USING COMPUTER VISION DEVICES TO EVALUATE BICYCLE AND PEDESTRIAN IMPROVEMENTS

FINAL PROJECT REPORT

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16. Abstract

The design of urban streets and sidewalks must balance the mobility and safety requirements of pedestrians, cyclists, transit users, freight vehicles, and auto drivers. Modern engineers and designers supplement traditional traffic engineering approaches that focus on metrics for automobiles and trucks with more formal consideration of people traveling by foot, bicycle, and bus. The advent of computer vision systems that record counts and pathways of all street and sidewalk users has created new opportunities for data collection, supporting insights that are not possible from the pneumatic tube counters or electromagnetic sensors that are commonly used to measure car and truck traffic. The resulting data can inform street designs that better accommodate all travelers and modes with greater safety. However, computer vision systems using emerging technology must demonstrate their ability to generate consistent, valid, and actionable data before their widespread adoption by urban designers and engineers.

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EXECUTIVE SUMMARY

The design of urban streets and sidewalks must balance the mobility and safety requirements of pedestrians, cyclists, transit users, freight vehicles, and auto drivers. Urban designers now supplement traditional traffic engineering approaches that focus on metrics for automobiles and trucks with more formal consideration of people traveling by foot, bicycle, or bus. The advent of computer vision systems that record counts and pathways of all street and sidewalk users creates new opportunities for data collection and supports insights that are not possible from the pneumatic tube counters or electromagnetic sensors commonly used to measure car and truck traffic. The resulting data can inform street designs that better accommodate all travelers and modes. However, computer vision systems using emerging technology must demonstrate their ability to generate consistent, valid, and actionable data before their widespread adoption by urban designers and engineers.

This project deployed six Numina computer vision sensors on one block of 8th St. near the state Capitol in downtown Boise, Idaho, that had undergone substantial improvements for pedestrians and cyclists. Local agencies had redesigned the block by reducing the car lanes from three to one, adding a protected bike lane, expanding the sidewalks, and changing on-street parking from parallel to back-in angle parking. The project was approved in 2020 and completed in 2021. Our project team analyzed utilization of the new facility by using Numina sensors from October 2022 to November 2023.

The *advantages* of computer vision systems relative to other approaches include the following:

- They can track the pathways of street users by mode and generate heat maps of where pedestrians, bicycles, and vehicle paths are most concentrated.
- They can identify, count, and locate non-conforming uses that could pose safety concerns, such as walking outside crosswalks, cyclists on sidewalks, pedestrians in bike lanes, cyclists traveling counter to the designed direction of bike lanes, and cars driving or parking in bike lanes.
- They can collect data over many weeks to reveal how users' behaviors on the street change with time of day, day of the week, and season.
- They have lower unit costs than manual counts when the cameras operate for weeks or months.

- In the case of computer vision systems like Numina's that record counts and pathways without saving raw video or other personally identifiable information, they offer better privacy than recording video footage.

The *disadvantages* of computer vision systems include the following:

- Their costs are higher than those of using tube counters.
- Their costs are higher than those of video and human coding for short periods of analysis.
- There are reliability risks when new technology is deployed, especially new software technologies that undergo regular updates and improvements.

Using the Numina technology, we produced findings in three categories regarding the new street design on 8th Street.

- Bikeway path design and maintenance
  - Placing a curb-protected bike lane for bike traffic in one direction across from a shared car and bike lane traveling in the opposite direction will invite some cyclists to travel in the curb-protected bike lane in the wrong direction.
  - Failure to keep bikeways clear of snow and ice will force winter cyclists into the street that's been plowed.
- Traffic calming and pedestrian enhancements
  - A significant share of pedestrian traffic crossed 8th Street outside the crosswalk.
  - This could be viewed as a success of the new street design because it reduced car traffic to a single lane going in one direction and reduced speeds with curb extensions and back-in parking, all of which made pedestrians feel safe to cross the street outside the crosswalk.
  - However, walking outside the crosswalk creates the potential for unexpected conflicts between pedestrians and cars and between pedestrians and cyclists.
- Pedestrian and cyclist use by day of week and weather
  - Friday was the peak day for cyclists, and warmer temperatures correlated with higher ridership, even in winter.
  - Estimates of daily use of facilities by cyclists and pedestrians are amenable to modeling by using the large data sets created with computer vision systems.

The data produced by the Numina sensors in the first two months of camera operation counted cyclists as cyclists <u>and</u> pedestrians, and thereby mischaracterized the counts and pathways of pedestrians. Numina updated their object detection algorithm several months after the cameras had been deployed to correct this problem. This problem and others associated with using an emerging technology to evaluate public infrastructure use prompted the research team to develop a practitioner's guide to using computer vision systems, which is included in Appendix A.

CHAPTER 1. INTRODUCTION

1.1. Background

In 2021, the City of Boise, Idaho, created a Vision Zero Task Force to identify policies and capital improvements to increase safety on city streets. Like other cities in the Pacific Northwest—including Seattle, Bellevue, Tacoma, Portland, and Eugene—Boise has adopted Vision Zero goals to eliminate traffic fatalities and severe injuries while increasing safe and healthy mobility for all. Boise supports walking and cycling as a healthy and low-emission alternative to car travel and has developed a network of grade-separated bike paths and marked bike lanes on streets throughout the city.

Boise's public redevelopment agency, the Capital City Development Corporation (CCDC) has tax increment financing authority that it uses to make infrastructure investments in parts of downtown. Those investments include streetscape improvements to enhance the pedestrian experience and to expand mobility choices throughout downtown to create a more active and accessible urban environment. The CCDC has undertaken numerous projects that reconfigure streets and sidewalks to improve pedestrian and bicycle safety by reducing speeds and conflict areas.

As part of the effort to expand access and improve safety for cyclists and pedestrians, Boise adopted a bicycle pathways master plan in January 2022. The plan coincided with the 50th anniversary of a successful effort to build bikeways along the Boise River known as the Greenbelt. The new plan was motivated by the following factors:

- Residents' desire to see Boise's pathway system expand beyond the Greenbelt to provide safe transportation and recreation to a broader geographic range of residents.
- Interest in exploring the use of existing utility corridors such as canals and railroads to provide connectivity without having to rely on the street network.
- New federal funding for bicycle and pedestrian improvements under the Safe Streets for All Program funded by the Infrastructure Investment and Jobs Act of 2021.

With a commitment to improved traffic safety, a plan for a more complete network of grade-separated pathways for non-automotive uses, local funding from the CCDC, and the prospects of new federal funding, stakeholders in Boise want to adopt best practices for the design of pedestrian and bicycle infrastructure to deliver maximum public benefit. Computer vision systems represent one new tool that planners can use to analyze how existing streets and sidewalks may be used to help plan for new infrastructure and to evaluate how new investments may perform after they have been installed. In contrast to pneumatic tube counters, computer vision systems can track pathways for pedestrians, bicycles, and cars to show the actual utilization of different zones in the streetscape. Computer systems also have the potential to identify zones of conflict, conflict frequency, and speeds in ways that tube counters cannot.

This project deployed six Numina computer vision sensors on one block of 8th St. near the state Capitol in downtown Boise that had undergone substantial improvements for pedestrians and cyclists. The CCDC, in conjunction with the Ada County Highway District (ACHD) and the City of Boise, had redesigned the block by reducing the car lanes from three to one, adding a protected bike lane, expanding the sidewalks, and changing on-street parking from parallel to back-in angle parking. The project was approved in 2020 and completed in 2021. Our project team analyzed utilization of the new facility using Numina sensors from October 2022 to November 2023.

The project team was led by Don MacKenzie from the University of Washington's Sustainable Transportation Lab and Mike Lowry from the University of Idaho in cooperation with the CCDC, ACHD, the City of Boise, and Kittelson & Associates, the engineering firm that had designed the improvements. The project was funded by PacTrans, the federally funded University Transportation Center (UTC) for the Pacific Northwest. PacTrans focuses on developing human-centered and transformative multimodal mobility solutions for an equitable Pacific Northwest. This project addressed PacTrans's regional research priority topics of bicyclist safety, complete streets, multimodal issues, and better data on active transportation.

1.2. Research Objectives

Our primary research objective in this project was to evaluate the practicality and the utility of using the Numina computer-based vision systems as a tool for evaluating how people in cars, on bicycles, and on foot interact with streetscapes and with each other. We deployed six Numina sensors on a block that had been recently reconfigured to slow car traffic, make it more amenable for use by cyclists and pedestrians, and reduce conflicts between cyclists and people parking and opening car doors. We were interested in seeing how the Numina sensors could help us evaluate whether people used the new facilities in the ways for which they were designed. For a number of these research questions, a computer vision might provide answers, but tube counters could not.

- The 8th Street improvements included wider sidewalks, tree plantings, vintage-style streetlamps on both sides of the street, a reduction in the number of northbound car lanes from three to one, and new traffic signals on crosswalks at the road intersections.

