

Leveraging Advanced Data to Deliver Multimodal Safety (LADDMS)

Stage 1 Implementation Report

Recipient name: Nashville Department of Transportation and Multimodal Infrastructure

Fiscal year of award: FY 2022

Period of performance: August 15, 2023 – February 15, 2025

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Executive Summary

The Leveraging Advanced Data to Deliver Multimodal Safety (LADDMS) Project, led by the Nashville Department of Transportation and Multimodal Infrastructure in Nashville, TN, provides protection for vulnerable road users and improves traffic efficiency. The approach utilizes privacy-preserving light detection and ranging (Lidar) sensors, which are paired with software package that permit real-time visualization of intersections, real-time detection of near-misses on the road network, and archived data capture in order to provide analytics to evaluate interventions that are aimed at improving road safety.

The project has exceeded the expectations of the Stage I grant application, through live visualization, live detection of dangerous scenarios, and the back-end data analytics that support rapid evaluation of the effectiveness of safety interventions. The project promises to transform how Nashville implements its Vision Zero Action Plan.

1. **Costs vs. benefits and savings** at scale, is approx. 1:4 (cost to benefit). Benefits are calculated using USDOT monetized values (by crash type) with conservative estimates of crash reductions based on other published Vision Zero interventions.
2. **Expectations were met or exceeded**, including community engagement (2 community events, 98 submitted surveys, ride-along/walk-along interviews), workforce development (26 staff trained), installation and continuous operation of sensors (13 sensors installed across 8 locations, 99.97% uptime), operation ahead of schedule (within 11 months rather than 15 months), collection of 90 days of data, and implementation of at least 2 interventions. The project exceeded original goals with a real-time viewer (running within seconds of each sensor install), integration with public transit schedules, and use of specialized vehicles and dedicated validation experiments to estimate accuracy of the sensors.
3. **Performance measurement data:** We performed two different classes of interventions (1) to reduce unsafe midblock crossing of pedestrians (**75% reduction at a dangerous point**, some midblock crossings moved to a less dangerous point), and (2) to reduce speeding (a **26-30% reduction**). We had preliminary results for each within 24 hours. We detected **6.1 near-misses/day**, (84-day average). The lidar sensors met or exceeded expectations on 12 metrics that our team evaluated.
4. **An at-scale implementation is feasible.** The corridor has the networking, power, and existing poles on which to mount sensors, streamlining environmental impact studies. Data storage/servers can accommodate the at scale implementation.
5. **The Stage I deployment was successful by every proposed metric**, data support the continued use of community input on privacy-preserving sensors. If recommended for award in Stage 2, all anticipated challenges have mitigation plans for continued maintenance and operations.
6. **Lessons learned** include direct coordination with equipment providers for procurement, use of locations already in the right-of-way, and the potential for transit impact based on automated bus recognition with sensors and integration with live transit data, as part of the potential expansion of Nashville's Rapid Transit system.

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Part 1 of 6: Introduction and Project Overview

Project description

Summary

The *Leveraging Advanced Data to Deliver Multimodal Safety* (LADDMS) initiative introduces an innovative approach to enhance road safety using cutting-edge sensor technology. Unlike traditional crash reporting methods, LADDMS focuses on identifying and addressing safety concerns that might otherwise go unnoticed while preserving community privacy.

Our primary goal is to protect the most vulnerable road users such as pedestrians and cyclists. By deploying *light detection and ranging* (lidar) sensors, our Stage I project demonstrated how the *Nashville Department of Transportation and Multi-modal Infrastructure* (NDOT) can identify and rectify safety issues that traditional crash reports may overlook. This data-driven strategy allows us to pinpoint specific areas of concern and implement targeted solutions to enhance safety for all. The power of the data becomes most evident when observed in real-time, as illustrated in Figure 1, demonstrated at NDOT's traffic management center in Figure 2 , and shown on a wearable device in Figure 3.

The near-miss data collected from the technologies in NDOT's Smart Grant project enables transportation professionals to proactively deploy safety improvements before incidents occur.

~ Diana Alarcon, NDOT Director

During our Stage I grant, we successfully prototyped the following initiatives: 1) **lidar sensors to count vulnerable road users and vehicles**, 2) **measurement of near-miss events**, and 3) the **quick response and evaluation of safety interventions from NDOT's Vision Zero Action Plan**.

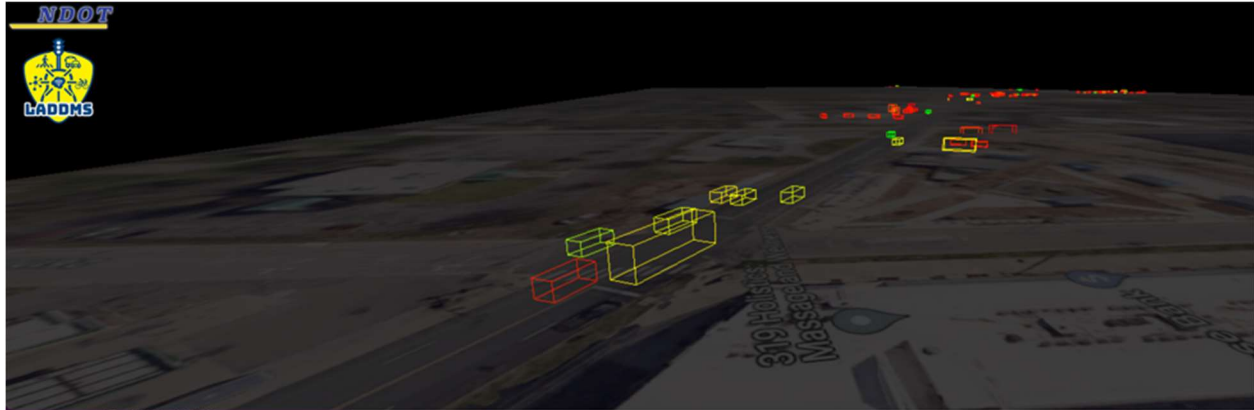


Figure 1 To appreciate the power of lidar data, please visit the live LADDMS viewer at <http://ndot-laddms.mogi.io> to see real-time information from our Stage I project.

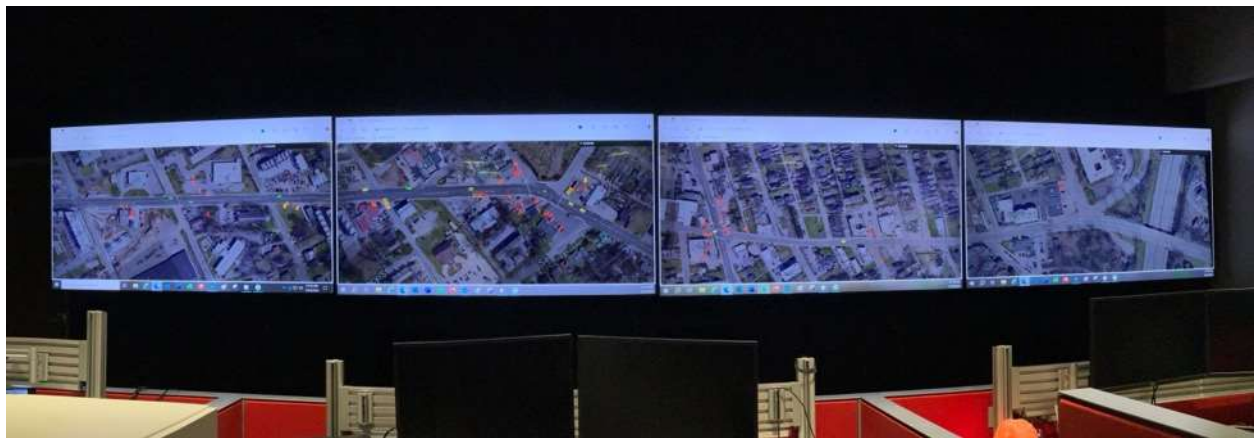


Figure 2 The LADDMS live view is integrated into the Nashville DOT Traffic Management Center as of July 25, 2024.

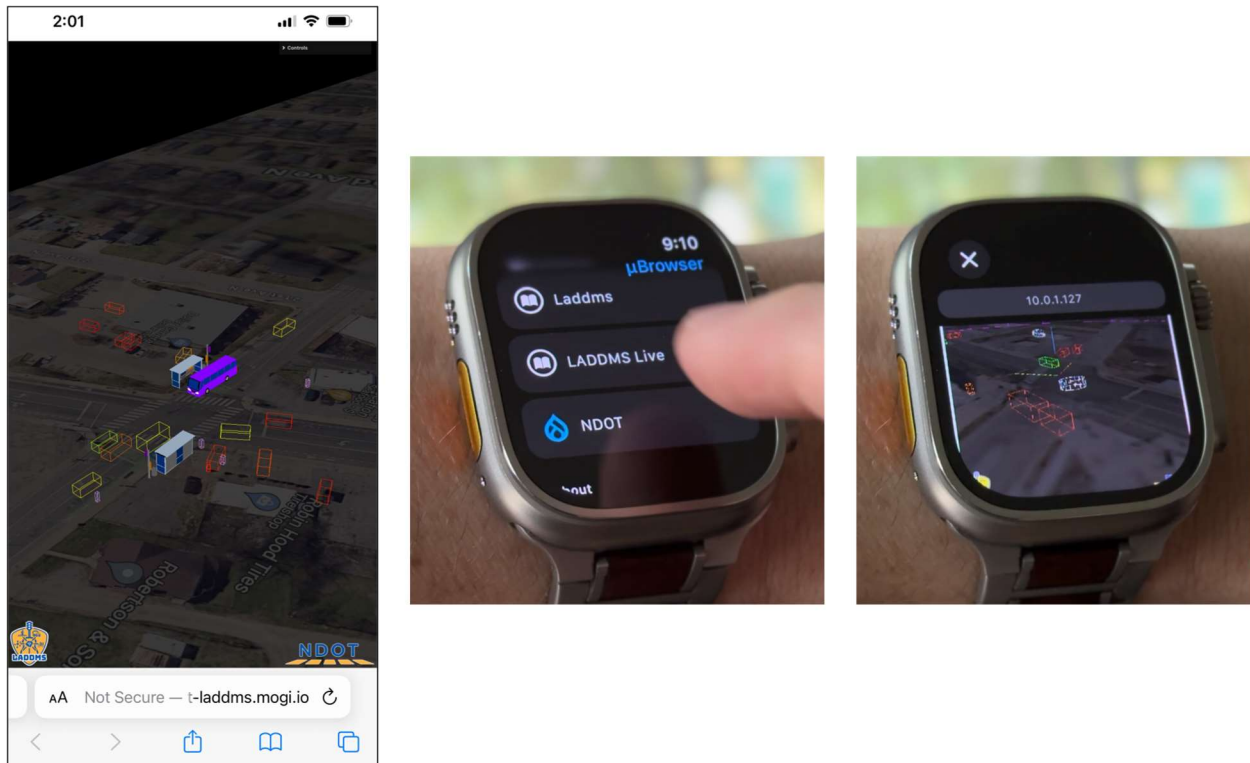


Figure 3. The LADDMS live view is also accessible on phones (left) and wearables (middle, right) as of July 27, 2024.

In Stage II of our project, we are focusing on implementing the technology at-scale along the Nolensville Pike corridor (I-24 to Harding Pl) while expanding our installation in North Nashville.

LADDMS is led by NDOT and supported by Metro Information Technology Services (Metro ITS), Tennessee State University, University of Tennessee Chattanooga, Vanderbilt University, Ouster, and Tennessee Department of Transportation (TDOT).

Real world issues

Currently, NDOT relies on crash reports from the Nashville Police Department, which are infrequent data points and often lack the detailed information necessary for thorough safety analysis. Moreover, it is estimated that 44-75% of pedestrian crashes and 7-46% of bicyclist crashes are not reported. Additionally, there is no established method for tracking “near-misses” involving pedestrians or cyclists.

Under-reporting of collisions involving pedestrians and mobility-impaired individuals, combined with traditional crash reporting methods, has created significant gaps in understanding the links between pedestrian safety and data accountability.

This project addresses these challenges by leveraging advanced technology to create a safer environment for Nashville's citizens. By identifying conflict points between vehicles and vulnerable road users within the studied area, we aim to provide comprehensive data that enhances safety measures for pedestrians and cyclists.

