut Street, primarily in the protected bike lane, with some travel in the unprotected bike lane (east of 33rd Street). The intent in developing the bike route in this way was to gather data that could be easily subset into protected and unprotected groups for comparative analysis. This is noted in green on the map below. The walking route was designed so as to maximize interaction with intersections, including intersections with the Chestnut and Walnut Street bike lanes. This is depicted as a dashed, blue line on the map. Ultimately, the project developed a heavier focus on the data and findings associated with the biking route and cyclist participants than with the pedestrian participants.

Limitations

During and after the data collection process, two limitations of the equipment became apparent. The first of which is a known limitation of the eye-tracker technology itself, while the second limitation is specific to use in a dynamic outdoor environment.

First, the version of the eye-tracker used for this project was wired, meaning that while the participant was walking or biking they had to carry not only a battery-pack for the eye-tracker on their belt, but also a large laptop in a backpack, connected to the battery-pack by cumbersome wires. A wireless version of the eye-tracking equipment is available and would be highly preferable for future outdoor uses such as this one. This type of wired equipment is more suitable for indoor uses such as a driving simulator.

Figure 8. Map of Study Route



Second, the eye-tracking equipment's data collection capabilities suffer on sunny days. While some of the best participant data collected captured up to 91 percent of gaze data during the test, collections taken on sunny days only captured gaze data ranging between seven percent and 32 percent of the test. Because the eye tracker uses an infrared camera to measure infrared light in the eyeball, other sources of infrared light such as sunshine can create noise and reduce the accuracy of the readings. In addition, clouds and shade cause changes in pupil dilation, which reduces the data's usefulness for providing information about dilation as caused by stress.

DATA ANALYSIS

The eye tracking equipment captures data on eye position and movement, pupil size and head position and movement. The variables captured include:

- Gaze Position: Where the participant was focused, on both an absolute grid in three dimensions, and a two-dimensional position within the outward-facing camera's field of view;
- Pupil Dilation: Pupil diameter and position;
- Fixation Duration: Length of time the participant was fixated on an individual point in the field of view;
- Eye movements are classified as saccades (quick, darting eye movements) or fixations (gaze is focused on a specific point in the field of view);
- Gyroscope: Head position; and,
- Accelerometer: Speed of head movements.

These variables were accompanied by the relevant demographic and experience information collected through administration of the short survey (see *Figure 7*, on page 13).

Preliminary Findings

Using the initial datasets collected in this pilot study, we identified some patterns and trends in the data. The purpose of this study was not to draw conclusions, but rather identify hypotheses for further investigation and to inform our recommendations in the next section, Part 4. We would need significantly more data to test these hypotheses to determine whether these initial ideas are verifiable conclusions or artifacts of a limited dataset.

The following section outlines preliminary findings related to safety on the Chestnut Street bike lane. Analyses are divided into a series of hypotheses and comparisons, including: protected versus unprotected lanes, pedestrians versus cyclists, and analysis of the sign placement at the transition at 33rd Street. These analyses are conducted using the variables captured by the eye tracking equipment.

Gaze Plots

The most basic data output from the Tobii Pro software is a gaze plot, which displays where the participant was looking within the front-facing camera's field of view throughout a selected interval, weighted by gaze duration. Red areas represent the areas where the participant spent the most time looking during the selected interval.

Comparing Gaze Data for Protected vs. Unprotected Lanes

The first analysis conducted with the eye tracking data output was a comparison of the gaze plots between segments on Walnut Street, which has a traditional, unprotected bike lane, and Chestnut Street (the protected bike lane).

In the example shown in *Figure 9*, the participant's gaze was more intensely focused on the center during the Walnut Street segment (top image), but also showed higher dispersion at the edges. On the Chestnut Street segment (bottom image), the participant's gaze is less intensely focused on the center, but less dispersed overall.