  How often did pedestrians cross 8th Street using the crosswalks on Bannock and Jefferson, and how often did they cross in the middle of 8th Street?
- The 8th Street improvements included a shared lane for cyclists and automobiles traveling north and another bike lane on the opposite side of the street with a curb separating cyclists traveling south from the roadway.

  Did northbound cyclists always use their designated lane mixed with cars, or did they use the southbound bike lane for traveling north?
- The 8th Street improvements included shifting auto parking on the east side of the street from parallel parking to back-in angle parking. One effect of this new configuration was that after parking, car users had a clear path to the sidewalk and an obstructed path to the street because of the open car door. This design was intended to reduce conflicts between car passengers opening their doors into the bike lane and conflicts between car passengers exiting their vehicle and cars driving north.

  Could Numina sensors show the share of people exiting parked cars that exited to the sidewalk in comparison to those that exited to the street?

  Could Numina sensors generate counts of conflicts or near misses in certain street zones?

  Could Numina sensors report vehicle and bicycle speeds?
- Numina sensors allow for long-term data collection at low marginal cost for additional data.

  How did street utilization by pedestrians and cyclists change by time of day, day of week, and time of year? In relation to auto usage? In relation to weather?

Numina emphasizes the privacy features of its system in its marketing to cities. Notwithstanding the profusion of cameras on private smartphones, building security systems, and automobiles, the public has mixed views about government surveillance (Madden, 2015). Using cameras to record and enforce traffic violations has been controversial in some communities and has led to a ban on the devices in Houston (McCartt and Eichelberger, 2012).

Numina makes a point of not storing images of pedestrians, vehicles, and cyclists within its system. Instead, it uses machine learning algorithms to classify objects and trace their paths through the camera's field of view and then stores images with those objects rendered as geometric shapes that cannot be tied to a particular individual. While reducing potential concerns about government surveillance, Numina's approach also prevents tracking objects across multiple fields of view using more than one sensor.

1.3. Report Organization

Chapter 2 reviews the existing literature about traffic monitoring and computer vision sensor technology. Chapter 3 describes the opportunities offered and challenges posed by the use of computer vision systems to inform street design, as well as the motivations for *The Computer Vision Guidebook for Practitioners* in Appendix A. Chapter 4 reviews the results of four different analyses of the Numina data. Chapter 5 concludes with key lessons learned and opportunities for future research.

CHAPTER 2. LITERATURE REVIEW

2.1. Importance of Design Evaluation

In 2019, cycling fatalities accounted for 2.3 percent of all U.S. traffic fatalities, despite representing only 1 percent of all trips and 0.2 percent of all person-miles traveled (*National Household Travel Survey*, 2017). Meanwhile, pedestrian fatalities in the U.S. increased by 51 percent from 2009 to 2019 and by another 3.9 percent from 2019 to 2020 (Ferenchak et al., 2022; National Highway Traffic Safety Administration, 2022). To address growing concerns, municipal agencies have come up with a collection of design guidelines to improve safety for cyclists and pedestrians. The American Association of State Highway and Transportation Officials (AASHTO) and the National Association of City Transportation Officials (NACTO) are two of the many transportation coalitions that have developed guides for multi-modal street design. The NACTO Urban Street Design Guide centers its recommendations around making "streets safer" and "more livable" for people cycling, walking, driving, and using transit (National Association of City Transportation Officials, 2013). The AASHTO Guide for the Development of Bike Facilities specifies the elements needed to make cycling "a more safe, comfortable, and convenient mode of transportation" (American Association of State Highway and Transportation Officials, 2012). With specific investments in multimodal transportation through the Infrastructure Investment and Jobs Act, these design guides are being applied to projects across the country, but their effectiveness relies on assumptions about how facilities and specific design elements will be used. Understanding the validity of these assumptions is an important step to informing future designs (Khedri et al., 2022).

2.2. Existing Literature and Motivation

There is substantial literature analyzing the effects of improved street design on safety (Barnes and Schlossberg, 2013; Pedroso et al., 2016), usage (Barnes and Schlossberg, 2013; Skov-Petersen et al., 2017; Parker et al., 2013; Fields et al., 2013; Goodno et al., 2013; Rossetti et al., 2019; Pedroso et al., 2016; Dill and Carr, 2003; Brown et al., 2016; Song et al., 2017; Hunter and Stewart, 1999), and experience (Monsere et al., 2012; Goodno et al., 2013). The motivation behind the current study was to understand how the planning assumptions of two common multi-modal design elements—contraflow bike lanes and back-in angle parking—compare with how they are used. This report fills the gaps in the existing literature in several ways.

First, many of the above studies focused on inferring causality and behavioral changes induced by infrastructure improvements. Thus, they concentrated on the *amount of increased usage* as opposed to the *amount of design-consistent usage*. Some reviews evaluated how people interacted with specific design elements (for shared lane markings, see Hunter et al., 2010; for pedestrian hybrid beacons and crosswalk markings, see Fitzpatrick et al., 2011; for bike lane width, see Schimek, 2018). To our knowledge, no studies in the existing literature evaluated (1) how people exited their vehicles after back-in angle parking[1] or (2) the share of bicycle traffic riding the intended direction in a one-way contraflow bicycle lane[2].

Second, most of the studies in the above literature observed usage over short periods of time and with consistent data collection windows. Therefore, they did not determine how usage changed across different seasons. This is another important consideration, as the same design guides apply to varying climates. Additionally, because the studies in the existing literature compared before/after data, they did not evaluate how behaviors changed because of the presence of car traffic.

Third, the studies in the existing literature collected data via GPS, surveys, counters, video footage, and direct observations. Per the National Cooperative Highway Research Program's Guidebook on Pedestrian and Bicycle Volume Data Collection, automated video collection methods provide more information about user and site characteristics than the other nine methods of volume collection (National Cooperative Highway Research Program, 2014). Specifically, the Numina computer vision sensors used in this study promise in-depth information about pedestrian and bicyclist travel behaviors, including count data and travel paths. This study sought to bridge the gaps in the existing literature by providing a comprehensive evaluation of the design-consistent usage of contraflow bike lanes and back-in angle parking, as well as by utilizing computer vision sensors that can collect data to inform future infrastructure investments while not retaining information that allows identification of individual travelers. The use of this anonymized computer vision technology to analyze public infrastructure investments could potentially help improve future street designs.

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[1] Searched Google Scholar and TRID with terms "angle parking," "diagonal parking," "back in angle parking," and "pedestrian," "passenger," "exit."

[2] Searched Google Scholar and TRID with terms "bicycle lane," "wrong way," "direction."

CHAPTER 3. OPPORTUNITIES AND CHALLENGES IN DEPLOYING COMPUTER VISION SENSORS

3.1. When to Use Computer Vision Systems

The design of urban streets and sidewalks must balance the mobility and safety requirements of pedestrians, cyclists, transit users, freight vehicles, and auto drivers. Modern urban street designers supplement traditional traffic engineering approaches that focus on metrics for automobiles and trucks with more formal consideration of people traveling by foot, bicycle, or bus. The advent of computer vision systems that record counts and pathways of all street and sidewalk users creates new opportunities for data collection and supports insights that are not possible from the pneumatic tube counters or electromagnetic sensors commonly used to measure car and truck traffic. The resulting data can inform street designs that better accommodate all travelers and modes.

In the *design phase*, computer vision systems can provide data to inform alternatives for new designs of sidewalks, crosswalks, bike lanes, curb elevations, and parking spaces by providing a nuanced picture of how existing users move across the streetscape. With information about existing utilization and potential conflict points, planners can design new infrastructure to enhance the mobility and safety of non-automotive users. Computer vision systems can also support evaluation *after project completion* to determine whether the actual utilization of the street improvements matches the project's design objectives.

The *advantages* of computer vision systems relative to other approaches include the following:

- They can track the pathways of street users by mode and generate heat maps of where pedestrians, bicycles, and vehicle paths are most concentrated.
- They can identify, count, and locate non-conforming uses that could pose safety concerns, such as walking outside crosswalks, cyclists on sidewalks, pedestrians in bike lanes, cyclists traveling counter to the designed direction of bike lanes, and cars driving or parking in bike lanes.
- They can collect data over many weeks to reveal how users' behaviors on the street change with time of day, day of the week, and season.
- They have lower unit costs than manual counts when the sensors operate for weeks or months.

- In the case of computer vision systems like Numina's that record counts and pathways without saving raw video or other personally identifiable information, they offer better privacy than recording video footage.

The *disadvantages* of computer vision systems include the following:

- Their costs are higher than those of using tube counters.
- Their costs are higher costs than those of video and human coding for short periods of analysis.
- There are reliability risks when new technology is deployed, especially new software technologies that undergo regular updates and improvements.

The following sections describe the opportunities and challenges of using computer vision sensors to evaluate multimodal designs based on our deployment of Numina sensors.

3.2. How the Numina Computer Vision System Works

As shown in Figure 3.1, the Numina sensor units include artificial intelligence systems that classify objects in the field of view (pedestrians, cyclists, cars, trucks, and buses) and then track the movement of those objects, with a new frame taken every 0.5 seconds. The object type and path are transmitted over the cellular network to a cloud storage system provided by Amazon Web Services (AWS), where Numina conducts additional post-processing. The cloud-based data are then available for analysis through a dashboard, an application programming interface (API), or custom reports.