Geographic area

Stage I

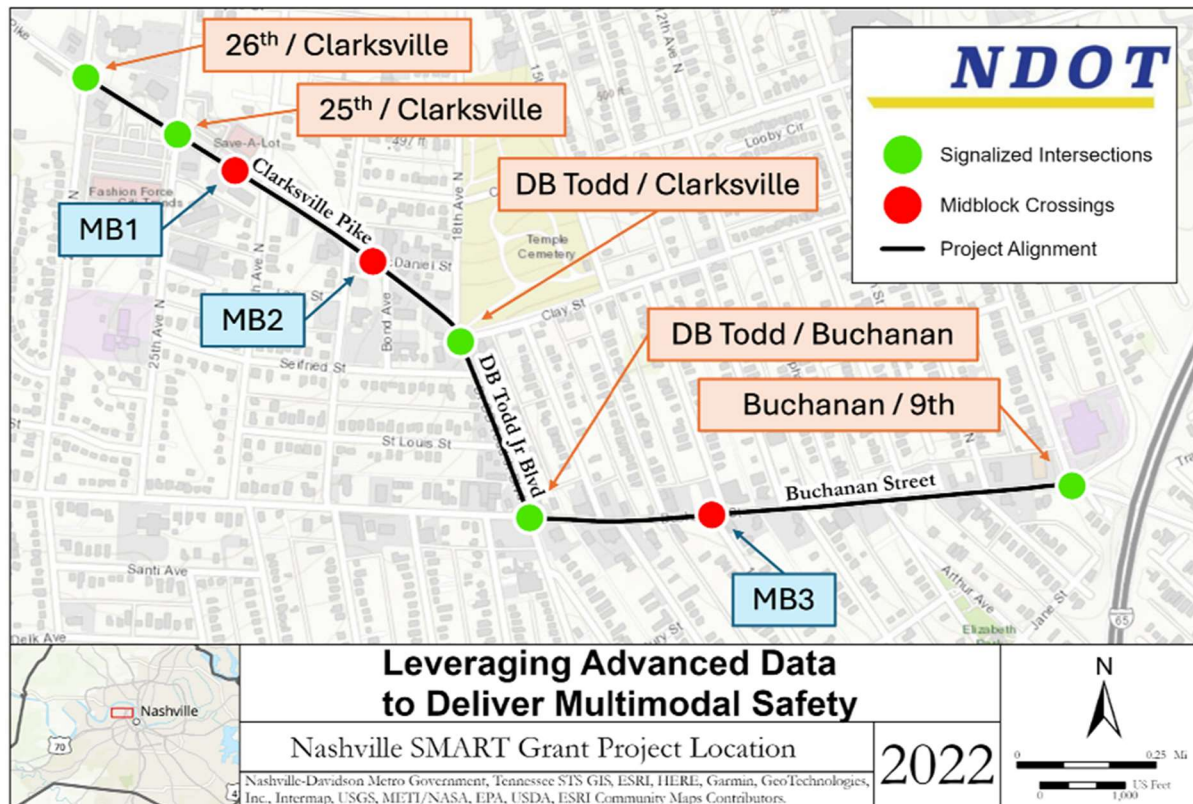


Figure 4 Stage 1 location in North Nashville includes 5 signalized intersections (green) and 3 mid-block crossings (red).

The Stage I project is conducted in North Nashville. Sensors will be located on Clarksville Pike, Dr. DB Todd Blvd., and Buchanan Street. See Figure 4 for a project map for Stage I.

The stage 1 project location is within Davidson County, Tennessee in the subarea of North Nashville and straddles the communities of Cumberland Gardens, Buena Vista Heights, Jones Buena Vista, and Elisabeth Park. The project corridor is roughly 2 miles from the downtown Nashville urban core with predominately single- and multi-family residential housing and commercial businesses. The roughly 2-mile project corridor starts at the intersection of Clarksville Pike and 26th Avenue North and travels southeast along Clarksville Pike to Dr. D.B. Todd Junior Boulevard. The project corridor then turns east onto

Buchanan Street and ends at the intersection of Buchanan and 9th Street North. There are existing fiber optic lines beneath these streets that will be utilized for this project.

In 2016, the US Department of Housing and Urban Development (HUD) assigned Nashville a Promise Zone designation, which encompasses the North Nashville neighborhood where our project is located. According to the [Metro Nashville Development and Housing Agency](#), “[Nashville Promise Zone] residents face ... infrastructure and safety concerns that make upward mobility, affordable housing and employment more difficult to obtain.” The mission of the Nashville Promise Zone is to foster intensive partnerships among Nashville’s organizations that serve high poverty neighborhoods, improve the collective impact of their service, and address revitalization in a collaborative way.

The project corridor has five signalized intersections and three midblock crossing locations (See Figure 4). On the project location map legend at right, green circles indicate intersections and red circles indicate mid-block crossings. The installation of our first intersection, located at 26th Ave and Clarksville Pike, is seen in Figure 5 and Figure 6. The North Nashville area is a midsized, urban part of the greater Nashville Metropolitan area. An area of interest within or adjacent to the project corridor is a large Nashville Metropolitan Development and Housing Agency residential area. Other notable corridor locations include the local Save-A-Lot grocery store at the corner of Clarksville Pike and 24th Street that serves as a community anchor, Temple Cemetery sites at the tri-corner of Clarksville Pike, 18th Avenue North, and Clay Street, and Jones Paideia Elementary Magnet School at the end of the project corridor.

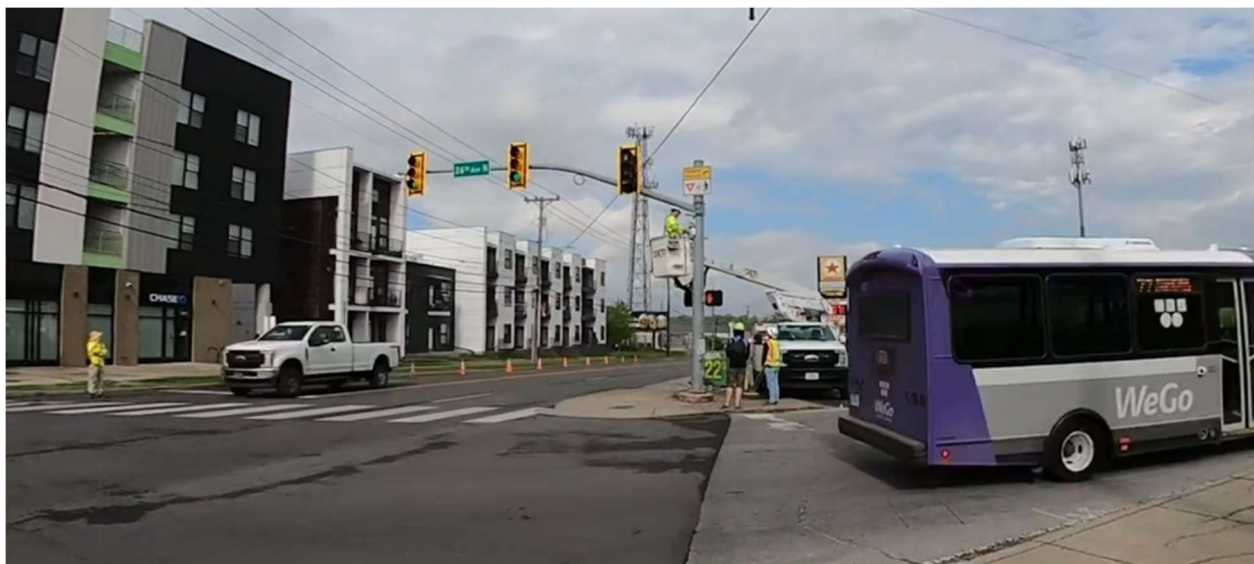


Figure 5 Photo from the Stage 1 installation at 26th Ave. and Clarksville Pike. The sensor is pole mounted with a bucket truck.



Figure 6 Detail of lidar sensor installation from Stage 1 intersection 26th Ave. And Clarksville Pike. The sensor and its power adapter are circled in red.

At scale implementation

In preparation for an at scale implementation, we have led a comprehensive analysis of our transportation network. Specifically, we performed a GIS analysis of our intersections and the high injury network to determine the optimal location for a full-scale implementation. We considered the following factors in the analysis:

- Locations within the High Injury network. We excluded corridors that are not located on the high injury network.
- Average annual daily traffic. We prioritized locations with more than 20,000 vehicles per day.
- Locations with pedestrian crashes. Within the high injury network, we prioritized locations with fatal crashes and pedestrian crashes
- Number of WeGo public transit bus stops. We prioritized locations near WeGo bus stops and further prioritized locations with more than one bus stop nearby.
- Opportunity Zones. We prioritized locations within local Opportunity Zones set out by USDOT and the State of Tennessee.
- Communications network. We considered the current communications network and planned upgrades to it (e.g., fiber upgrades and network architecture upgrades that improve network security and data availability).

Based on these factors, we selected the Nolensville Pike community, another area with a

highly multimodal transportation landscape that is in significant need of safety study and improvement (See the Appendix 2022 Nolensville Pike Study). Figure 7 shows the full-scale implementation and the breakdown of the mid-block and intersection install locations. Importantly, many of the crashes involving vulnerable road users on this network occur at mid-block locations, which is why we have elected to significantly expand our focus on these areas along the corridors.



Figure 7 Stage 1 (orange) and proposed full scale implementation (blue & purple). Top shows the North Nashville installations (current and proposed). Bottom shows the Nolensville Pike proposed installations.

Deployed technology

Keywords: intelligent sensor-based infrastructure, systems integration, smart technology traffic signals

The original project envisioned using lidar and video to identify safety issues outside of traditional crash reports. As the project matured, the LADDMS team took into account community feedback to eliminate the use of video due to potential privacy concerns.

LADDMS exclusively uses lidar sensors to detect and count vulnerable road users and vehicles. The sensors are connected to an edge computer that automatically converts the raw data into trajectories of road users (Figure 8, Figure 9). These trajectories are

continuously processed to provide high quality counts and near-misses between vehicles and vulnerable road users in real-time.

The specific setup uses Ouster lidar sensors. A complete install includes two 128 channel lidar units and an edge compute device that processes the lidar data into anonymous trajectories.

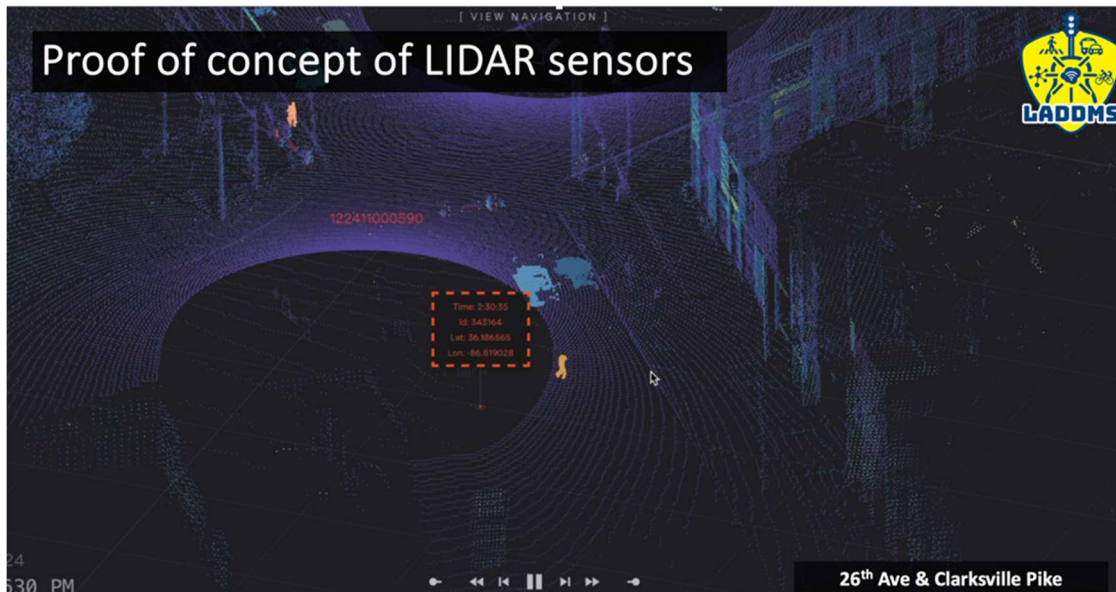


Figure 8 Illustration of the deployed technology. Complete point cloud of lidar install from 26th Ave. and Clarksville Pike. Two pedestrians (orange) and two vehicles (light blue) are visible, including one pedestrian crossing behind two moving vehicles.

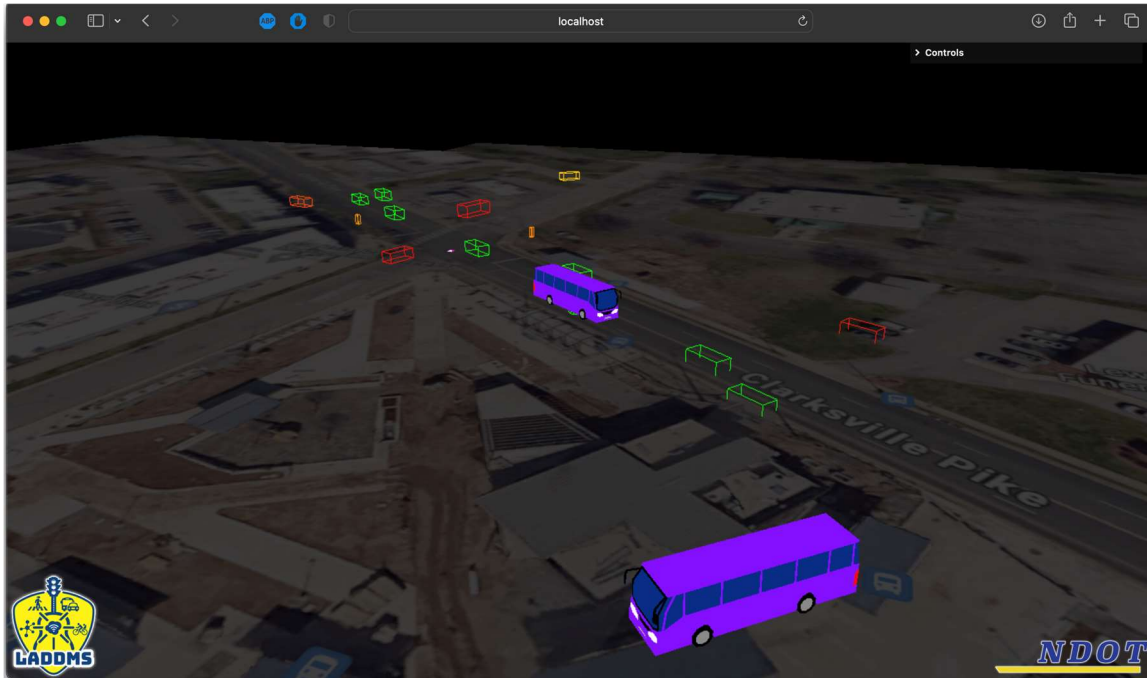


Figure 9 Screen shot of the LADDMS live viewer which displays vehicles color coded by the speed of travel. The raw point clouds are not stored, but the bounding boxes are permanently retained for data analysis and project evaluation. Busses are also automatically detected and rendered in the color (purple) of our local transit agency, WeGo.