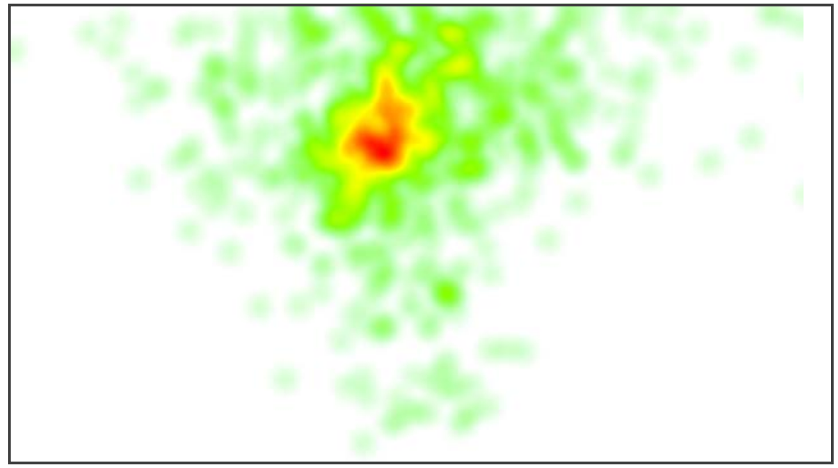
We hypothesize that this is evidence of higher stress for the cyclist on Walnut Street (unprotected), as they are fixated straight ahead rather than engaging in safe scanning behavior. Participants may also be forced to check over their shoulder more often as cars approach from behind, increasing the likelihood that they miss a hazard in front of them.

A method for checking this quantitatively would be to compare standard deviations in the X and Y coordinates of the gaze position data between the two segments to determine differences in the spread of eye movements between the two segments. Supplementing gaze positions with accelerometer and gyroscope data can determine whether participants turn their heads more often or with greater urgency on one segment over the other. Finally, an assessment of video data can help to determine the frequency of head-turning movements.

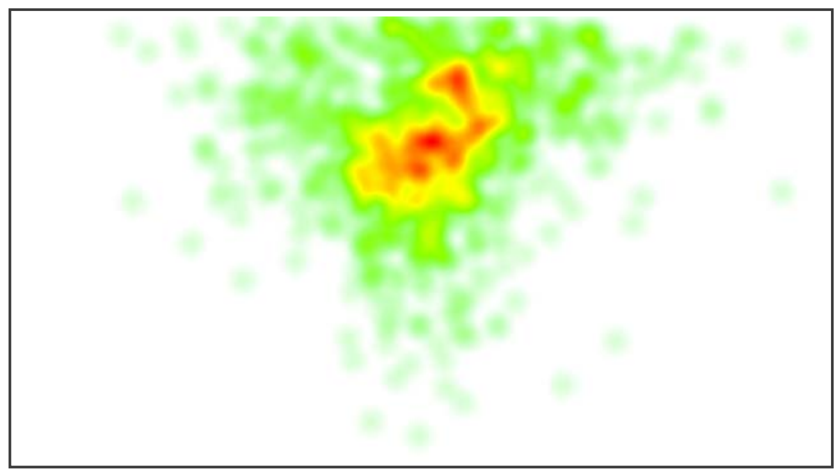
Figure 9. Gaze plots: Cyclists on Walnut Street and Chestnut Street

gaze location weighted by duration

WALNUT STREET: Unprotected bike lane



CHESTNUT STREET: Protected bike lane



Pupil Dilation / Stress Response

Previous studies have shown that pupils dilate under stress (Kolb & Wishaw, 1990). Therefore, pupil diameter data provides the opportunity to assess involuntary stress responses in the participant. However, this analysis presents significant challenges in a real-world setting. The primary reason pupils change size is to adjust to changes in light conditions. Because light conditions change often as participants pass from shade into sunlight, simple plots of pupil diameter are more likely to show variations in light than variations due to stress response. These plots were interesting, but did not immediately show reliable patterns due to the significant number of uncontrolled factors.

Regardless, pupil diameter analysis has the potential to provide meaningful information if analyzed in combination with other stress-related factors in a data learning environment. A possible control input would be to collect baseline data under controlled lighting conditions, and use an established method of producing a stress response to collect data to inform data learning. Additional useful data inputs not collected in this study include galvanic skin response (a measure of involuntary sweat response), heart rate and respiration rate. Locational data could help to associate perceived responses with specific locations, to control for changes in stress factors related to geography, such as light conditions or topography of the route.