The data generated by the sensors are volumes by date and time (15-minute intervals) and by mode (pedestrians, bicycles, cars, trucks, and buses). The data include overall volumes, volumes in "behavior zones," and heat maps. "Behavior zones" are subsets of the camera view that are of interest for analysis (e.g., a bike lane). The Numina dashboard is an effective tool for understanding the data available, but the API is faster and allows for integration into other programs. If a custom analysis is preferred, the Numina team also offers engineering time for purchase.

The data that are transferred to the AWS cloud do not include any personally identifiable information, and no complete camera images are stored long-term on the pole-mounted units. Instead, the objects are rendered as colored rectangles that signify the object type, and those rectangles trace pathways that can be used to analyze street use. However, during the two-week accuracy testing phase at the beginning of a deployment, Numina captures and retains more frequent images so that its staff can review how well the system's reports (shown on the right side of Figure 3.1) match the reality that the camera sees (shown on the left side of Figure 3.1). This allows users to make informed interpretations of the data that are generated.

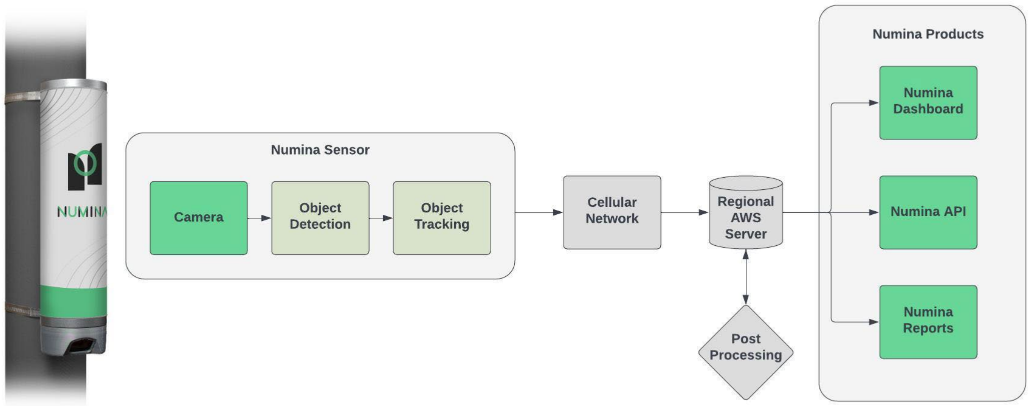


Figure 3.1 How the Numina sensors capture and report data.

3.3. Sensor Installation

Obtaining permission to attach the sensors to the streetlamps took longer than we had hoped, despite strong support from city leadership. We had intended to put sensors on the adjacent block, but late in the process we learned that those lamp posts were owned by the State of Idaho rather than the City of Boise, so we were unable to use them. Instead, we mounted six sensors on streetlamps owned by the City of Boise on N. 8th St., as shown in Figure 3.2. The existing streetlamps had outlets that made them well-suited for installation, but they were not tall enough to meet the recommended height of 15 feet. As a result, we mounted the sensors at 10 feet, which led to a smaller field of view with more obstructions. Scheduling the installation date also took time. In our case, the city employed contractors to help with the installation, which took over a month to finalize. During the installation, all stakeholders (data users, installation team, sensor company) had to be available as the sensors were installed, and all parties had to work together to validate the view.

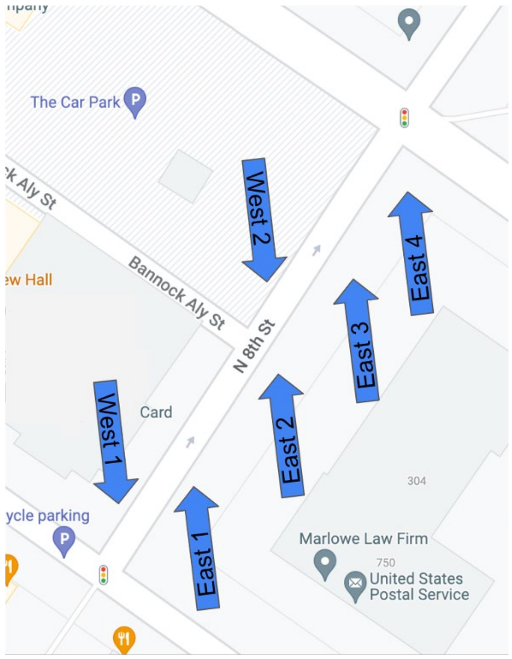


Figure 3.2. Sensor locations and names on N 8th St.

3.4. Calibration Period

Once the sensors had been successfully installed, the Numina team conducted a "two-week accuracy review period" to prepare an accuracy rating for the sensors. During this time, the algorithm-generated counts were compared with the ground truth, which was determined by manually counting anonymized footage. This was done over random time samples to prevent any surveillance use and to minimize occlusion if the streetscape was too busy. However, because we installed the sensors in November in Idaho, very few pedestrians and cyclists were available to be captured by the sensors during the random time samples. Therefore, the Numina team could not prepare an accuracy rating for the system. We concluded that installing the sensors during peak periods is necessary to ensure a useful accuracy rating.

Although an accuracy rating was not established because of the limited pedestrian and bicyclist counts, the Numina team conducted a custom analysis to identify the most accurate zones or "coverage areas." Within the camera field of view, there was a smaller region where the sensors provided the most accurate data reading. This reduction in the field of view, about 10 percent, left the area containing the most consistent track lines for the most accurate analysis, which allowed us to restrict our analysis to the areas in the field of view with the most reliable data readings.

3.5. Pedestrian and Cyclist Count Accuracy

Significant undercounting of pedestrian and cyclist utilization is a common issue across many counting technologies because of their low accuracy in classifying these modes, as shown in the recent findings published by the North Carolina Department of Transportation (Ozan et al., 2021). In our early implementation of the Numina system, the sensors struggled to distinguish among and separately count pedestrians and cyclists without additional post-processing. Instead, the sensors captured a bicyclist as a bike and a pedestrian. This led to inaccurate classifications of pedestrians and bicyclists. Figure 3.3 illustrates that the pedestrian and bicyclist counts in the bike lane of N 8th St. were very similar over one week of data. The likelihood that the sensors were double counting the two modes was subsequently confirmed by Numina's review, and they made efforts to implement changes to improve accuracy.

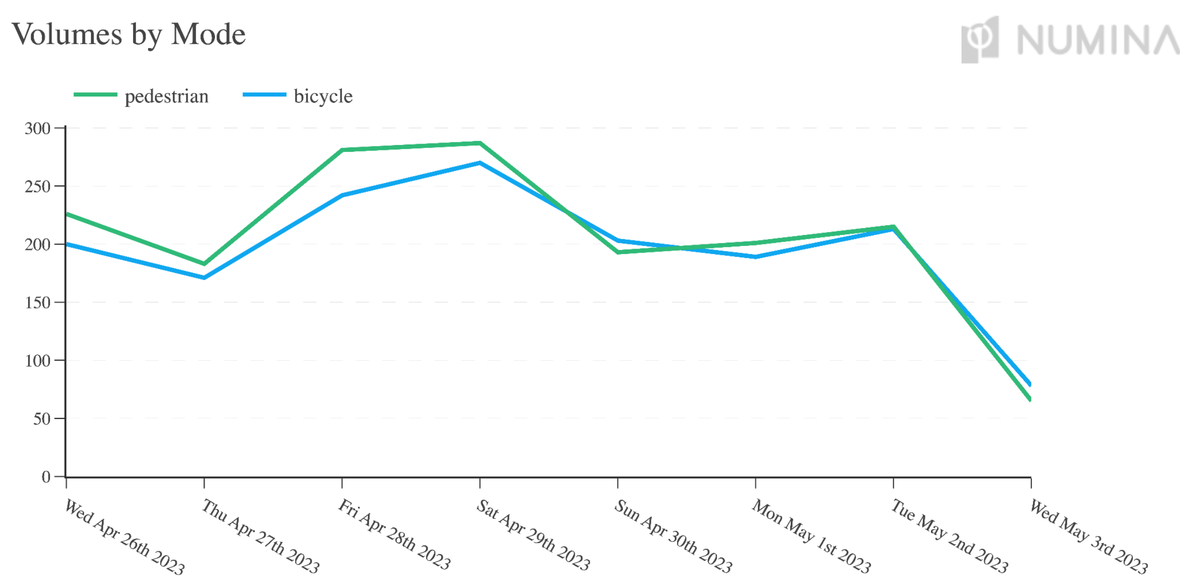


Figure 3.3 Count data for bicyclists and pedestrians in the bike lane on N 8th St. over one week

3.6. Software Updates

Start-up companies employing software constantly try to improve their product. While this can lead to a product that is not as stable as more established technologies, it also means that the product and its data are constantly improving. During our six-month implementation of the Numina sensors, we experienced this firsthand. The development team made various updates both to the classification algorithms for the sensors and to the dashboard and API that provide access to the data. The flexibility of the software allows updated classification algorithms to be retroactively applied to collected data, which could potentially improve the accuracy of the data, even after their collection.