Stage II Goals and outcomes

Our Stage II goal is to set the standard for safe operation of corridors for all road users through targeted Vision Zero interventions. The desired outcomes are:

Deployment and Community Impact. Our Stage II lidar deployment will observe 45,000,000 vehicle miles of travel annually on the Nolensville Pike Corridor, which is on the High Injury Network. Over the past five years, this corridor has experienced 48 serious injury or fatality crashes, including 18 involving pedestrians. The corridor is scheduled for Vision Zero interventions – examples include new pedestrian signals, curb modifications, high-visibility crosswalks, and lighting improvements, to name a few – which will be informed and validated through rigorous data analysis in Stage II.

Real-time Vulnerable Road User Counts. By collecting continuous count data on vulnerable road users, we will uncover usage patterns and trends which will improve our ability to understand the root causes of crashes and the effectiveness of proposed and deployed interventions.

Transformative Safety Analytics: LADDMS will provide advanced safety analytics. Based on preliminary data from Stage I, we anticipate identifying 180 near-miss events per day, with post-encroachment times of less than one second.

Community Engagement: Building on the insights gained from Stage I, fostering collaboration with the community is essential for effective community outreach and engagement, ultimately ensuring that we address local needs and fulfill community expectations.

Workforce Development: We will expand our training programs by partnering with new agencies outside of middle Tennessee that have not previously used lidar. Our collaborators, Nabco and Stansell Electric Company, will assist us in scaling our training programs. Our university partners will provide traffic operations staff with the knowledge to utilize this technology. Dissemination through organizations like ITE, ITS Tennessee, and ITS America will further support our workforce development goals.

Our project also aligns directly with the SMART Grant program goals as outlined next.

Safety

Improve the safety of the transportation network for all roadway users with increased focus on pedestrians, bicyclists, and other vulnerable users, and improve emergency response.

- Goal: Expand Safety Measures. Implement advanced safety measures on a larger scale, covering additional neighborhood segments in North Nashville and in the Nolensville Pike Corridor, consisting of Nolensville Pike and Harding Place.
- Goal: Protect Vulnerable Users. The project's technological innovations seek to reduce the frequency and severity of crashes to more closely protect pedestrians, bicyclists, and other vulnerable users such as mobility-impaired individuals, students, and individuals experiencing homelessness. Vehicle speeding, lack of multimodal infrastructure, and poor lighting conditions in the area have put heavier safety burdens on non-vehicular roadway users. We also hope to increase the safety and accessibility of the streets by coordinating service improvements with WeGo and engaging the school staff to better understand issues and problem hot spots.
- Goal: Support Vision Zero. Align with the city's Vision Zero Implementation Plan to create safer transportation environments and reduce the frequency and severity of crashes.
- Goal: Improve Crash Data Collection and Quality. Ensure that the safety data collected are of high quality and emphasize capturing near-misses and other safety data of pedestrians and multimodal users.
- Goal: Analyze and Assess. Analyze the collected data to identify traffic safety issues and recommend countermeasures. Assess the impact of existing and new countermeasures on all road users, as well as the overall efficiency (e.g., travel time reliability) and modal usage distribution of the corridor.

Reliability

Increase the reliability and resiliency of the transportation system, including data management and security.

- Goal: Improve Travel Time Reliability. Assessing the travel time reliability and signal system efficiency through the use of lidar along the corridor provides the opportunity to make improvements that will reduce frustrating conditions such as stop and go driving and idling along the corridor, thus improving travel time reliability and livability for residents.
- Goal: Improve Reliability of the Transportation Infrastructure. Better integrate existing smart technologies and infrastructure with proposed LiDAR and other technologies. For example, NDOT's TMC will be able to more easily collect and monitor these near-misses to dispatch emergency response or other information to keep the transportation network connected and responsive.
- Goal: Improve Cybersecurity. Implement measures to protect transportation infrastructure from cyber threats, ensuring system reliability and data security.

Partnerships

- Goal: Effectively Engage Community. NDOT will host two (2) in-person public survey events at minority owned businesses along the project corridor in the first quarter of the Stage II grant, following our successful model in Stage I. Staff will be on-site to explain to guests the purpose and need of the project and facilitate a mapping exercise where attendees can provide input. Staff will also be riding the WeGo buses on the local route to solicit feedback from riders. Our Stage I activities demonstrated that we can learn from those who live, travel, work, play, and visit the community to more effectively deliver a valuable community project.
- Goal: Foster Collaborations with the Private Sector. NDOT will hire local contractor for procurement and deployment of lidar detection technology. LADDMS university partners work closely with Ouster (lidar manufacturer) on their hardware, software, and data products.
- Goal: Demonstrate Leadership and Organizational Capacity. The contractor will be requested to help explain purpose and need of devices to students and community members during installation. NDOT hopes to have at least 20 students and 10 community members to witness installation of devices that will be affecting their community. NDOT and TSU leadership (with assistance from Vanderbilt) will facilitate the execution of this goal, which is also outlined in the Workforce Development Plan.

Integration

- Goal: Safety and Technology Expansion. Identify and select key intersections and mid-block segments for at-scale implementation. The installed LiDAR devices at the selected locations will gather and deliver real-time traffic data that can communicate with NDOT's

TMC. We will also explore communicating near-miss data into state level databases to improve safety decision-making.

- Goal: Improve EMS Response and Preparedness. Develop a seamlessly integrated transportation ecosystem that can connect and communicate with existing ITS infrastructure to inform decision-making and more quickly and effectively dispatch services to where needed. The installed LiDAR will connect to NDOT's existing ITS network and be monitored from the TMC, located at their offices downtown.
- Goal: Improvement of Transportation System Status Quo. The project will support NDOT's priorities, including expanding the smart infrastructure network, addressing near-misses, and enhancing data collection for user counts and safety analysis. Collaboration with multiple stakeholders will ensure data consistency and transparency.

Workforce development

- Goal: Increase Knowledge and Skills. Develop a workforce training program with area electricians. Develop and implement hands on training to prepare workers for new technologies that will improve safety of transportation systems.
- Goal: Increase Collaboration Between University Research and NDOT Staff. The project team will host technical exchanges on emerging research and practical application areas.

Community impact

The Stage II proposal builds upon the successful Stage I deployment in the North Nashville community and expands to the Nolensville Pike community, another area with a highly multimodal transportation landscape that is in significant need of safety study and improvement (Figure 10).



Figure 10 Nolensville Pike, a Stage II LADDMS location, shows pedestrian risks.

Prior to implementation the project team began direct community engagement activities aimed at gathering input on vulnerable road users, both within North Nashville (see our Stage I activities reported later), and at our proposed Stage II location along Nolensville Pike. A recent public survey gathered community feedback from 580 people along Nolensville Pike. Key findings are: 79% of people feel uncomfortable or very uncomfortable biking, and 66% feel uncomfortable or very uncomfortable walking.

To support the analysis and site selection, we analyzed all crashes on the proposed installation locations (Crash data obtained from Metro Police Department). We further overlaid the analysis with the range of lidar units deployed in Stage I (80 m). Between Jan. 1, 2023, and July 17, 2024, there were 1,935 property, injury and fatal crashes located in the field of view of the proposed sensors. This includes 630 injuries and 12 fatalities. Pedestrians were involved in 39 of the crashes resulting in 4 fatalities. These qualifications and risk factors have led to the designation in the Nashville High Injury Network for 100% of the project roadways.

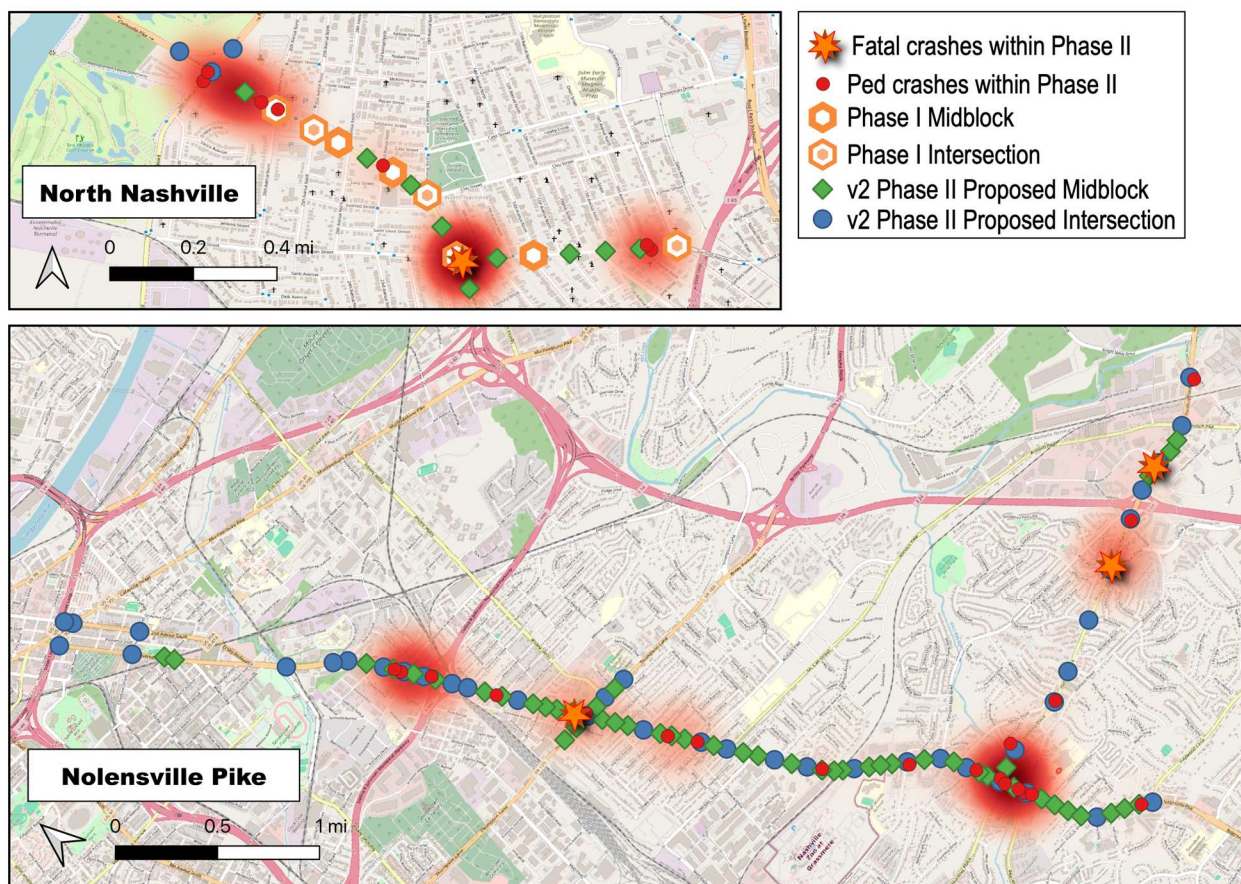


Figure 11 Project maps (Stage I and proposed II) with fatal crashes, pedestrian crashes, and a heat-map of vehicle-vehicle crashes on the site location (last 18 months of crash data shown).

The two project sections and their project-impacted Census tracts (2020 definitions) intersect with five separate local Opportunity Zones, as defined by USDOT and the State of Tennessee.

For further insights into the density of crashes along the Stage II site, along with zoomed in perspective on the sensors and their detection range, see Figure 12, Figure 13, Figure 14, Figure 15.