Comparing Gaze Plots for Different Modes of Transportation

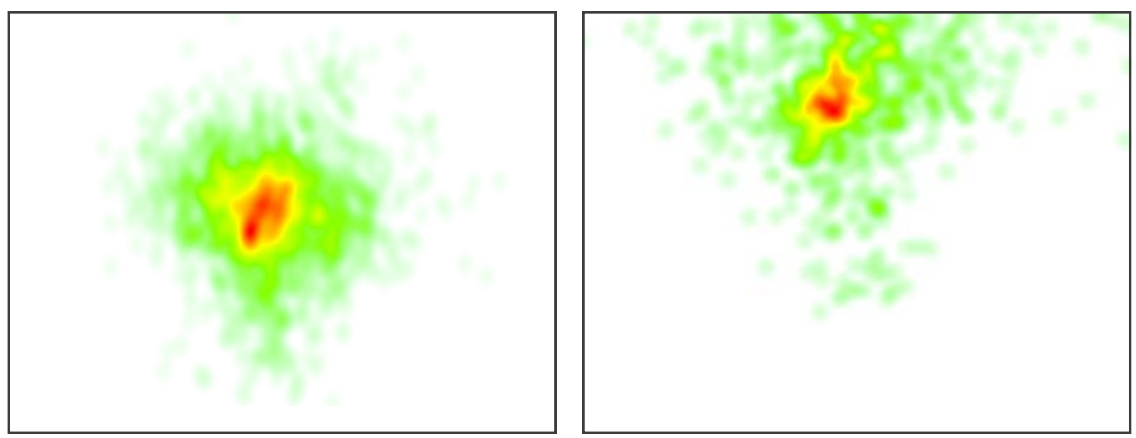
Patterns emerged when comparing gaze plots from cyclists in the analysis to gaze plots of pedestrians. In the limited data we were able to analyze, most pedestrians' plots were centered in the field of view and showed little dispersion (*Figure 10*). By contrast, most cyclists' gaze plots were shifted up from the center of the field of view, and showed significantly more dispersion.

We hypothesize that cyclists are generally looking toward the top of their field of view to compensate for the hunched-over riding position of the bicycles used by participants in the study. We also hypothesize that the lower dispersion in pedestrian data could result from two separate factions:

1. Pedestrians are more able to turn their heads to look at something, while cyclists have to peer with their eyes due to hazards involved with turning the head away from straight-ahead for more than a brief glance;
2. Pedestrians feel fewer threats and thus look away from center much less, because of the relatively protected nature of sidewalks.

Figure 10. Gaze plots: Cyclists and Pedestrians on Walnut Street

PEDESTRIAN CYCLIST



Future studies should control for the type of bicycle used, as variations in bicycle design can potentially cause significant shifts in head and gaze position. Future study should also investigate gyroscope data to determine if head position varies significantly between different modes. Further mode comparison study should also include other types of street users such as drivers and users in wheelchairs.

This sort of investigation can be used to test engineering standards from sources such as the *Manual on Uniform Traffic Control Devices* (MUTCD). The MUTCD dictates that bicycle signage should be at least 4' off the ground. However, further study could potentially show that cyclists are more likely to see pavement markings than signs, implying that there may be significant safety and communication benefits to improving pavement markings for cyclists.

Evaluating Effectiveness of Signage

Another function of the Tobii Pro software is the Areas of Interest function, which allows the analyst to select an area of interest within the field of view to evaluate how the participant interacts with the specified area. We used the Area of Interest function to evaluate whether or not the participant looked at the sign informing them of the upcoming crossover from left-side parking protected bike lane to right-side conventional bike lane at 33rd Street. We were only able to apply the area of interest function to one participant's ride. In that instance, the user did not look at the sign on the left while approaching the intersection. Instead, the participant's gaze was focused toward motor vehicle traffic to the right, as shown in *Figure 11*.

Unfortunately, the area of interest function is difficult to use in this real world application. In the most common applications of the Area of Interest function (such as evaluating how a user interacts with a website or grocery store shelf), the participant is stationary. In the case of this study, the user is moving quickly on a bicycle. To perform an area of interest analysis for an entire segment would require selecting areas of interest on a frame-by-frame basis—a tedious and nearly impossible task.

This feature could be useful for future study if applied at a limited number of locations to determine where participants' gaze is focused around a selected piece of infrastructure, such as a sign. This sort of study could suggest the best locations for prominent signage at specific locations. But even in this limited capacity, the analysis would likely be quite time-consuming if performed manually.

What Can We Do With Eye Tracking?