3.7. Motivation for the Practitioner's Guide

The initial installation of the sensors posed several challenges, including the calibration issues and inaccuracies in pedestrian and cyclist counts discussed above. As a result, the first few months were primarily spent troubleshooting and learning what the Numina data would reliably reveal about street utilization. Ultimately, because of the limitations of the Numina system and the low mounting height of the sensors, which created occlusions that inhibited path tracking, the Numina sensors did not generate reliable data for the research questions related to the pathways taken by people leaving cars parked in back-in parking stalls.

In response to these challenges, our team developed the *Guide to Using Computer Vision Sensors*. This brief manual serves as an easy-to-read resource detailing how to utilize computer vision sensors and the best practices for a successful deployment. It is included as Appendix A to this report.

CHAPTER 4. ANALYSIS OF NUMINA SENSOR DATA ON 8TH STREET IN BOISE

4.1. Introduction

This chapter discusses three example analyses that used the Numina sensors in downtown Boise. These analyses explored issues related to bicyclists and pedestrians with data collected over six months. The first analysis looked at jaywalking and wrong-way bicycling. The second analysis investigated bicycle location based on weather conditions to identify whether bicycle facilities were used correctly and maintained. The third analysis used count data to produce a model of pedestrian and bicyclist activity, which could better inform planners about the usage of facilities.

These example analyses aimed to understand the potential for computer vision. Count data were primarily retrieved from sensors West 1 and West 2, shown in Figure 3.2.

Shown in Figure 4.1 are the bike facilities of downtown Boise. As can be seen, 8th Street is one of the more complete north/south corridors in downtown Boise. For an alternative bike route, a bicyclist would need to go all the way to 15th Street, which would be a significant detour. This made 8th Street an ideal candidate for this analysis, as we could expect that it would frequently be used by bicyclists commuting round-trip.

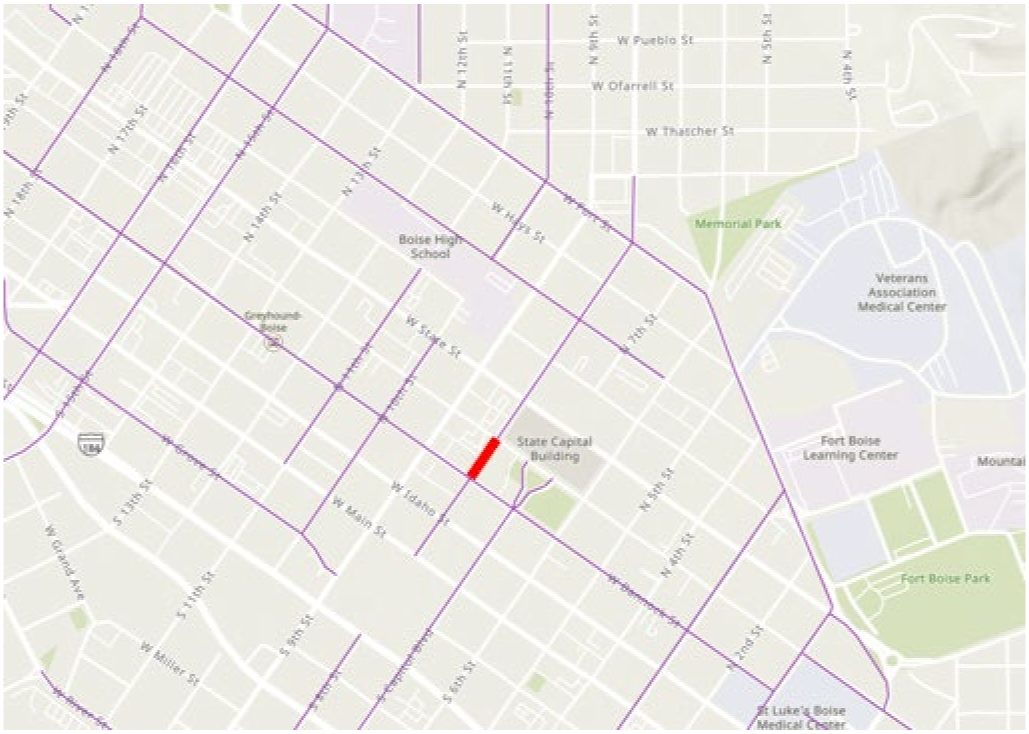


Figure 4.1 Map of the downtown Boise bike lane network

4.2 Jaywalking and Wrong Way Bicycling

The first example analysis explored the extent of jaywalking and wrong-way bicycling. Jaywalking presents safety issues when drivers do not anticipate a pedestrian in the roadway. In addition, bike lanes are narrow, and riding in the wrong direction, especially in separated bike lanes, puts cyclists at risk of injury. This analysis allowed us to explore the computer vision's ability to monitor travel direction and to judge trends in directionality for cyclists and pedestrians. Identifying trends in the usage of facilities can help planners make educated decisions about them.

An additional service that Numina offers at an increased cost is its custom analyses. These custom analyses require extra work by Numina engineers to use the technology in ways that are not yet available on the Numina dashboard or API. Our team had one of these custom analyses done to determine the directionality of pedestrians and cyclists and identify trends. These analyses were done with data from sensors West 1 and West 2 for the period between November 2 and November 23, 2022. The process involved identifying tracks that had a high number of user paths following the same trajectory (i.e., start, mid, end points, and angle).

Objects were then matched to a track if their path was in close enough proximity to the track. The paths used to identify these tracks are shown in Figure 4.2

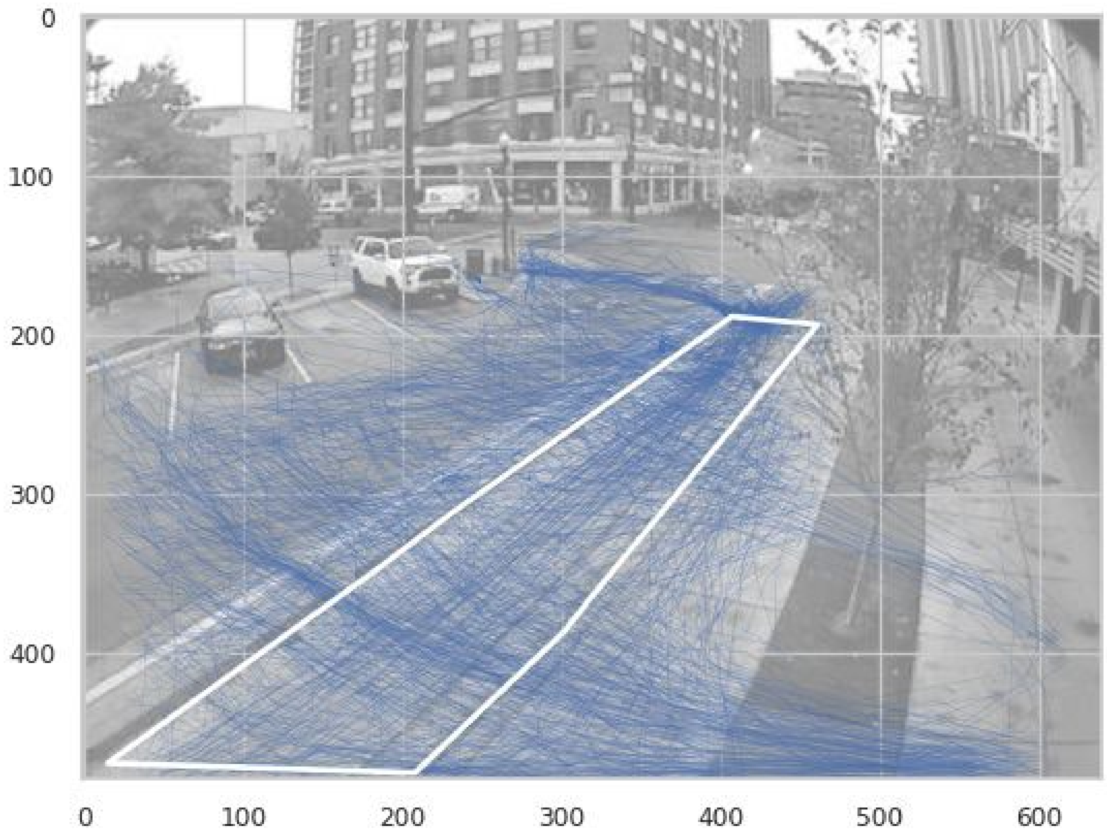


Figure 4.2 Paths used for the pedestrian custom analysis

Numina's engineers identified nine pedestrian tracks that crossed the bike lane zone on sensor West 1, and they were able to assign percentages to each of these tracks. These tracks are shown in Figure 4.3 along with the counts associated with them.