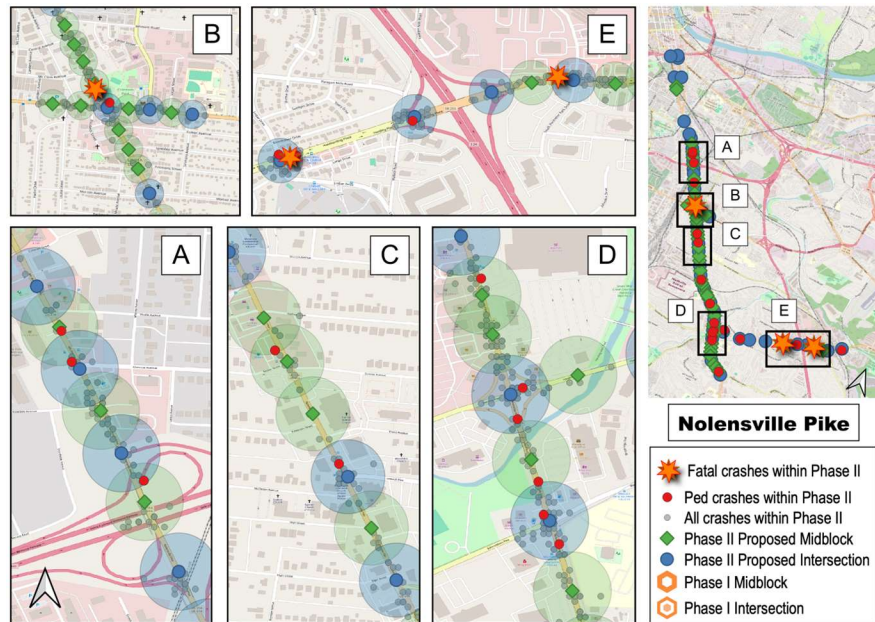


Figure 12 Detailed view of the Nolensville Pike Corridor including sensor installation locations, pedestrian crashes, and fatal crashes since January 1, 2023. Insets A-E are shown in relation to the full corridor coverage shown on the right.

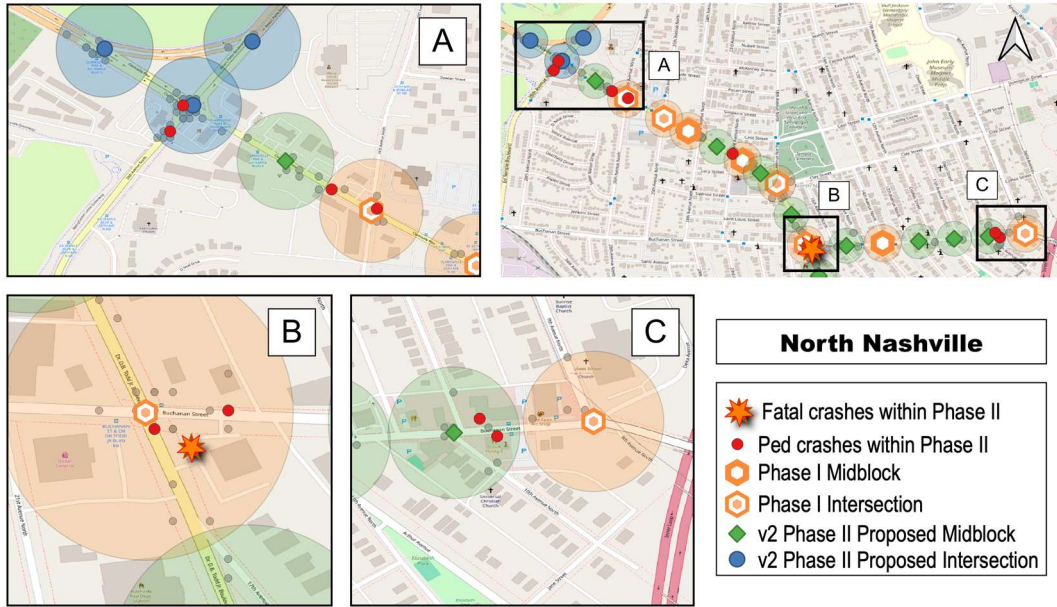


Figure 13 Detailed view of the North Nashville Corridor including sensor installation locations, pedestrian crashes, and fatal crashes since January 1, 2023. Insets A-C are shown in relation to the full corridor coverage shown on the top right.

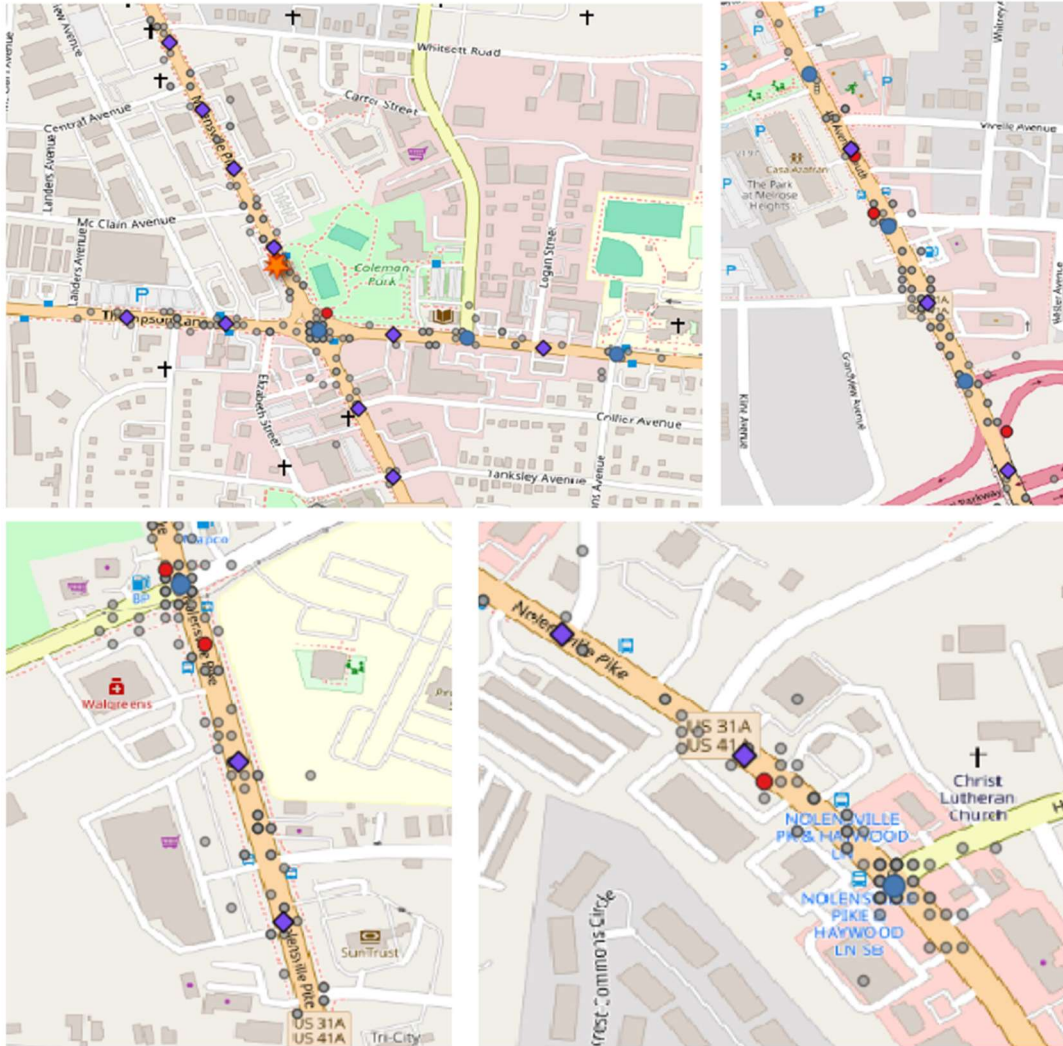


Figure 14 Nolensville Pike, part of the Nolensville Pike Corridor Stage II deployment. Images show vehicle-vehicle crashes (grey) pedestrian crashes (red), and fatal crashes (orange stars). Proposed intersection and mid-block sensors shown in blue circles and purple diamonds (mapped to centerline of the roadway).



Figure 15 Harding Place, part of the Nolensville Pike Corridor Stage II deployment. Images show vehicle-vehicle crashes (grey) pedestrian crashes (red), and fatal crashes (orange stars). Proposed intersection and mid-block sensors shown in blue circles and purple diamonds (mapped to centerline of the roadway).

Stage I Project scale

The stage 1 deployment included 13 lidar units installed at 5 intersections in north Nashville and 3 mid-block crossings. Due to the geometry of the intersections, we installed a pair of lidar units at opposite ends of the intersection, per the recommendation of the manufacturer. This reduces occlusion and increases accuracy. The project will also create a mobile lidar trailer in Fall 2024 and has received additional funding from the Tennessee Department of Economic Development to purchase a second lidar trailer in collaboration with Austin Peay University and the city of Clarksville, TN which is the neighbor of the Fort Campbell Army base.

Stage I summary of project activities

Major project milestones

- Project kickoff: August 2023.
- Community engagement events at Bag Lady's restaurant and on WeGo busses (Figure 16, Figure 17, Figure 18, Figure 19).
- Tennessee State University Research Symposium: LADDMS student Atiqur Mallick received 3rd Place award for Engineering Graduate oral presentation, March 25, 2024 (Figure 20).
- Vendor/Contractor trainings: April 2024 (Figure 21)
- LIDAR Installation for 1st Intersection: April 15, 2024 (Figure 22, Figure 23)
- USDOT Project Location Visit: April 16, 2024
- ITS TN Conference: May 15-17, 2024, focusing on Workforce Development. The event featured a keynote address from Nashville Mayor Freddie O'Connell speaking about the impact of the LADDMS Smart grant.
- Workforce Development: Continued training activities with vendors and contractors (Figure 24, Figure 25, Figure 26).
- Remaining Intersections/Mid-blocks Installation: July 2024.
- LIDAR Data Analysis and validation: Summer 2024.
- TNGO award to expand lidar to Clarksville, TN in collaboration with Austin Peay University and the City of Clarksville, July 2024.



Figure 16 Community input was provided through surveys and through interactive brainstorming at Bag Lady's in December of 2023. The input helped us shift to a lidar sensor solution.



Figure 17 Photos from LADDMS community engagement event at Bag Lady's Fry Joint (a local minority owned business in North Nashville). Survey participants were provided coupons to redeem at the business. The team also met with community members on the sidewalks and on WeGo busses in the neighborhood.

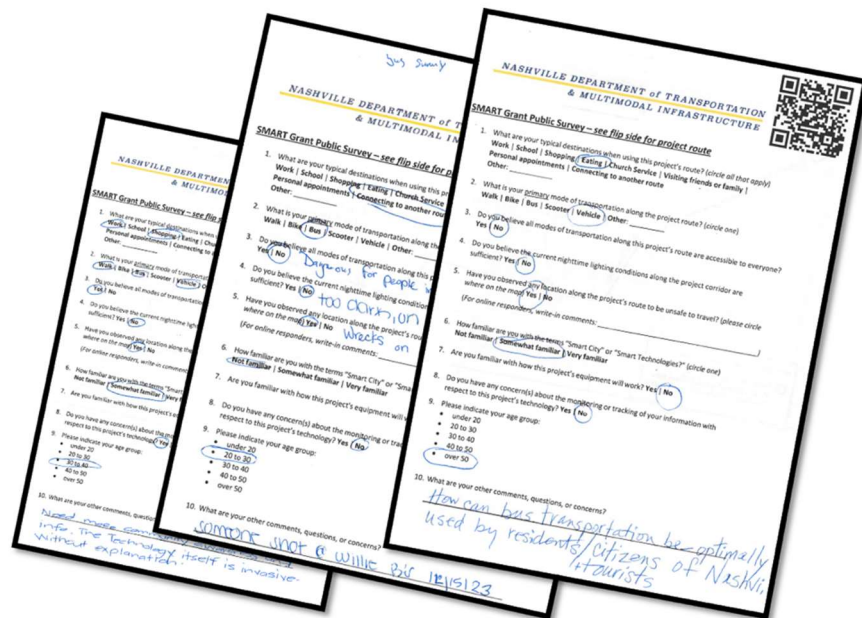


Figure 18 We received a total of 98 paper and online surveys. 64 paper surveys were collected over two community events, with 34 surveys collected online.



Figure 19 LADDMS team member Tupac Moseley (Tennessee State University MS student) interviews a North Nashville resident to get valuable feedback on the LADDMS project and the use of lidar to improve safety. See the full video at <https://ndot-laddms.org>.

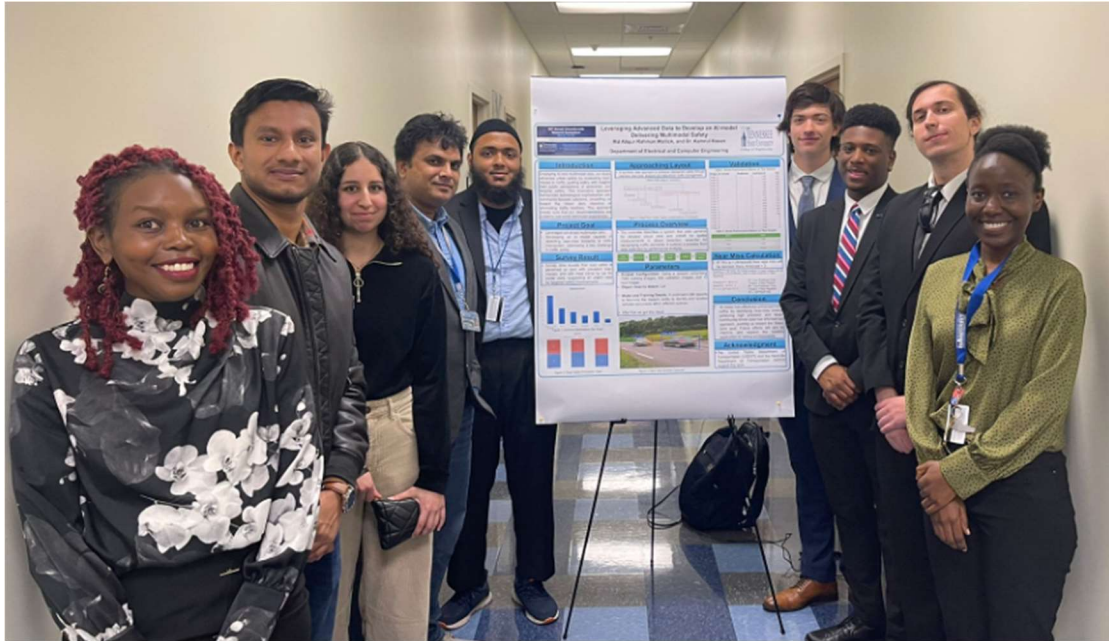


Figure 20 LADDMS presented at the 46th Annual Tennessee State University Research Symposium Student Oral & poster presentations Week of March 25th, 2024. Team member Atiqur Mallick received 3rd Place award for Engineering Graduate oral presentation.