Based on the results of this pilot eye tracking study, we have identified a number of areas for further study. Eye tracking could prove useful for evaluating both user and infrastructure-related questions.

Potential user-related questions for further study include:

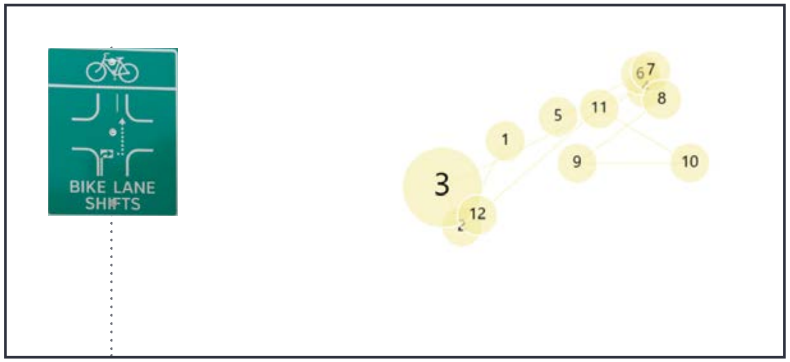
- *How do gaze points compare across different styles of bicycle, and how do those differences affect users' ability to see traffic around them?*
- *How does head position vary between walkers, cyclists, drivers, and other street users?*
- *How do gaze patterns vary between users of different age, experience level, sex, etc.?*

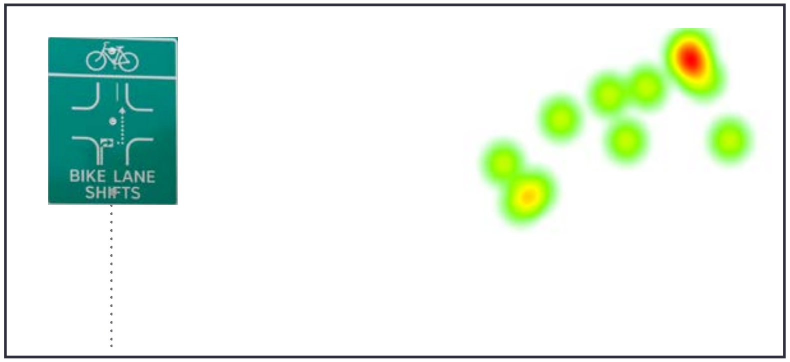
Infrastructure-related questions for further study include:

- Do street users see the signs directing them?
- How comfortable are participants in different street conditions?
- How does quality of the pavement affect user experience?

Further studies should also seek to establish a more controlled test environment (such as a closed course or simulator) to test experimental infrastructure and road conditions in a setting that ensures participant safety.