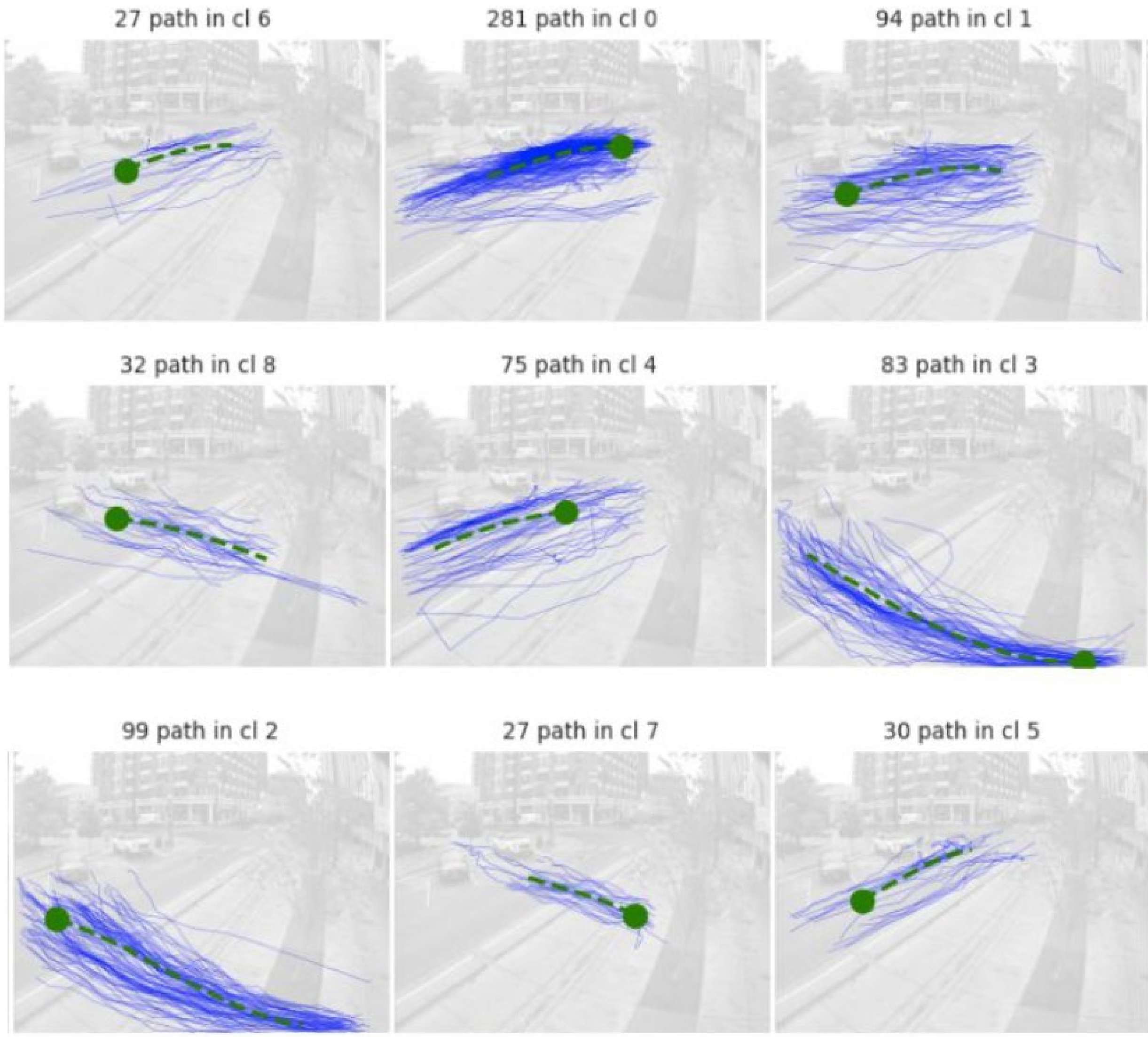


Figure 4.3 Pedestrian tracks identified by Numina

These counts were then divided by the total number of paths to determine the percentages of users following each path. These percentages are shown along with their respective paths in Figure 4.4, and they provide some interesting takeaways about pedestrian behavior.

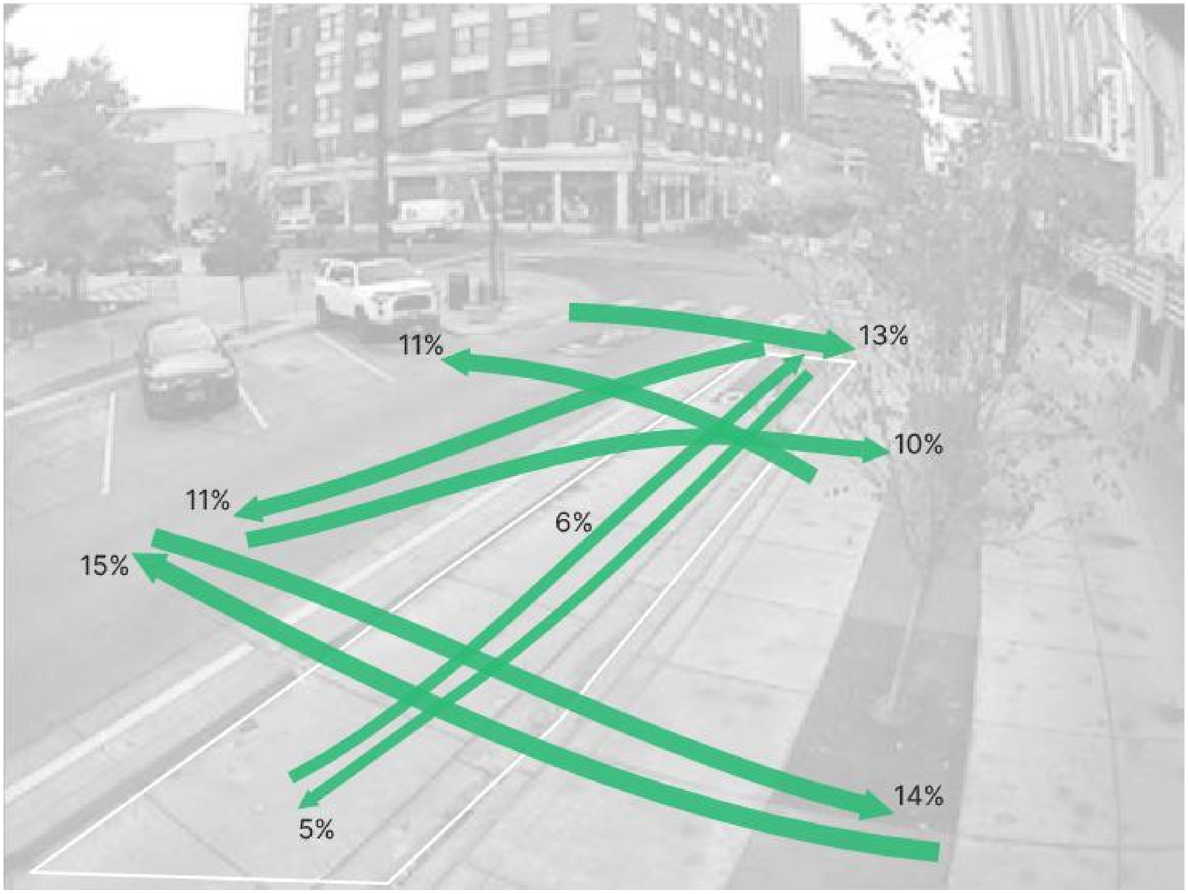


Figure 4.4 Pedestrian directionality percentages

The first notable observation is that a higher proportion of pedestrians crossed the streets by means other than the crosswalk. Six of the tracks took pedestrians across 8th street, with only one being a legal crosswalk. These six tracks accounted for 74 percent of the pedestrians captured on the West-1 sensor bike lane zone. Only 13 percent of pedestrians were identified in the crosswalk track, meaning that of pedestrians crossing the street, only about 17.5 percent of them did so by the desired (crosswalk) route. This outcome is not unexpected on a low volume road with street parking. This behavior is especially reasonable for a segment that is one way, because it means that pedestrians need to look only one way to identify cars and cross safely (aside from cyclists in the contraflow lane).

The second noteworthy takeaway from this analysis is the proportion of pedestrians who walked in the bike lane. Two of the tracks were enclosed entirely within the bike lane and accounted for 11 percent of pedestrians recorded in the bike lane zone of the West-1 Sensor. For the time that the sensors were in operation, the West 1 sensor had an average daily pedestrian count of 2,835. While this behavior may seem inconsequential on a low volume segment, the numbers mean that we could expect 312 pedestrians to walk in the bike lane rather than on the sidewalk. This does not present a major concern, but planners would prefer that designs be used as intended because the designs were made with safety in mind.

A similar analysis was done for cyclists traveling in the bike lane zone, and three tracks were identified from this analysis. These tracks and their percentages are shown in Figure 4.5.