Figure 21 Bench testing of the first lidar sensor prior to installation allowed all project partners a chance to learn and exchange knowledge of the technology.



Figure 22 Photos from the first LADDMS lidar installation located at 26th Ave and Clarksville Ave. in April 2024.



Figure 23 Left. In large signal control cabinets, the space allows all additional sensing equipment to be co-located with the signal controller. Right. Zoom in on the lidar installation.

Activity spotlight on workforce development

We briefly spotlight our workforce development activities prototyped in Stage I. We developed a new workforce training program for the two largest signal maintenance contractors in middle Tennessee, Stansell Electric Company and NABCO Electric Company. The infographic in Figure 24 Summarizes the surveys we conducted after the events to assess the quality of the activities.

LIDAR INSTALLATION TRAINING - PARTICIPANT SURVEY RESULTS

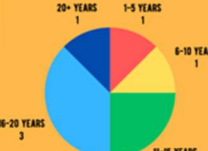
This infographic will show highlights and insights gained from reviewing the survey results regarding the recent LIDAR Bench Scale trainings at Stansell Electric Company in Nashville, TN and Nabco Electric in Chattanooga, TN.



01. EMPLOYEE BACKGROUND

There were a total of eight (8) responses to the survey with an even split of 4 responses from Stansell and Nabco employees each. Out of these 8 participants, only 1 had previous experience working with the LIDAR equipment and software. This one individual stated that this bench scale will significantly improve his job performance.

YEARS OF FIELD EXPERIENCE



02. PRESENTATION & TRAINING RATINGS

"Please rate how you felt about the PowerPoint Presentation."



"Please rate how you felt about the LIDAR Systems Setup Experience."



"Please rate how you now feel overall about using LIDAR."



03. POST-TRAINING CONFIDENCE RATINGS

- How confident do you think you are in doing the bench test? ★★★★★
- How confident do you think you are in doing a stand-alone street installation? ★★★★★
- How comfortable do you think you are in using the LIDAR software after this training session? ★★★★★
- How effectively did the trainers address your questions and concerns? ★★★★★

04. COMMENTS ON HIGHLIGHTS & IMPROVEMENTS

The participants were given the opportunity to leave comments on what they enjoyed from the bench scale demonstration and suggestions for any areas of improvement for future trainings.

Positive Feedback

- The PowerPoint was very in-depth, thorough, and educational. "It made it very easy to ask questions."
- The LIDAR systems setup was "informative", "super easy and quick", and it was nice to learn and operate the equipment before going out into the field.
- The LIDAR software is "amazing" and it was well-received on its ability to see traffic & pedestrians in real-time.
- Comments regarding the overall experience appreciated "the patience to answer questions and dive into the questions to make us understand it", "the hands-on learning experience", and "being able to see the product in person and the software that it uses."

Future Improvements & Suggestions

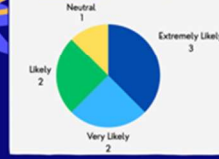
- Troubleshooting to ensure that an active unit in service can be shown in the software to attendees.
- Providing more instructions on the set-up process of the LIDAR unit and computer.
- Creating a more streamlined experience to reduce the number of moving parts while practicing the system setup.
- Extending the classroom time to become more comfortable with the install and learning more in-depth how the software works, as the time felt "a bit rushed".
- One participant believed that they would need more information and real-world experience to get a matured opinion on the LIDAR unit & application.
- Another believed a field visit would have been a great addition as well.

05. IMPACT RATINGS

Do you feel that the training session will improve your job performance?



How likely are you to recommend this training to a colleague?



06. CONCLUSION

Overall, both trainings were successful endeavors based on the positive survey feedback. The PowerPoint presentation and instructors were highly received, with noteworthy comments about it being informative and helpful. The hands-on experience of the practice installation were distinctly appreciated, but there were suggestions for a smoother installation process with instructions for future sessions. The participants are excited to see the future of LIDAR applications.

Figure 24 Summary infographic of our training sessions with Stansell and NABCO Electric Companies

Training Sessions for Stansell Electric Company Technicians

On May 21st, a comprehensive training session was conducted for the technicians at Stansell Electric Company. This hands-on training focused on practical aspects of LIDAR technology, ensuring that the technicians are proficient in installation, maintenance, and data collection.



Figure 25 Photos from the Stansell training session in spring 2024

Training Sessions for Nabco Electric Technicians. Following the successful initial training, a subsequent session was held on June 10th for the technicians at Nabco Electric. This session built upon the previous training, providing advanced insights and reinforcing the skills necessary for effective LiDAR implementation.



Figure 26 Photos from the NABCO training session in spring 2024

Our workforce development initiatives are critical to the success of our projects. By continuously improving our training programs based on survey feedback, we ensure that our technicians are equipped with the knowledge and skills needed to drive innovation and enhance road safety in Tennessee.

Other planned activities in Stage I

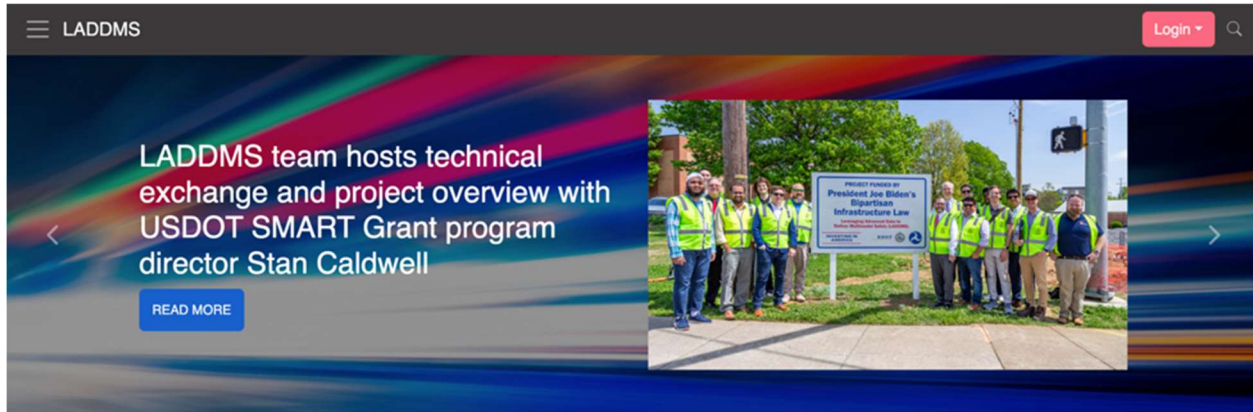
- Continuation of data monitoring and analysis
- Integration into coursework at partner universities
- Further dissemination of project results in professional and community events.

Partners involved in Stage I:

- AECOM
- Metro (Nashville Gov't) Information Technology Services
- Tennessee State University
- University of Tennessee Chattanooga
- Vanderbilt University
- Nashville Electric Company (NES)
- Stansell Electric Company
- Nabco Electric Company
- Ouster

Dissemination of project findings

Our dissemination activities occurred through news articles in the local community, development of a project website (Figure 27) containing our latest project developments and featuring the project in keynote talks at high visibility events that were attended by more than 215 practitioners (ITS Tennessee) and 250 academics (National Science Foundation Smart and Connected Communities Meeting).



Project Description

Welcome to the forefront of urban safety innovation in North Nashville!
The Leveraging Advanced Data to Deliver Multimodal Safety (LADDMS) initiative represents a new approach to enhancing the safety of our



Figure 27 Our project website features news items, project milestones, report-outs of our technology advances, workforce development activities, and our team partners.

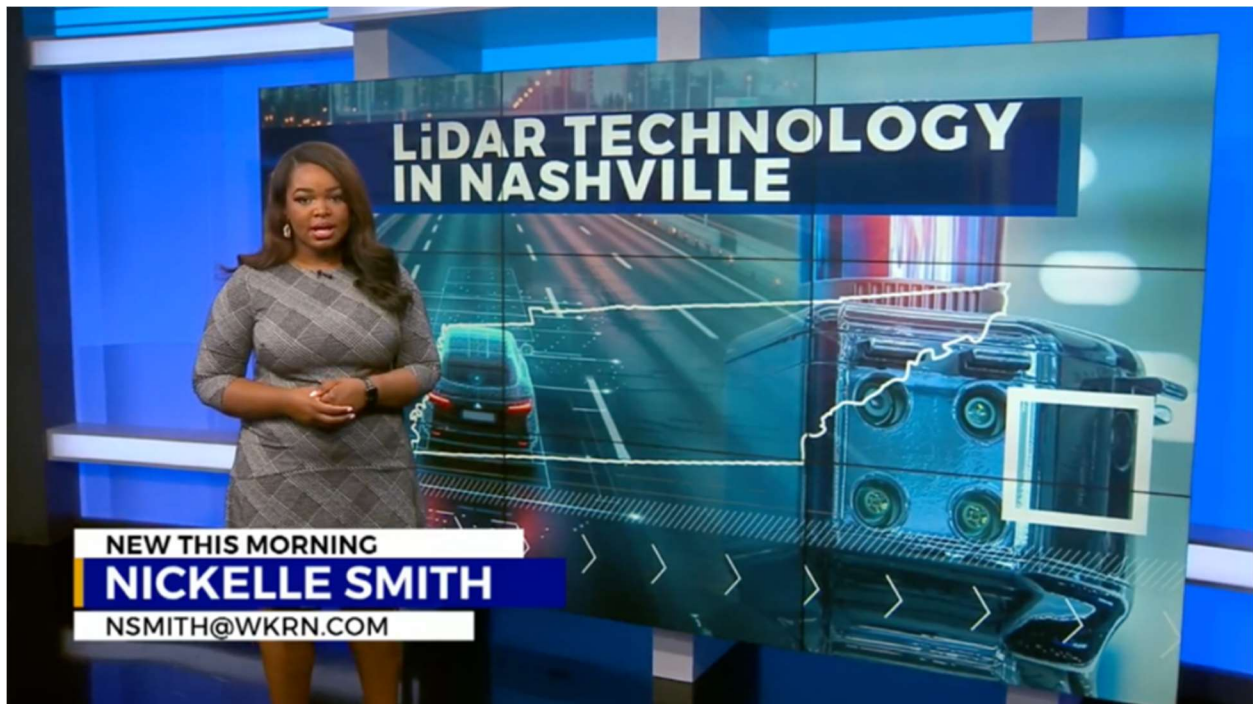


Figure 28 The LADDMS project has been featured in several media outlets, including on WKRN with Nickelle Smith.

Our work has been featured in the local television stories (Figure 28).

- WKRN Nickelle Smith, June 5, 2024. NDOT devices capture near-miss traffic data in Nashville. <https://www.wkrn.com/news/local-news/nashville/ndot-devices-capture-near-miss-traffic-data-in-nashville/>
- WSMV, Michael Warrick, June 5, 2024. NDOT installing devices to track near-miss traffic incidents in North Nashville. <https://www.wsmv.com/2024/06/05/ndot-installing-devices-track-near-miss-traffic-incidents-north-nashville/>
- WKRN Mye Owens, March 24, 2023. New NDOT cameras will track ‘near miss’ crashes in North Nashville. <https://www.wkrn.com/news/local-news/nashville/new-ndot-cameras-will-track-near-miss-crashes-in-north-nashville/>

It was disseminated in the following academic and industry conferences

- National Science Foundation Smart and Connected Communities meeting. The project was also featured in Mayor Freddie O’Connell’s keynote address (Figure 29) delivered to more than 230 academics at the 2024 NSF Smart and Connected Communities Principal Investigator’s meeting in February 2024.
- ITS Tennessee Annual Meeting. The project was featured in Mayor Freddie O’Connell’s keynote address (Figure 29). The LADDMS team delivered a second technical presentation on Lidar at the event. The team provided a live demonstration of lidar in the demo booth at the event. More than 215 participants attended.



Figure 29 Nashville Mayor Freddie O’Connell featured the LADDMS project in his keynote address delivered to more than 250 academics at the 2024 NSF Smart and Connected Communities Principal Investigator’s meeting in February 2024.

Major changes

Based on community feedback surrounding potential privacy concerns with video data, we moved away from video camera installations to exclusively use lidar sensing. Video detection systems were not tested directly against lidar sensing, but the project team is very confident that lidar detection compares favorably and is a turn-key solution for object detection at intersections and midblock locations. Lidar sensor range, as installed, is approximately 70m from the center of the intersection. This detection range is sufficient for intersection actuation and analytics, but not compatible with long-range advance detection capabilities in the current form. However, other lidar hardware may support this range and capability.