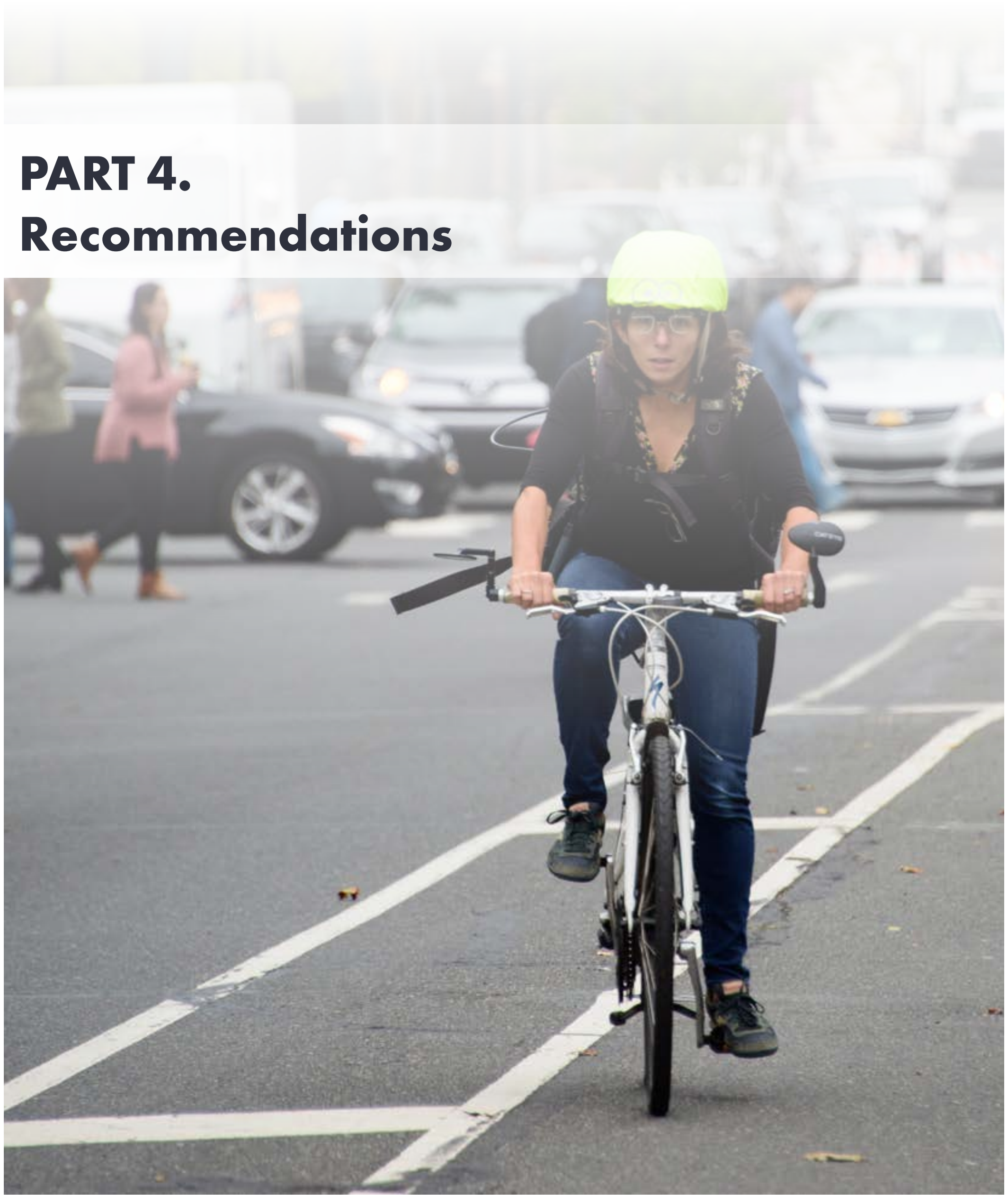
Figure 11. Gaze plots: Cyclists and Pedestrians on Walnut Street





Application of the Area of Interest function allows the analysis of specific objects, such as the sign at the intersection of 33rd Street and Chestnut Street. The photo above includes notation of the participants gaze, also represented by the gaze plots on the right. Findings indicate the participant did not see the sign in advance of the lane transition.

PART 4. Recommendations



Through this evaluation and based on the data collection described in Part 3, recommendations are identified that address safety of the bike lane. Recommendations are broken up into four categories:

- Markings and signage;
- Mixing zones;
- Intersection at 34th Street; and,
- Transition at 33rd Street.

The first are general recommendations that apply to sections throughout the protected bike lane. The last two zoom in on two specific locations, at 34th and 33rd Streets, to examine how projects can handle an increase of vehicle lanes and lanes switching sides of the street, respectively.

These recommendations are especially important for the city to consider as they move forward with further protected bike lane projects, and underscore the importance of evaluating projects so further infrastructure can improve upon past projects.

Markings and Signage

We observed various situations in which the signage in and around the protected bike lane inadequately conveyed the rules to users. For example, signs geared towards cyclists were often too tall, as we observed tracking cyclists' eye movements missing the informational sign leading up to 33rd Street. The National Association of City Transportation Officials (NACTO) *Urban Bikeway Design Guide* notes that such information and wayfining can be more visible than signs, but the guide stops short of recommending pavement markings for other uses (NACTO, 2011). In future projects, the city should always use pavement markings to indicate information to cyclists especially.

Signs can often be just as difficult for vehicle drivers to see, which is why yield and turn information is often conveyed with pavement markings. However, we noticed that the protected bike lane made some signs even more difficult for drivers to notice.

Parking signs are still located on the sidewalk on Chestnut, even though the parking spaces themselves are located on the other side of the protected bike lane. This made it especially difficult for drivers to tell what the regulations are for a given on-street space. While driveway entrances were marked as no-parking zones with white X's, it did not immediately seem clear where drivers were supposed to enter these driveways. More clear pavement markings could alleviate these issues. Loading zones should especially be marked off to differentiate them from metered or medium-term parking spaces.