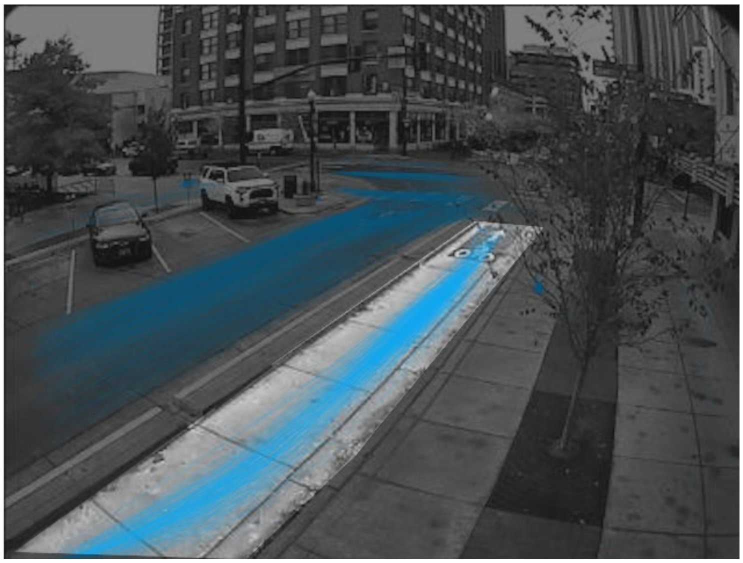


Figure 4.5 Paths used for bicycle custom analysis

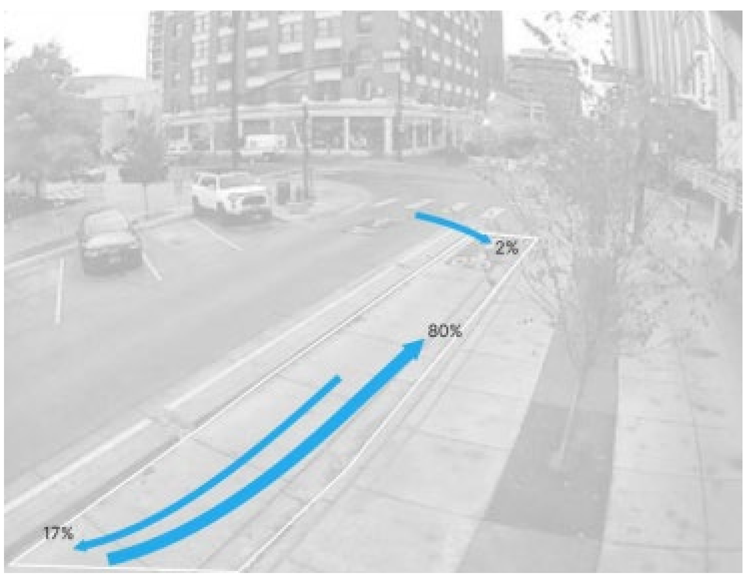


Figure 4.6 Bicycle directionality (West 1)

Farther north on the segment, using the West 2 sensor, a similar analysis was conducted to determine the directionality of cyclists in the bike lane. The results varied slightly between these two sensors, but each produced interesting insight into bicyclist behavior. The paths used to identify tracks and the subsequent tracks along with their percentages are shown in figures 4.7 and 4.8, respectively.

Figure 4.7 Paths used for bicycle custom analysis (West 2)

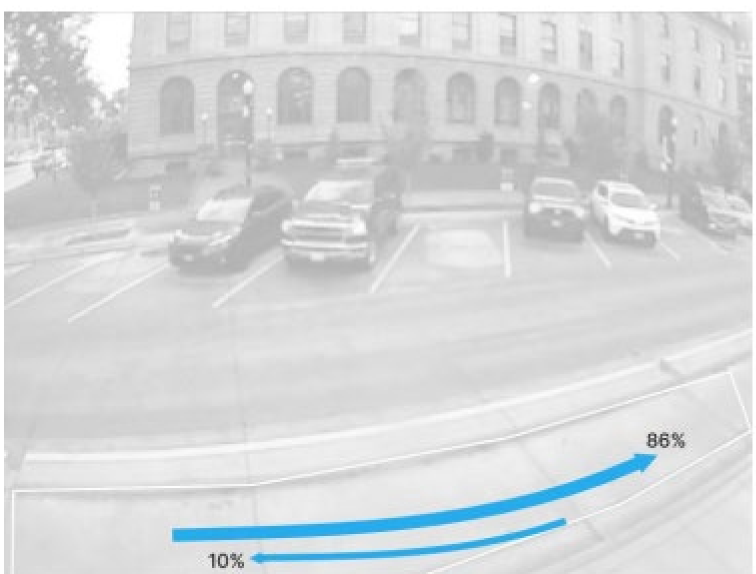


Figure 4.8 Bicycle directionality (West 2)

The average feed count for the duration of time that the sensors were operational on West 1 was 236. This means that if anywhere between 10 to 17 percent of cyclists rode the wrong way in the bike lane, then we could expect that 24 to 40 cyclists improperly used the bike lane each day. While this number is far from the total number of cyclists, improper usage of facilities is a cause for concern. It raises the issues of why the facilities are not being used as intended, as well as how city planners can encourage better compliance with their design expectations. It may be that a separated bike lane is more attractive to some cyclists even if they are biking against the designed direction of travel.

4.3 Weather Impact on Bicycling Location

The second analysis investigated bicyclist riding locations under varying weather conditions. Weather data were accessed via Python code from the National Centers for Environmental Information (NCEI). The intention behind this analysis was to determine whether facilities were still correctly being used in adverse weather conditions and to inform city planners about how the facilities should be maintained to promote bicyclist safety. The hypothesis for this analysis was that cyclists rode in the wrong direction because of the bike lane being separated because the bike lane was left unplowed.

For this analysis, we analyzed a 68-day window using data collected from the West 1 sensor. Counts from this sensor were compared for two different detection zones, which were identified as “Bike Lane” and “Street. These detection zones are pictured in figures 4.9 and 4.10, respectively.

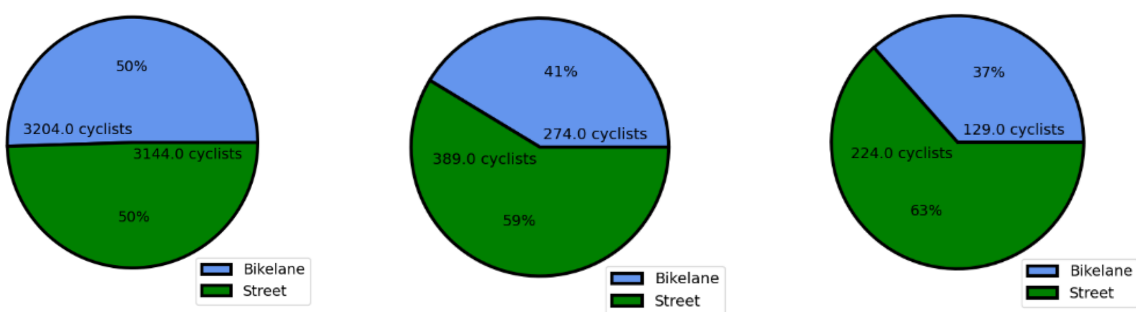
Figure 4.9 Bike lane detection zone

Figure 4.10 Street detection zone

Data from these detection zones for dates between December 1, 2022, and February 6, 2023, were integrated with data from the same date range collected at the Boise Airport weather station. Python code was utilized to flag days that fell into the following categories: Non-Precipitation, Precipitation, Snow, and Cold with Snow. Some days fell into multiple categories; for example a cold day with snow would concurrently be identified as a snow day and a precipitation day. Counts were then retrieved for each of these days and compiled for the Bike Lane and the Street zones. The results are displayed in Table 4.1, as well as visually in Figure 4.11

Table 4.1 Ridership locations based on weather

Weather	Counts		Percentages	
	Bike Lane	**Street**	**Bike Lane**	**Street**
All	3418	3593	48.8%	51.2%
Non-Precipitation	3204	3144	50.5%	49.5%
Precipitation	897	1005	47.2%	52.8%
Snow	274	389	41.3%	58.7%
Cold (<30 F) with Snow	129	224	36.5%	63.5%



(a) (b) (c)

Figure 4.11 Street vs bike lane ridership on days with (a) no precipitation, (b) snow, (c) cold and snow.

Table 4.1 and Figure 4.11 indicate that the proportion of cyclists utilizing the bike lane facilities on 8th Street decreased in adverse weather conditions. As was expected, the counts for days without precipitation were approximately equal, with a slightly higher proportion utilizing the bike lane. This balanced usage was expected because the intention of the geometric design was that northbound cyclists would ride in the street with vehicular traffic while southbound cyclists would use the separated bike lane. This balanced distribution indicated that cyclists likely used the street in this manner: riding in one location for their trip to work and the other for their return home.

Days with snow not only showed a decrease in ridership, with an average of 60 cyclists per day in comparison to the overall average of 103 cyclists per day, but also showed a shift in the proportions of cyclists detected in each zone. This trend indicated improper usage of the facilities, which presents a danger to cyclists riding the wrong way in the vehicular lane of travel. While the true cause is unknown, we hypothesize that cyclists experienced worse conditions in the uncleared bike lane and chose instead to take the risk of riding in the street. However, further work would be needed to rule out the possibility that selection bias drove this shift, i.e., that those who biked in the street were disproportionately likely to continue riding in adverse conditions.