Part 2 of 6: Proof-of-Concept or Prototype Evaluation Findings

Summary

This section provides technical details to support our overall assessment that the system is working well above our expectations. We first discuss system performance, and present the technical highlights of the project including:

- The system is able to accurately detect near-miss events.
- The system is able to rapidly assess interventions designed to reduce out of crosswalk events.
- The system is able to rapidly assess interventions designed to reduce speeding.

Then we report the findings of our three evaluation plan performance measures, each of which was met with overwhelmingly positive findings.

Finally, we report on the sensor performance along nine performance measures, all of which were met or exceeded compared with comparable ITS technologies used in practice.

System performance and evaluation

Can we accurately measure near-miss events? Yes.

Main result: Lidar accurately identifies near-miss events using post-encroachment time between pedestrians and vehicles. We manually inspected individual 68 near-miss events to validate this finding.

Approach: We define near-miss events using post-encroachment time as the measure of safety. *Post Encroachment Time* (PET) is one of several well-defined *surrogate safety measures*, which aim to give insight into unsafe conditions that may or may not directly result in a crash. Intuitively, the post encroachment time is the time separation between when a vehicle and pedestrian occupy the same spot on the roadway. PET is directly implemented in Ouster's BlueCity software and can also be easily calculated on the raw data generated by the lidar unit.

We provide an example. Consider a pedestrian that walks across a crosswalk at time zero. Two seconds later, a car passes through the crosswalk where the pedestrian was recently standing. The resulting PET between the pedestrian and car is two seconds.

For interpretation, when the path of a pedestrian and a vehicle conflict, we save the time that the pedestrian arrived at the conflict point, denoted t_{ped} , and the time the vehicle arrived at the conflict point, denoted t_{veh} . The post encroachment time can then be calculated as:

$$PET = t_{veh} - t_{ped}.$$

Note that with this convention, when a pedestrian arrives at the conflict zone before the vehicle (i.e., t_{ped} is smaller than t_{veh}), the PET is positive. When the vehicle arrives first (which can happen when the pedestrian waits for the vehicle to cross), the PET is negative. A PET of zero means the pedestrian and the vehicle occupy the conflict point at the same time (i.e., a crash is observed).

For accuracy when calculating conflicts, we compute the PET considering the size and shape of the vehicle and pedestrian, both of which are directly measured with lidar.

Findings: On July 25, 2024, at the intersection of Clarksville and 26th Ave, we examined a total of 2.36 million datapoints for near-miss events. We filter the data to identify trajectories of vehicles and pedestrians with a class confidence of 0.8 or greater (it is easily generalizable to other classes) and with more than 20 datapoints (2 seconds) of observations. This filtering resulted in 17,026 total objects. For these objects, we calculate the PET and save all events that have a PET within the range [-2 sec, 2 sec]. This filtering resulted in a total of 394 events that were further inspected.

We immediately observe that a large number of “collisions” are observed (defined as PET of 0.0). By inspecting the trajectories of the vehicles and pedestrians, we determined that these events can be explained by people getting into/out of parked cars that are visible in the sensor. This inspection motivated a straightforward filter to eliminate incorrectly labeling people entering vehicles as near-miss events or collisions.

We introduce a filter to remove these “people getting into/out of parked car” events, which works as follows. We calculate the space-mean speed of the vehicle over the 4 second window (two seconds prior and two seconds after) the PET=0.0 event is observed. If the vehicle has a space mean speed that is less than 5 mph, we remove the event. This value can be further refined with robustness testing but upon manual inspection of the data results in removal of 326 events, leaving 68 events that remain.

Of the remaining 68, events, we analyze the type of interaction. We find that 89.7% (61 events) are settings in which the PET is negative, i.e., the car arrives to the conflict point prior to the pedestrian. While concerning, these events are deemed not as dangerous as PET events in which the pedestrian arrives first. The remaining 7 events are events in which the pedestrian arrives to the collision point first.

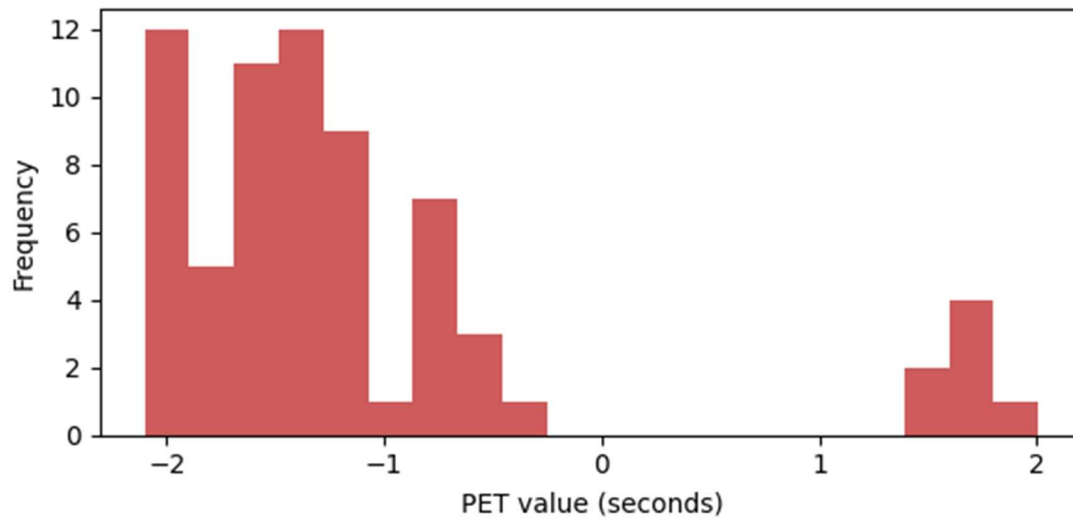


Figure 30. Breakdown of the PET events less than or equal to 2 seconds. 89.7% of the events have a PET negative, which means the vehicle reached the conflict point before the pedestrian. The remaining 7 events are events in which the pedestrian arrives to the conflict point first.

We manually inspect each of the 68 PET events by visualizing the time evolution of the vehicle and pedestrian leading to the near-miss. Figure 31 shows four examples of near-miss events where the PET is between one and 2 seconds.

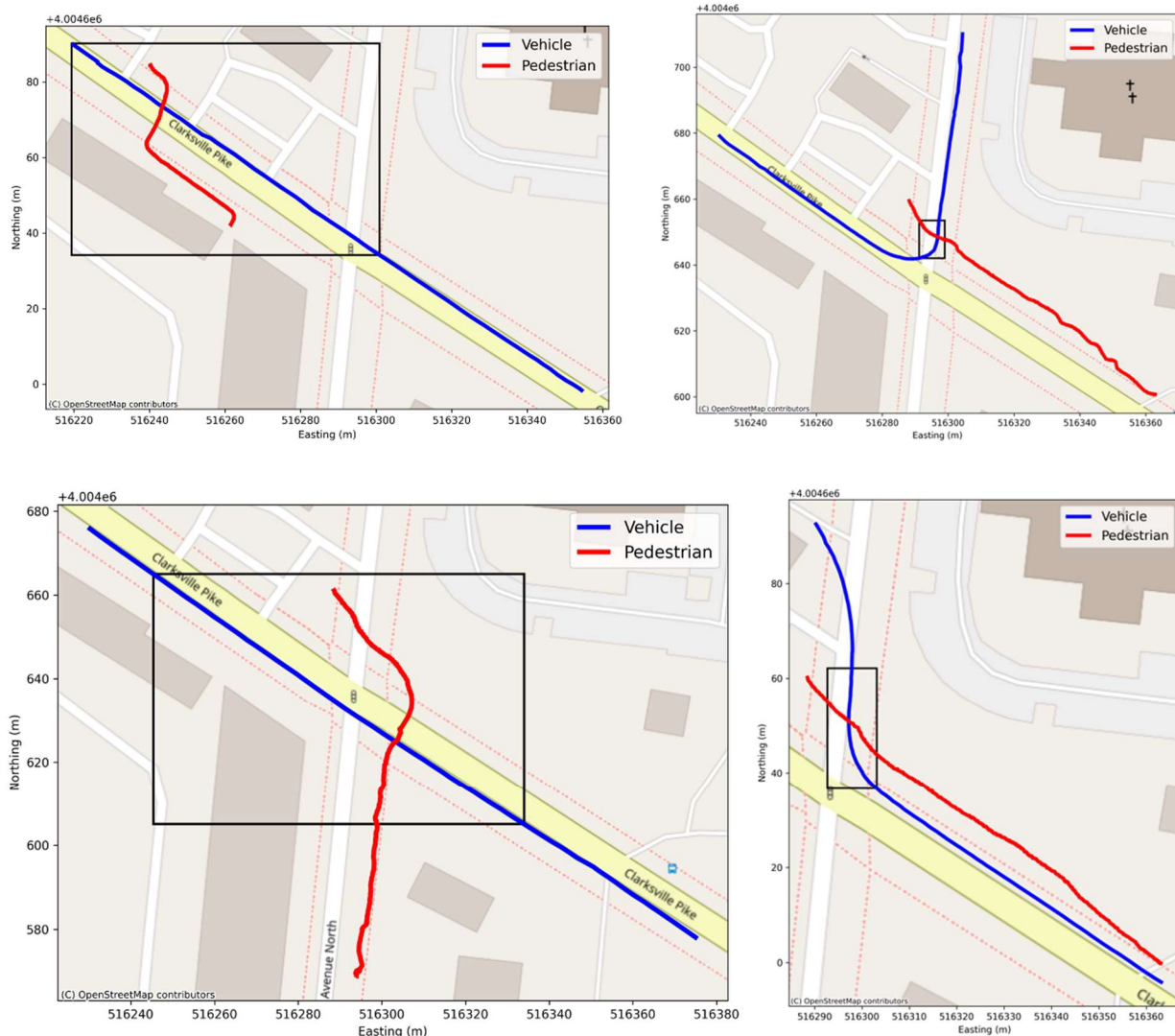


Figure 31. Visualization of four of the seven events with a PET between zero and 2 seconds (i.e., settings in which the pedestrian arrived at the conflict point prior to the vehicle). The trajectory of the pedestrian is in red, the trajectory of the vehicle is in blue. Top Left: PET=1.8s; pedestrian crosses the street from bottom to top, immediately followed by a vehicle traveling right to left. Top Right: PET=1.5s; pedestrian crosses the street from right to left, immediately followed by a vehicle turning left at the intersection. Bottom Left: PET=1.8s; pedestrian crosses the street from bottom to top, immediately followed by a vehicle traveling left to right. Bottom Right: PET=2.0s; pedestrian crosses the street from right to left, immediately followed by a vehicle turning right at the intersection.

We further inspect in detail (Figure 32) the trajectory of one near-miss event to illustrate the types of timeseries analysis we performed for each of the 68 events. The figure shows 12 frames of the trajectories of a pedestrian and a vehicle which have a near-miss event (also shown in the bottom left of Figure 31). In Figure 32, the pedestrian starts on the sidewalk along 26th Ave (up the figure) and walks across Clarksville pike, and then proceeds to cross 26th Ave north. The full trajectory is shown in red dots, with the current location of the pedestrian indicated by a red diamond. A vehicle travels along Clarksville Pike (from the

upper left to bottom right in the figure). The trajectory of the vehicle is shown as a solid black line, with the current location of the vehicle shown as a grey rectangle. The top left plot shows the pedestrian occupying the conflict point at 12 minutes and 58.16 seconds past the start of the hour. The pedestrian clears the conflict around 12:59.76. The vehicle arrives at the conflict point just after 13:01:36. The recorded PET is 1.8 sec, which accounts for the exact arrival and departure times from the conflict area that are difficult to visualize precisely in the figure.

Based on the above analysis and by visualizing and manually inspecting each of the 68 events, we conclude that lidar is able to accurately detect near-miss events.