Spaces where conflicts between cyclists and vehicles should receive extra attention from safety improvements. In these cases, the *NACTO Urban Bikeway Design Guide* recommends colored—usually green in the United States—road markings can increase cyclists' visibility and raise users' awareness of the conflict (NACTO, 2011). Through areas where driveways cross the protected bike lane, to facilitate right turns from the protected bike lane, and through intersections where conflicts are observed, green road markings should be strongly considered.

Mixing Zones

Of course, intersections are always sources of conflict, and this is especially true where motor vehicles must make left turns across the path of the protected bike lane. On Chestnut Street, these left turns are handled by having cyclists and vehicles merge before the intersection so vehicles are not turning directly through cyclists' paths.
While these types of mixing zones seemed to work well in our observations, we believe features to increase visibility are worth considering in future projects. The aforementioned green pavement markings would work well in these mixing zones to reinforce cyclists' priority in addition to the "sharks' teeth" yield markings and small signs.

Features that ensure extra visibility of cyclists to motorists are also important. It can be difficult for drivers to see cyclists in the protected bike lane if the street parking is occupied leading up to the mixing zone. Removing an extra parking space would help increase this visibility, especially when cyclist speeds may be high, as at the bottom of a hill.

The space leading up to the mixing zones do not need to be kept empty, though. This space should be considered for bicycle parking, or even Indego bikeshare stations, which would further encourage the bike lane's use while keeping cyclists easily visible to drivers.

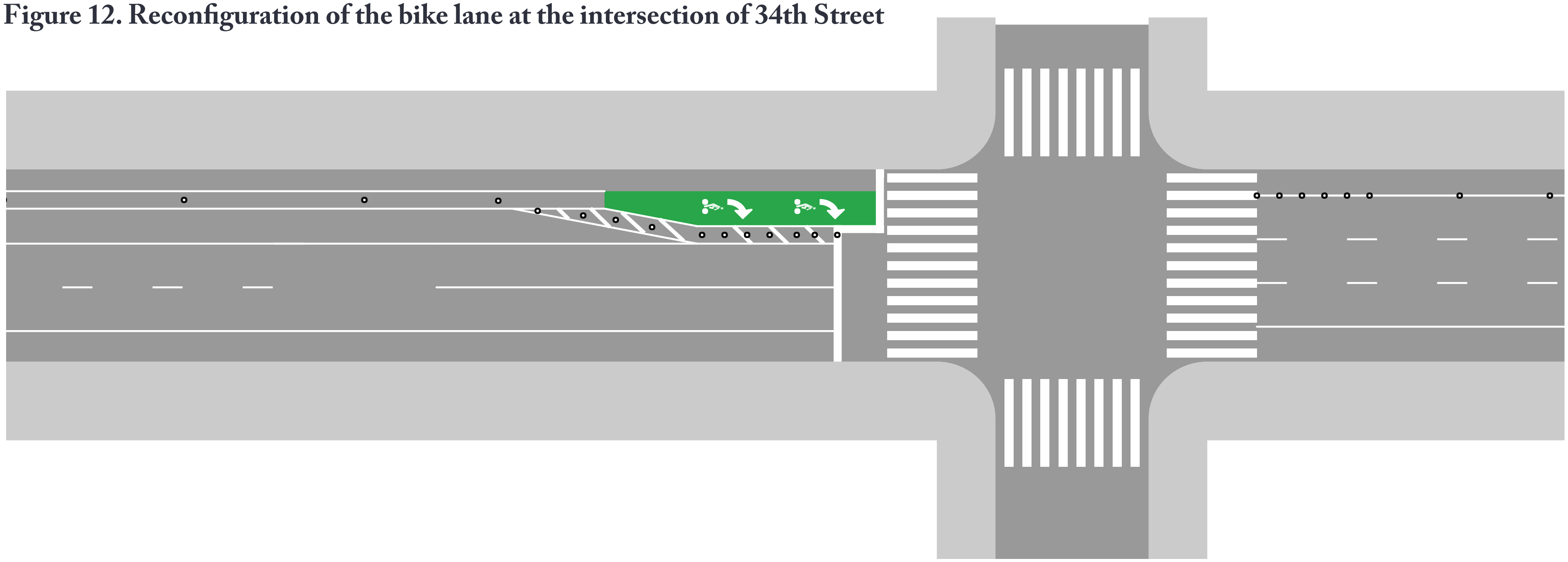
Additional traffic calming devices should be considered for mixing zones as well. Informally, vehicles were observed turning across the mixing zone from the leftmost vehicle lane at high rates of speed, which further decreases visibility of cyclist and allows for more dangerous, higher speeds. Blocking off the mixing zone from other travel lanes to the right with bollards would act as a traffic calming device that would force safer driving behavior and add to mixing zones' safety.