A look at the geometry of this road segment shows that ordinary snow removal equipment was unable to plow and de-ice the protected bike lane because of the concrete barrier. Although this barrier was crucial for bicycle protection on ordinary days, it presented a hazard by preventing snowplows from reaching the bike lane. It is our belief that cyclists chose to ride in the plowed street rather than the slick and slushy bike lane when making southbound trips, which shifted the proportions to just 41 percent bike lane ridership on snowy days and only 37 percent on days that had both snow and an average temperature of less than 30 F.

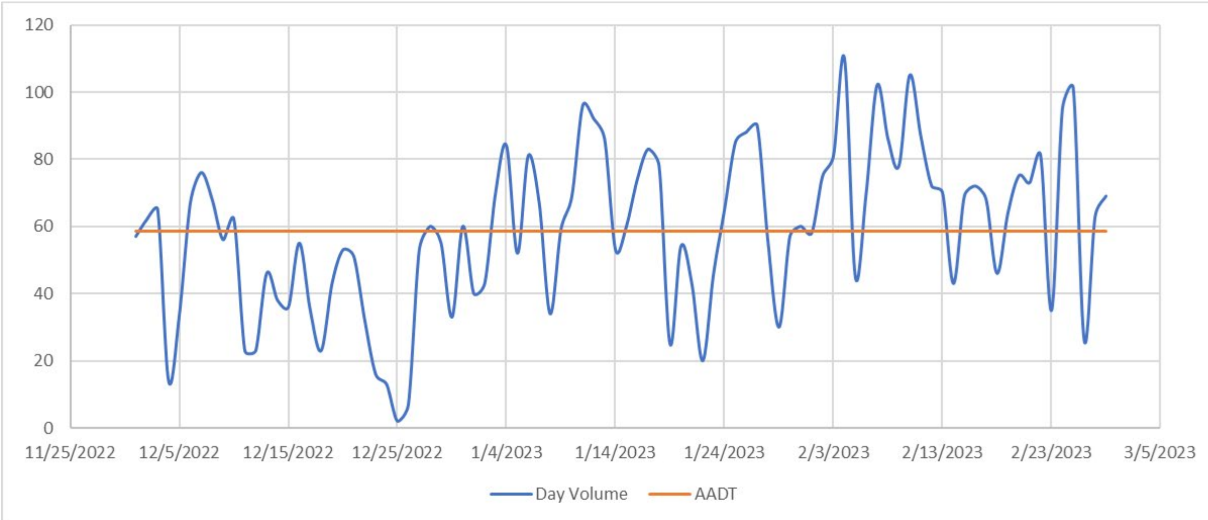
One could argue that these trends were of no concern and would have no impact on bicycle safety. After all, cyclists often ride within the lanes of traffic and behave as vehicles. However, while this is typically true, cyclists do not ordinarily do this on one-way streets such as 8th Street. The data suggested that this is what was happening on snowy days as cyclists rode in the single opposing lane of traffic to travel southbound. These trends highlight the importance of proper bike lane maintenance, especially in communities that wish to encourage cycling as a commuter alternative.

4.4 Bicycle and Pedestrian Count Models

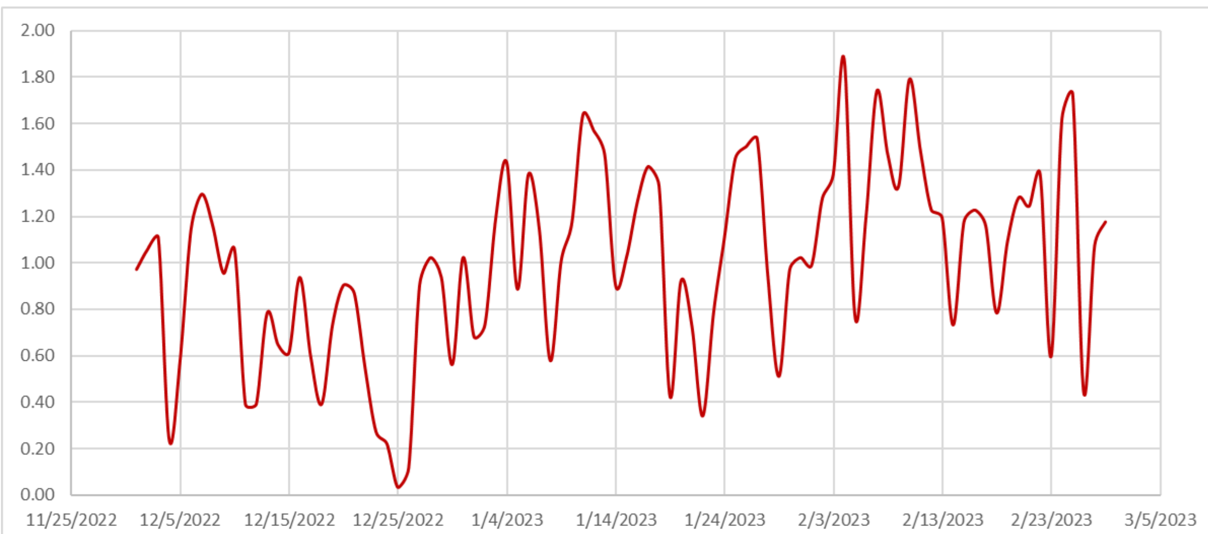
The third analysis focused on creating a model to predict bicycle ridership based on weather conditions and the day of the week. The model provides planners with a tool to forecast demand for bike facilities and estimate ridership fluctuations. This analysis aimed to identify how factors such as weather and day of the week affect bicycle and pedestrian counts and to create a model to predict these counts. This analysis also used data from the West 1 sensor and specifically analyzed data from this sensor's screen line, shown below in Figure 4.12.

Figure 4.12 Screen line for bicycle and pedestrian volume counts

Daily volumes for this screen line were collected over a three-month period, from December 2022 to February 2023, after the correction of the Numina system's initial overcounting of pedestrians. An average of these counts was calculated and plotted with each day's counts to demonstrate fluctuations from this average over time. This is shown in Figure 4.13a. Next, each day was divided by the average to develop a day factor that would indicate what percentage of the average was present on a particular day. These day factors are plotted in Figure 4.13b and were the variable predicted by our model. This was done with the hope of being able to transfer the model to other locations within the same range of climatic conditions.



(a)



(b)

Figure 4.13 Bicycle daily (a) volume and (b) day factor

Figure 4.13 shows fluctuation around an average of 59 cyclists per day, with a range of between two and 110 cyclists. A Python script was written to identify the day of the week, precipitation, temperature, and wind for each day. These data were used to do multiple linear regression and create models for predicting the day factor. Various configurations of variables were used, including ones that distinguished between weekdays and weekends, whereas others identified each day separately. Finally, the model in Table 4.2 was selected.

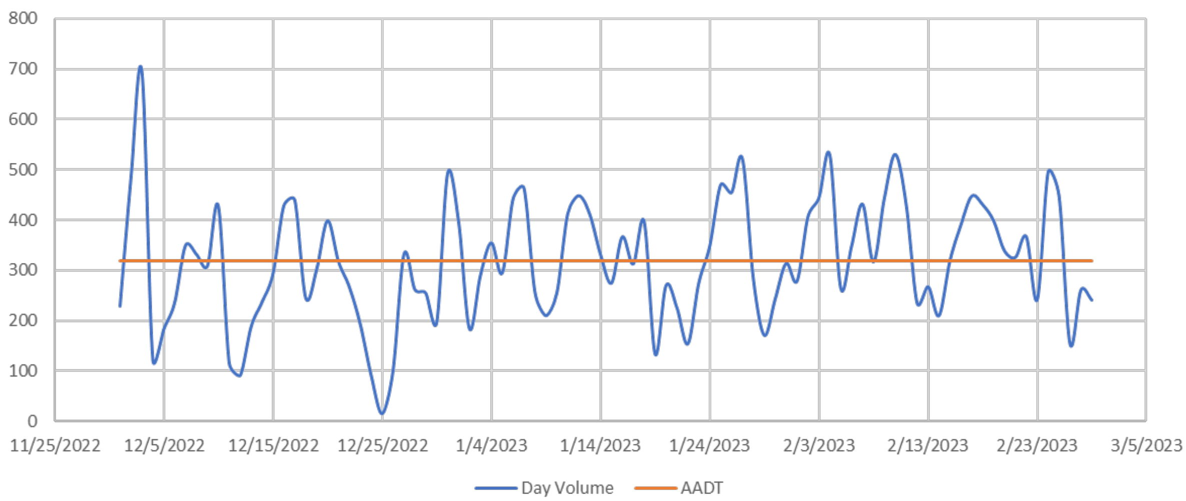
Table 4.2 Bicycle volume prediction model