PET=1.800051 at 12:58.56

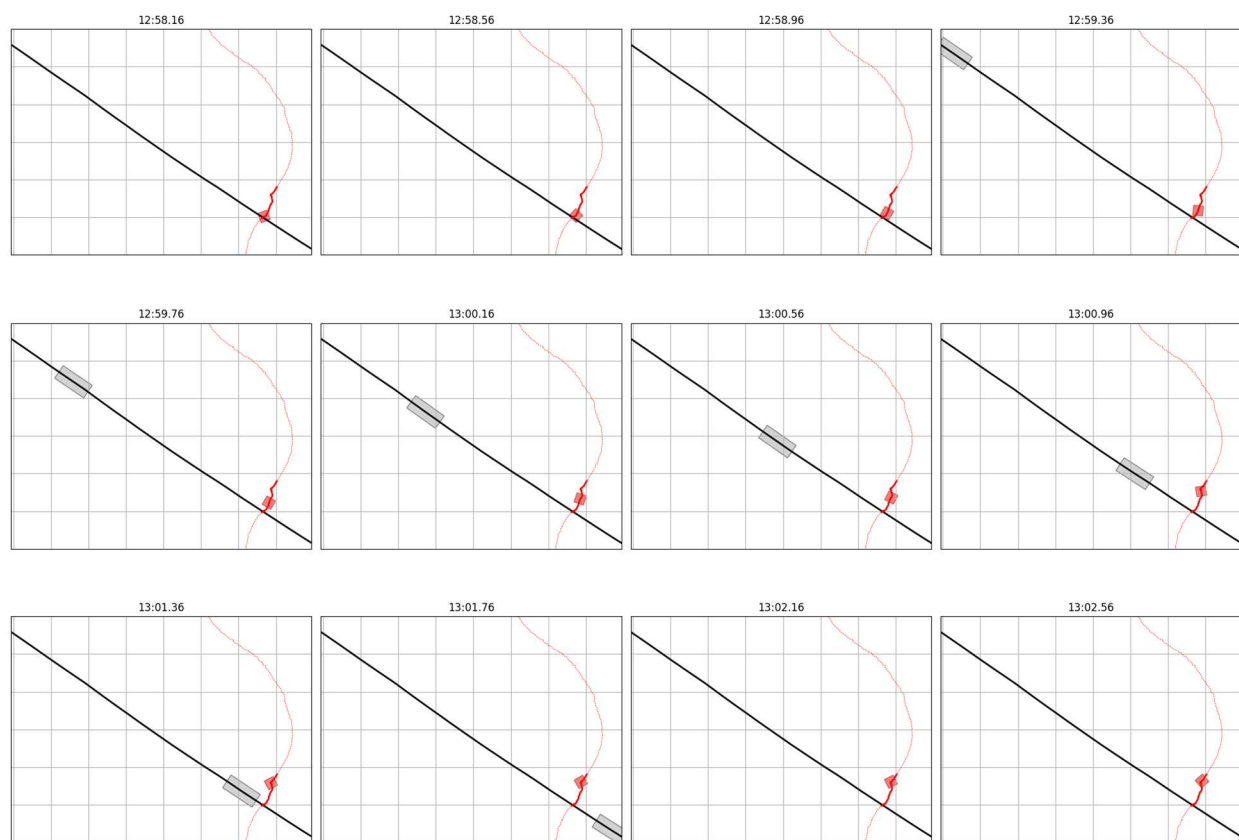


Figure 32. Visualization of a series of 12 frames in increasing time of a near-miss event with a post encroachment time of 1.8 seconds. The path of the pedestrian is shown in red, walking from the bottom to the top of each image, with the location of the pedestrian drawn with a red square. The trajectory of the vehicle is shown in black, driving from the left to the right, with the location of the vehicle at the given frame shown as a grey box.

It is an interesting question to determine if there are other safety critical events that are not detected as low PET events. For example, a pedestrian and a vehicle that do not have conflicting paths have an infinite PET. One can imagine having a large vehicle pass at a very high speed, only inches from a pedestrian walking on the side of the roadway. This event is certainly dangerous but is not captured by the default near-miss PET as defined above. In our future research, we are exploring approaches to create buffers around the vehicle and pedestrian and repeat the PET calculation. Such an approach would automatically detect events such as the hypothetical one described above. We are in discussion with Ouster about these extensions and will continue the research through the remainder of the project.

Can we rapidly evaluate safety interventions designed to reduce out of crosswalk events? Yes.

Main result: The share of crosswalk events in a targeted area were reduced by 75%, as shown in Figure 33. Before the intervention, the share of crossings in the treatment zone was 33.4% of all crossings. After the intervention, the share of crossings in the targeted area was reduced to 8.2%, which is a 75% reduction compared to the pre-intervention share.

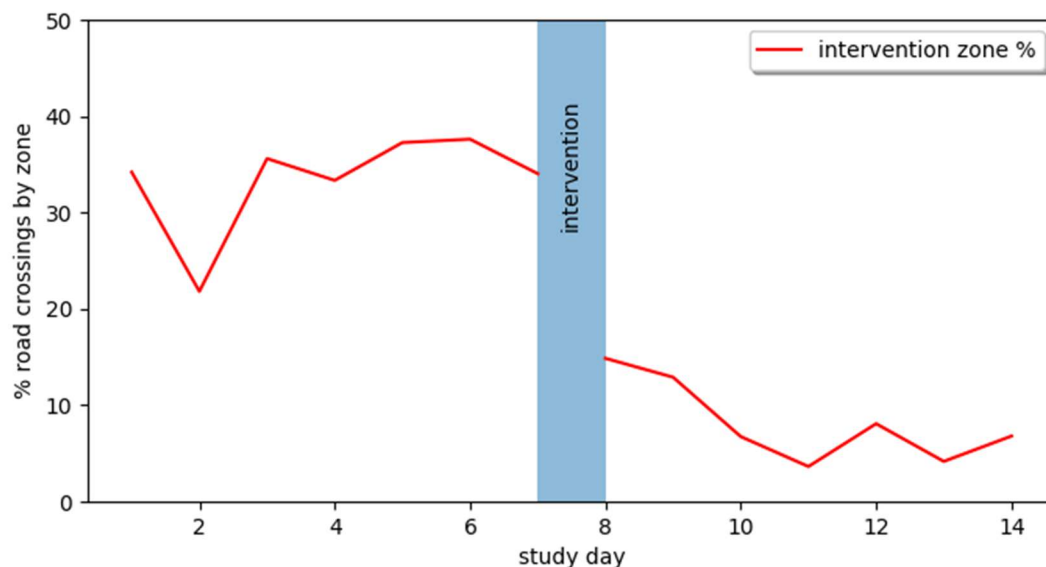


Figure 33 Percent of road crossings occurring in the intervention zone for 7 days before and 7 days after the intervention was deployed. The share of out-of-crosswalk events in the treated zone decreased by 75%.

Issue: In less than 24 hours after installing our first sensor at 26th Ave and Clarksville Ave, a large number of out of crosswalk events were immediately observed. The most concerning crossings occurred near the intersection but away from the crosswalk. Using the BlueCity

software (Figure 34) we see in red the trajectories of individual pedestrians, with a large number of crossings occurring near a small alleyway between two buildings.



Figure 34 A large number of out of crosswalk events were observed immediately after our first lidar installation completed. Using this information a temporary intervention was designed. Yellow box (added to improve visibility) highlights the problematic crossings.

Intervention: To determine if the lidar sensor can detect changes in pedestrian patterns, two temporary interventions were deployed in early July 2024. The interventions were temporarily installed and with discussion with community members. The interventions are shown in Figure 35.

The signal timing plan was modified to immediately prioritize pedestrian calls. Signage was placed to inform pedestrians of the changes to the signal. At the same time a temporary fence was placed to funnel pedestrian traffic towards the signal. We emphasize this temporary measure (the fence) was designed to test the potential of the sensor to detect changes in the pedestrian patterns to validate the technology and was not configured as a long-term strategy.



Figure 35 Temporary interventions were deployed on Clarksville Ave and 26th Ave. Left. The signal was modified to immediately prioritize pedestrians in response to ped calls. Right a temporary fence was installed to reduce out of crosswalk events at a problematic area.

Approach. To test the ability of the sensor to identify a change in pedestrian volumes in the intervention area, we analyzed the data for 7 days prior and 7 days after the intervention. Three zones were configured and the fraction of people crossing in each zone is determined. The zones are shown in red, yellow, and green in Figure 36 (with trajectories also visualized). The green zone defines pedestrian crossings that are considered to occur within the crosswalk. The red zone defines pedestrian crossings that are occurring in the treatment area. A third zone, shown in yellow, defines crossings that are far from the intersection. We create this zone to be able to measure how the crossings in the treatment area are shifted (e.g., do they move to the crosswalk that has been retimed, or do they shift away from the intersection?) We can compare the fraction of crossings at the crosswalk, in the zone of the intervention, and an area further away from the intersection but outside of the area of the interventions.

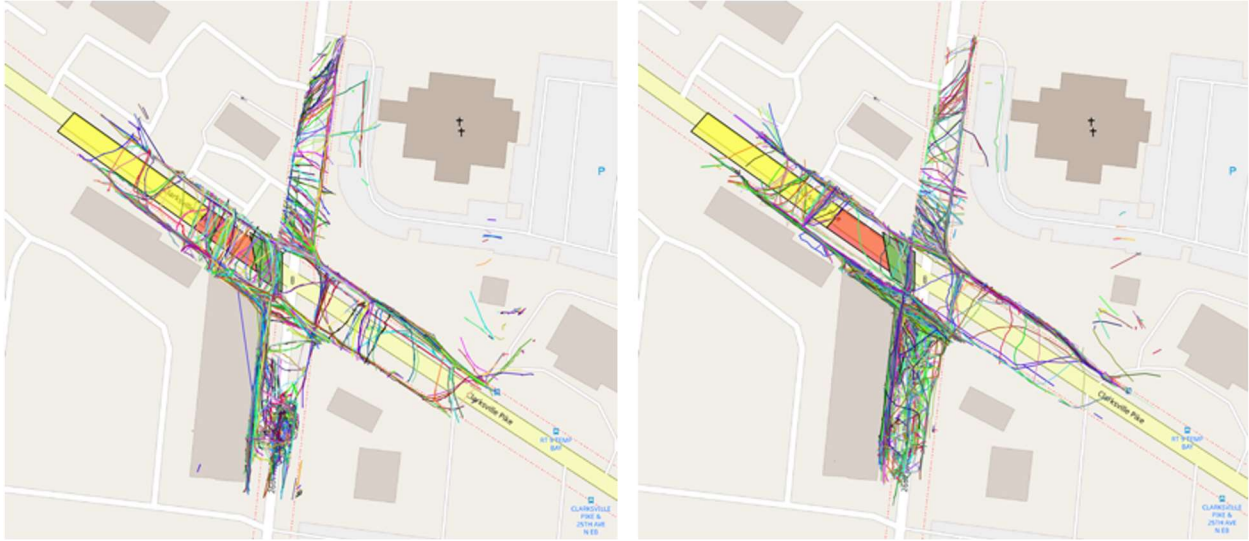


Figure 36 Left. Visualization of one day of data (June 26, 7am-6pm) of out of crosswalk pedestrian crossings prior to treatment. Each trajectory is given a fixed color. Three zones are defined on Clarksville Ave. The green zone is defined as “in the crosswalk”, the red zone is defined as the crossings that occur in the area that will receive treatment, and the yellow zone is a region outside the crosswalk but that was not treated. Prior to treatment, many crossings occur in the red zone. Right Visualization of one day of data (July 10, 7am-6pm) of out of crosswalk pedestrian crossings after treatment. Many trajectories shift from the red zone to the yellow zone.

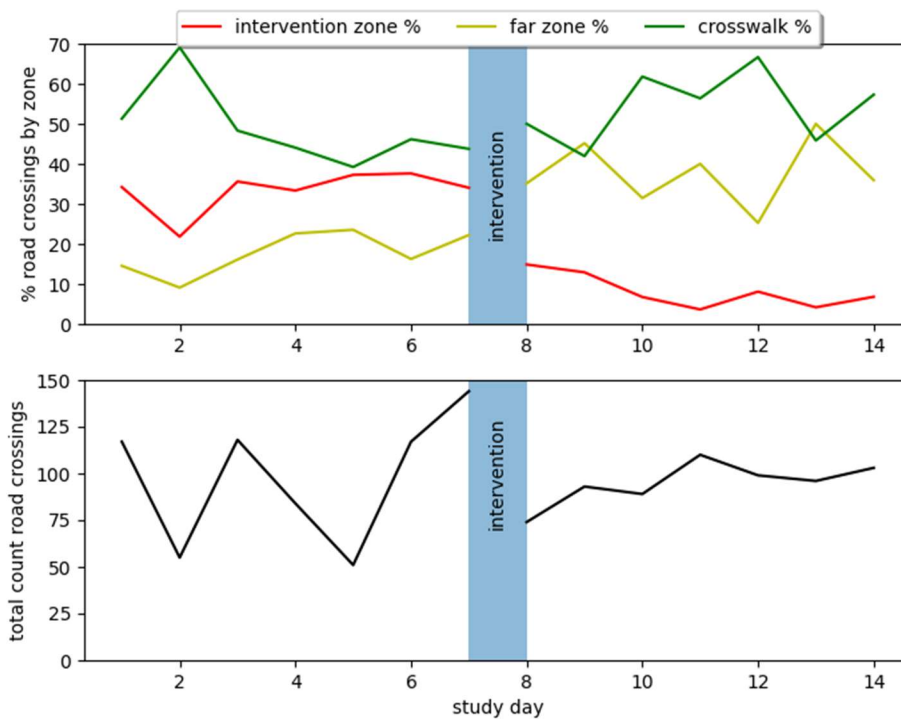


Figure 37 Percent of crossings in each zone. Top. Plot of the percent of road crossings by zone. While the intervention zone share (red) was reduced by 75.4%, the share of crossings in the crosswalk remained steady. The share of crossings shifted to the yellow zone.

Findings: The main finding is shown in Figure 33. The two treatments combined reduced the share of crosswalk events in the treatment area by 75%. A closer inspection of the data shown in Figure 37 reveals that the percent of crossings occurring within the crosswalk pre- and during the intervention are roughly steady at approximately 50% (48.8% before, and 54.3% after). The number of crossings in the yellow zone increased from 17.8% to 37.6%, which is an unexpected finding. In other words, the treatment worked to reduce crossings in the problematic zone but did not shift the crossings to the desired location.