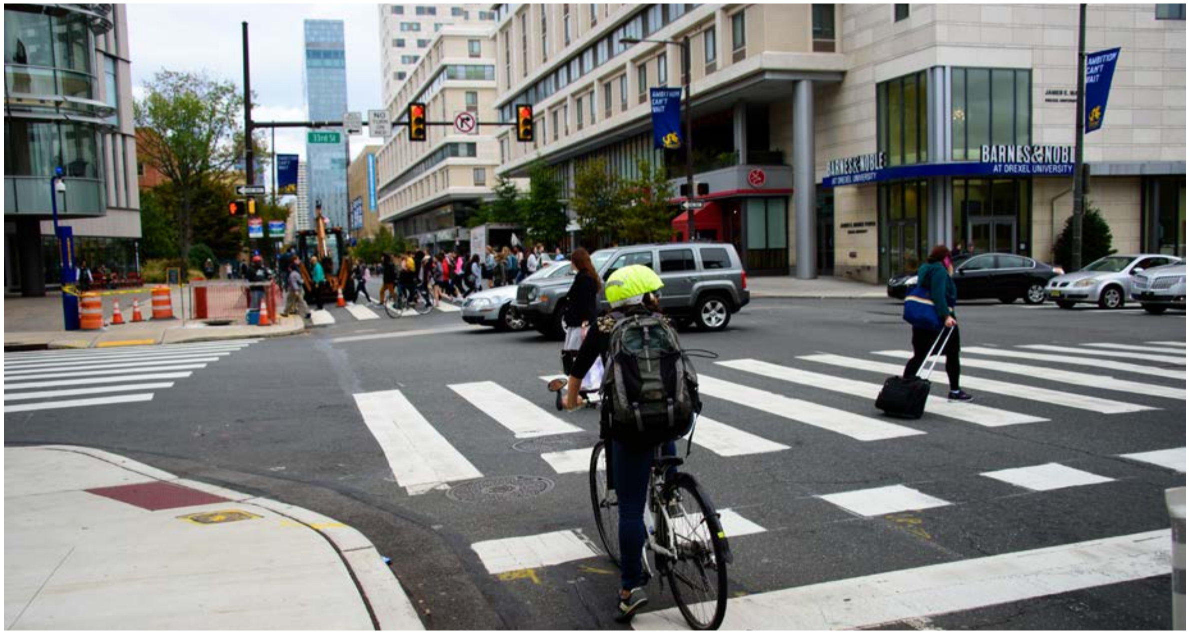
Intersection at 34th Street

The first intersection we look more closely at is as Chestnut Street crosses 34th Street. Here, a third travel lane opens up on Chestnut Street west of 34th Street. While the reasons are unclear, we observed it being used in two major ways: one, for vehicles to quickly pass others that had slowed or stopped for the traffic light, and second for vehicles to stop to make purchases at the Starbucks coffee shop on that corner.

We would therefore recommend that in similar situations, vehicle travel lanes open after intersections instead of right before. This extra space can be used for more short-term parking or for added cyclist safety. For example, many cyclists turn right from the bike lane on to 34th Street. While a small box is provided to the left of the bike lane, its usability could be greatly increased with a right-turn box in the space currently occupied by the third travel lane. *Figure 12* provides an example of how these changes could work.

Figure 12. Reconfiguration of the bike lane at the intersection of 34th Street





Study participant waits for the light to change at the intersection of 33rd Street.