Variable	Coefficient	P-value
const	-0.16	0.33
avg_temp	0.03	0.00
precip_ind	-0.37	0.00
monday	0.31	0.01
tuesday	0.55	0.00
wednesday	0.54	0.00
thursday	0.47	0.00
friday	0.63	0.00
saturday	0.49	0.00
wind	-0.02	0.086

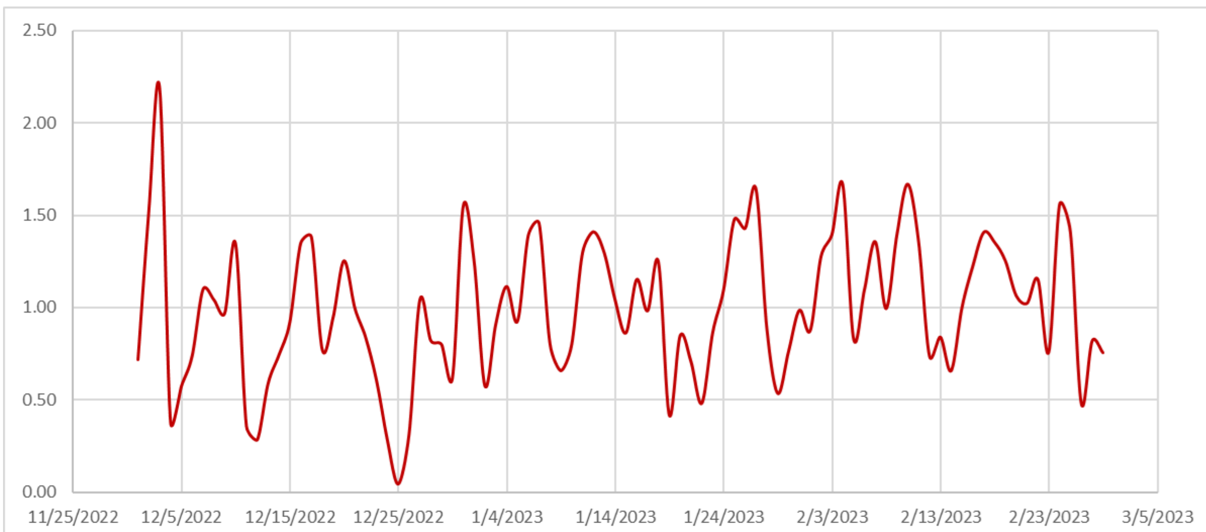
Our bicyclist prediction model had a fairly good fit, with an adjusted R-Squared of 0.52. Its coefficients showed trends that were expected, such as increased ridership on days without precipitation and a positive relationship between temperature and bicyclist counts. We were also able to identify which day had the highest ridership, which was Friday, and which day had the lowest ridership, which was Sunday. Each of the variables was found to be statistically significant at the 0.1 level.

We followed the same process for pedestrians. This highlighted the usefulness of the Numina sensors in distinguishing among different roadway users, as well as the benefit of our Python code, which allowed us to synthesize the large amounts of data in a short amount of time. The counts and day factors are displayed in Figure 4.14. As expected, the sensor recorded a much higher number of pedestrians, but the same principles were applied in creating a model that would predict proportions of the average for given conditions.

A model similar to the one that was made for cyclists was created for pedestrian counts. The notable difference was the exclusion of wind as a variable for pedestrian counts. This variable was removed because it had a high P-value. The coefficients and P-values for this model are shown in Table 4.3.



(a)



(b)

Figure 4.14 Pedestrian daily (a) volume and (b) day factor

Figure 4.14 shows fluctuation around an average of 318 pedestrians per day, with a range of between 15 and 695 pedestrians. The pedestrian model had a slightly worse fit, with an adjusted R-Squared of 0.50. It did show trends similar to those of the bike model, with precipitation having a negative effect on pedestrian counts, increased temperature resulting in higher counts, and Friday having high counts. Precipitation was shown to have a more drastic impact on pedestrian counts than on bicyclist counts, whereas temperature had less impact than in the bicyclist model.

Table 4.3 Pedestrian volume prediction model

Variable	Coefficient	P-value
const	0.34	0.03
avg_temp	0.01	0.00
precip_ind	-0.40	0.00
monday	0.09	0.42
tuesday	0.25	0.02
wednesday	0.27	0.02
thursday	0.32	0.00
friday	0.60	0.00
saturday	0.61	0.00

4.5 Summary

In summary, three analyses were conducted with the Numina sensors to provide examples of how computer vision technology can be helpful for traffic monitoring and infrastructure planning. First, we looked at wrong-way riding and jaywalking through a custom directionality analysis to identify how often cyclists and pedestrians misused facilities. This analysis revealed that pedestrians frequently crossed the street in locations other than the designated crosswalk and that cyclists rode in the wrong direction to a greater extent than designers had likely anticipated.

The second analysis involved integrating weather data and using a Python script to compare the proportions of ridership locations between baseline and adverse weather conditions. Counts were compared between the bike lane and street for days with precipitation, snow, and cold temperatures. The proportions for these days revealed a decline in bike lane ridership proportion on days with unfavorable weather conditions. This decline might have been due to an inability of the city to operate snowplows in the bike lane, creating unideal cycling surfaces.

For the third analysis, we created bicyclist and pedestrian prediction models to inform planners about the proportion of the mean they can expect based on given weather conditions and day of the week. These models reinforced assumptions about how weather affects pedestrian and bicyclist counts, and they allowed us to quantify the extent to which the weather did so. Creating such models will help jurisdictions make informed decisions and will help engineers develop new solutions. This study was constrained by a short, 3.5-month timeframe. Future work should seek to develop demand models with a full year of data. Furthermore, the modeling would be improved by employing time series regression techniques.

CHAPTER 5. CONCLUSION

5.1. Findings and Lessons Learned

The key findings from this work fall into in four categories.

5.1.1 Computer Vision Systems

- Computer vision systems for tracking street use by pedestrians, cyclists, and cars are a promising but evolving technology. Public owners of streets and sidewalks and their design teams need to approach the claims of computer vision vendors with some skepticism and put performance guarantees into contracts.
- The ability to analyze pathways and counts at different screen lines within the camera's field of view can enable new types of analyses.
- The cost of deploying these systems is higher than that of conventional tube counters, but they generate much more data and can therefore answer heretofore difficult to address questions about street and pathway use. Over longer periods of analysis the unit costs of the data will fall.

5.1.2 Bikeway Path Design and Maintenance

- Placing a curb-protected bike lane for bike traffic in one direction across from a shared car and bike lane traveling in the opposite direction will invite some cyclists to travel in the curb-protected bike lane in the wrong direction.
- Failure to keep bikeways clear of snow and ice will force winter cyclists into the street that has been plowed.

5.1.3 Traffic Calming and Pedestrian Enhancements

- More than half of the pedestrian traffic that crossed 8th Street walked outside the crosswalk.
- This could be viewed as a success of the new street design because it reduced car traffic to a single lane going in one direction and reduced speeds with curb extensions and back-in parking, all of which made pedestrians feel safe to cross outside the crosswalk.
- However, walking outside the crosswalk creates the potential for unexpected conflicts between pedestrians and cars and between pedestrians and cyclists.

5.1.4 Pedestrian and Cyclist Use by Day of Week and Weather

- Friday was the peak day for cyclists, and warmer temperatures correlated with higher ridership, even in winter.
- Estimates of daily use of facilities by cyclists and pedestrians are amenable to modeling by using the large data sets created with computer visions systems.

5.2. Research Limitations and Future Research

Like other automated systems, including pneumatic counters, the Numina sensors required careful validation of their output. Because of problems in the classification algorithms initially used by Numina, the team had to apply corrections to the early months of data with help from Numina staff. We view this project as an early application of an emerging technology. More work needs to be done to validate the data output of these systems in different settings over time. As the data output improves, so will the strengths of the models and the conclusions that urban designers can draw from the results.

Several areas present opportunities for future research:

- Research can investigate the use of computer vision systems to develop counts of crash-near-misses and the application of these results to setting investment priorities in addition to data on actual crashes.
- Research can investigate the use of computer vision systems to measure speeds of vehicles and cyclists to identify areas for future enforcement or design changes.
- Ex-ante evaluation of streetscape use can be conducted to develop design ideas in project development, followed by ex-post evaluation of a completed projects to determine how well the actual use of the new project met the design objectives.
- Future work should seek to benchmark the computer vision results with other technologies, such as Lidar- or Bluetooth-based solutions.
- This study was constrained by a short, 3.5-month timeframe. Future work should seek to develop demand models with a full year of data. Furthermore, the modeling would be improved by employing time series regression techniques.

Improvements in the application of machine-learning algorithms to process images from pole-mounted cameras and their deployment in real-world applications hold promise for informing and improving street design for all users.

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APPENDIX A: PRACTITIONER’S GUIDE TO COMPUTER VISION SYSTEMS FOR EVALUATING THE USE OF URBAN STREETS

APPENDIX B: PYTHON WRAPPER FOR NUMINA API

Link to Python code.