Transition at 33rd Street

One of the most controversial moments of the Chestnut Street bike lane occurs at its intersection with 33rd Street, where it currently ends and the unprotected bike lane picks up on the opposite side, right, of the street. While we are aware of plans for the protected bike lane to continue through this intersection and into Center City, in a network of 30 miles of protected bike lanes, as Mayor Kenney indicated as a goal, situations in which a bike lane must shift from one side of the street to another are likely, so we feel these recommendations will be important for the city going forward.

As noted earlier, the sign that indicates to cyclists how to safely navigate this change —by waiting for the red light, crossing at the crosswalk, and continuing through the intersection with the next green light — was not seen by our participants in the eye tracking study.

This was confirmed by observations counting cyclists' behavior directly, where there were none observed following the sign's recommendations. Road markings will be especially important in these situations, with arrows pointing cyclists in the correct direction, and green pavement showing cyclists' priority as they cross the street. Moving the vehicle stop line back to accommodate the space for cyclists to safely cross the street should also be considered.

Additionally, the most cyclists' wait time can be minimized, the less likely they are to break rules. To decrease their wait time, more opportunities for cyclists to cross from one side of the street to the other should be included. In this case, we observed one cyclist who crossed the street with the green light and waited on the opposite side of 33rd Street for the Walk signal crossing Chestnut Street.

By formalizing this movement with the same pavement marking treatments as the current preferred crossing pattern, wait times can be decreased to no more than one light cycle, instead of often more than one currently.

PART 5. Conclusion

This project aimed to identify a new method to understanding infrastructure design. By complementing field observations with eye-tracking data, a more thorough understanding of the Chestnut Street protected bike lane was gained. Opportunities for improvement have been identified, as well as weaknesses with guiding regulations for bicycle infrastructure.

Future Research

The benefit and the challenge of this project was navigating the use of eye tracking equipment, traditionally used in closed, indoor settings, on public streets. This made it very difficult to control for many variables, such as sunlight and sunlight. Likewise, conducting tests in the public realm limited the possibility of collecting baseline or control group data to which we could have conducted comparisons to assess infrastructure and safety. For example, many of our hypotheses relate to the visibility of signage for different users. Without the capacity to test signage options (i.e. moving 33rd street transition sign to new locations or adjusting its height; painting the pavement), we are unable to test any associated changes in perception or behavior. Access to a controlled environment would allow for this type of testing specific variables and hypotheses.

The research related to stress and eye-tracking could be enhanced in future research projects through integration of additional sensors, such as heart rate or galvanic skin response (i.e. reflexive sweat response to stress) to complement the data output related to gaze and pupil dilation.

There are other variables associated with cyclist safety and evaluation of infrastructure that would benefit from eye tracking analyses. In addition to evaluating specific design interventions, future research could: study the effects of differences in bicycle type (e.g. mountain versus road bike); determine how the quality of pavement affects user experience; or study gaze points, head position, and eye movement across multiple modes (pedestrians, cyclists, drivers).

Discussion

A key takeaway from this project is that bicycle infrastructure should not be an afterthought, and when car standards are modified for cyclists, they may not best meet the needs of bicycle users. To ensure that future bicycle infrastructure is as safe and useful as possible, design considerations must take into account the bicyclists' experience, including interaction with existing infrastructure and other road users.

Use of eye-tracking data can greatly contribute to thoughtful design. Further data collection and research of eye tracking data is necessary to make robust, statistically significant conclusions with a large enough sample size, but this project demonstrates the types of insights that may be gained from this approach.

While this project points to challenges and opportunities of the new Chestnut Street Protected Bike Lane, the aim is not to be critical of the City agencies that worked hard to implement the bike lane. Instead, the aim is to point out design considerations that should be taken into account in the future in Philadelphia—especially given Mayor Kenney's goal to install 30 miles of protected bike lanes—but also in cities across the county.

A commonality that Philadelphia has with many American cities is a lack of funding for safe cycling infrastructure. In recent decades, continued funding shortfalls have kept cities from bringing all existing infrastructure into a state of good repair, let alone allowing for the installation of new bicycle safety infrastructure. This is why cash-strapped cities are slow to pay new bike infrastructure, despite its relative cost-effectiveness.

It is incumbent upon residents to voice support for safe infrastructure for bicyclists and pedestrians, knowing that infrastructure projects take time and often come with growing pains. Infrastructure safety data can not only inform proper design, but can also help make the case.

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