This intervention analysis is an extremely valuable result for the lidar technology, because 1) it enabled a rapid identification of a safety concern; 2) it allowed an intervention to be deployed and immediately assessed; 3) it demonstrated the value of the data from the project. The intervention had an unexpected effect on the location of the crossings, which would have otherwise been impossible to quantify.

Can we rapidly evaluate safety interventions designed to reduce vehicle speeding on the corridor? Yes.

Main result: The share of super-speeders (defined as traveling above 40 mph in a 25-mph zone, and above 60mph in a 40-mph zone), decreased by 30% and 35% at two treated areas in the corridor. The problem was identified, treated, and analyzed for impact in a four-day window, which is a 10x speedup compared to traditional NDOT procedures.

Issue (DAY 1): Within 24 hours of completing the remaining seven lidar installation locations, we observed speeding on the corridor, which directly aligned with community input we received during our earlier engagement events. Some vehicle speeds were observed in excess of 70 mph on a 40 mph stretch of Clarksville Ave.

Intervention (DAY 2): Within 24 hours of the speeding observation, NDOT mobilized 4 speed trailers and installed them at two locations (one trailer in each direction) along Clarksville Ave and on Buchanan Ave. The trailers are shown in Figure 38. They are placed at approximately the same location facing oncoming traffic in each direction. The location on Clarksville Pike has a speed limit of 40 mph, while the location on Buchanan Ave. has a speed limit of 25 mph.



Figure 38. Midblock speeding intervention. A set of four speed trailers were placed on Clarksville Ave and Buchanan Ave. Top left: zoom in of one of the speed trailers, also shown in Top Right on Clarksville Ave. Bottom left and Bottom right show two speed trailers located on Buchanan Ave near a mid-block crossing.

Approach and Data Collection (DAY 3): To assess the impact of the speed trailers, we analyzed the before/after data beginning on day 3. We calculate the speed of all vehicle trajectories passing by on Wednesday July 24, 2024, with vehicles passing by on Thursday

July 25, 2024. The trailers were installed before 9am on July 25, and only data after 9am on both days are considered. We limit the analysis to vehicle trajectories that are at least 2 seconds long and have an average class confidence above 0.8.

To reduce the sensitivity of any single measurement, for each individual trajectory, we compute the 85-percentile speed of the trajectory. This eliminates any potential erroneous fast measurements, and also reduces the effect of vehicles stopping or slowing (which would reduce the average speed, even though portions of the trajectory are fast).

We further classify each trajectory as a *speeder*: vehicles traveling more than +10 mph over the posted speed limit, or as *super-speeder*: vehicles traveling more than +15 mph over a posted 25 mph speed limit (≥ 40 mph); vehicles traveling more than +20 mph over a posted 40 mph speed limit (≥ 60 mph).

Findings (DAY 4): We completed our preliminary analysis on day four. First consider the midblock location on Buchanan Ave (posted speed limit: 25 mph). During baseline data gathering before intervention, we observed a total of 4,256 trajectories. Of these, we observed 598 vehicles (14.1%) traveling more than +10 mph over the speed limit. We observed 96 vehicles (2.3%) traveling more than 40 mph (a well-known vision zero threshold at which 90% of pedestrians struck by a vehicle will be killed).

After the speeding trailer intervention, we observed a total of 4,520 trajectories, which is a slight increase in total number of vehicles. We observed 471 vehicles traveling more than 10 mph above the posted speed limit, and 69 vehicles traveling more than 40 mph. In terms of share of the total traffic, we see that the share of super-speeders decreased by 35% (the share dropped from 14.1% before treatment to 10.4% after), while the share of speeders decreased by 26% (the share dropped from 2.3% to 1.5%). The fact that there remain 69 vehicles still traveling in excess of 40 mph suggests further, permanent interventions are worth investigating.

We next consider the midblock location on Clarksville Ave. (posted speed limit: 40 mph). Our baseline data before intervention observed 7,163 vehicles. Of these, we observed 3,226 vehicles (45%) traveling more than +10 mph over the speed limit. We observed 550 vehicles (7.7%) traveling more than 60 mph.

After the speeding trailer intervention, we observed a total of 7,206 trajectories, which is a slight increase in total number of vehicles. We observed 2,625 vehicles (36%) traveling more than +10 mph over the posted speed limit, and 390 vehicles (5.5%) traveling more than 60 mph. In terms of share of the total traffic, we see that the share of super-speeders decreased by 30% (the share dropped from 7.7% before treatment to 5.5% after), while the share of speeders decreased by 19% (the share dropped from 45% to 36%). The large number of speeding vehicles still traveling in excess of 60 mph on Clarksville Pike remains concerning.

Beyond the importance of reducing speeding, this approach also highlights a new operating mode to improve the safety of vulnerable road users. Data from lidar allows continuous monitoring of the performance of the corridor, and it is easy to spot issues almost immediately after the sensors are turned on. Because of the commitment to Vision Zero within NDOT and the Office of the Mayor, we are able to rapidly deploy interventions to address issues discovered in the data. Due to partnerships created through SMART grant funding, these interventions can be immediately assessed, and monitored over longer periods to continuously evaluate performance. Compared to traditional operating procedures, which can easily take months rather than days, we conservatively estimate a 10x improvement in our ability to identify, deploy and evaluate interventions to promote road safety for vulnerable road users.

Evaluation plan performance measures

The project milestones from our evaluation plan are below. The results of our evaluation are also included.

Months 1-4

Scheduled activities:

- Stakeholder outreach, notice of project implementation to surrounding neighborhood organizations, and businesses
- Begin enrolling local staff in workforce training sessions/classes to support tasks of the project.

Evaluation metrics

- Number of community groups contacted: ITS Tennessee (215 participants), Walk Bike Nashville, NSF Smart and Connected Communities research community (230 participants), TSU Research Symposium (80 STEM students and 40 visitors), Bag Lady's & WeGo bus rides (98 participants)
- Estimated participant reach: 663)

Months 5-7

Scheduled activities:

- Incorporate feedback and data into project management plan
- Training sessions begin (virtual sessions followed by on-site instruction)

Evaluation metrics:

- Number of training sessions held: We held 3 training sessions (one at Vanderbilt, one at Stansell Electric Company, and one at NABCO Electric Company)
- Number of people who completed training sessions: 26 (7 at Vanderbilt, 9 at Stansell, 6 at Nabco; 4 at Vanderbilt - Clarksville exchange)

Months 8-15

Scheduled activities:

- Begin installation of LiDAR at identified intersections and midblock crossings (NDOT, Universities)
- Project lead staff, employees, and student workers implement majority of project tasks, including device installation, data collection practices, and quality control
- Training of local staff

Evaluation metrics:

- Number devices installed: 13 lidar units
- Number of intersections/blocks instrumented: 5 intersections (2 lidar units per intersection) and 3 mid-block crossings (single lidar unit per mid-block crossing)

Months 16-18

We have conducted preliminary analysis to inform our decision to advance to a full-scale implementation. These activities will continue, and our numbers will be refined.

Scheduled activities:

- Monitor devices, ensure smooth operations of data connection and feedback mechanisms

Evaluation metrics:

- Device uptime: The device uptime was measured at 99.93%.
- Near-misses recorded: The number of near-misses between vehicles and non-vehicles (defined as post encroachment time of less than 2 seconds) is 20.1 near-misses/day, with a standard deviation of 6.6 near-misses per day. The analysis was conducted over an 86-day window from April through July 2024.

Sensor performance and evaluation

The accurate assessment of the proposed system's performance is essential to validate its effectiveness and reliability. One critical aspect of the system's performance evaluation is the identification and monitoring of near-miss scenarios, which directly impact the safety

and functionality of the system. In this section, we will outline the performance measures employed to evaluate the proof-of-concept of the proposed system. The outcome of the following measures will verify the functionality of the system, its performance and effectiveness, and the ability to deploy the system at scale.

Most of the analysis below focuses on a single installation at 26th Ave. and Clarksville Avenue. This location was our first prototype, which allowed us to refine the design and testing procedures for the other locations. Consequently, we have significantly more data available for analysis on this location.

Accuracy of Pedestrian Count

The ability of the proposed system to accurately detect vulnerable roadway users (VRUs). We will measure the system's detection accuracy by comparing the number of true positives, true negatives, false positives, and false negatives against ground truth data.

Main result:

The sensor accurately detects non-vehicles, allowing quantification of crossings and events with non-motorized vehicles that were previously impossible to measure with traditional methods available to NDOT.

- 103 Pedestrian detection crossings were manually verified with the following statistics:
- 100% true positives, 1.9% false positives, 0% false negatives.

Approach:

We bring a temporary video camera (used only for count validation; cameras are not part of our deployed system) to walk the intersection at 26th and Clarksville. Two pedestrians from the LADDMS team walked across all four crosswalks alternating between talking clockwise, counterclockwise, walking together and walking independently, and CCW, together. The trajectories of the pedestrian crossings as recorded by lidar are shown in Figure 39.

The temporary validation video data was manually annotated to count all crossings. Figure 40 shows a single frame from the validation study. On the top is a screenshot of the data in the live viewer, in which pedestrians are colored yellow and vehicles are colored blue. The numbers shown in the image correspond to the cumulative count of pedestrian crossings up to that frame. The bottom shows the time synchronized video frame (from the temporary validation camera used only in this experiment). One pedestrian in the crosswalk foreground is visible, a second pedestrian is also visible on the adjacent corner of the intersection.

The method for counting crossing events works as follows: two planes are created, each of which splits two crosswalk areas in two; if a pedestrian trajectory crosses from one side of a plane to another, the count of crossings is incremented up by 1; as a consequence of the limited field of view of the ground truth annotated video data, crossings are only counted when within 25 meters of the intersection.

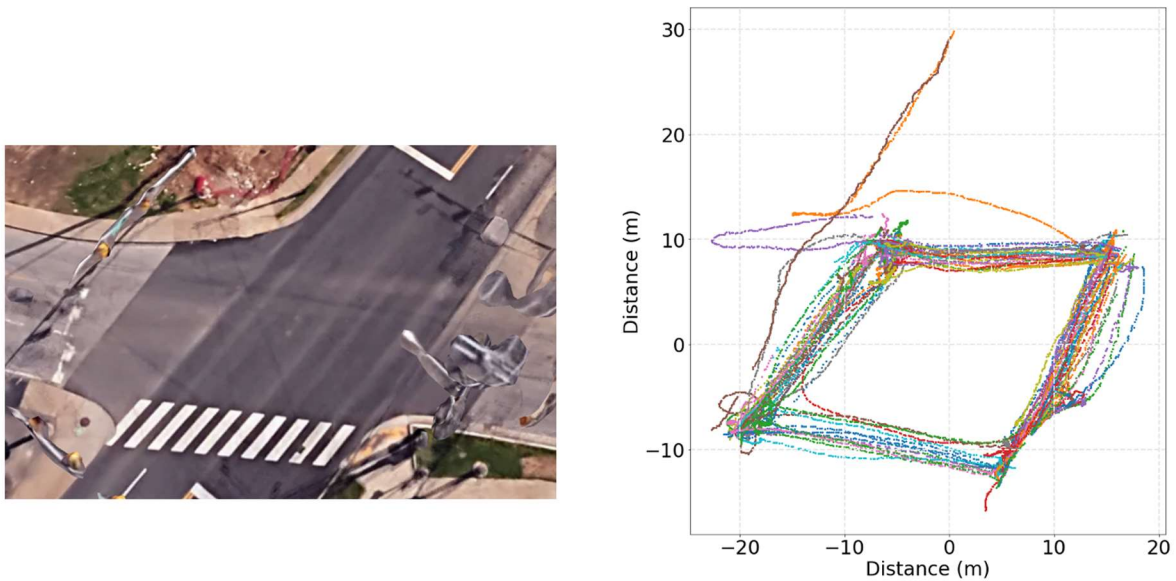


Figure 39 All of the pedestrian crossings captured in the LIDAR pedestrian validation dataset. Pedestrian trajectories are tracked inside and outside of the crossing zones. Each trajectory is assigned a color, and the center is 0,0.



Figure 40. Single frame from the pedestrian validation study. Top. Live view of the lidar detections, with vehicles in blue and pedestrians in yellow. Numbers correspond to cumulative counts observed. Bottom. Temporary video camera used to manually annotate the pedestrian crossings for comparison to the lidar detections.

Findings:

In the manual validation, 103 pedestrian crossings are counted, with 105 crossings counted from the analysis of lidar data. This resulted in the following statistics: 100% true positives (lidar detected a valid pedestrian), 1.9% false positives (lidar detected a pedestrian that is not present in the video), 0% false negatives (lidar missed a pedestrian that is visible in the video).

When increasing the classification confidence threshold to 60%, the two false positives are removed. Four pedestrian crossings which occurred more than 50 meters from the intersection were outside the field of view of the validation video data but were captured by the lidar sensors. One interesting case involving pedestrians in the validation data: the lidar classification has appropriate difficulty with certainty from an observed cyclist walking their bike, switching between cyclist and pedestrian classifications, and when the cyclist starts riding their bike classification becomes confident in the cyclist class.

Figure 41 illustrates the value of the automatic counting enabled by lidar. The figure shows 6 days of data around July 4, 2024, of all pedestrian and bicyclists by direction of travel at the 26th Ave. and Clarksville Pike location. Continued monitoring of counts will allow identification of the most critical times of day for pedestrian traffic, the direction, and changes in the ped/bicycle traffic as conditions on the corridor evolve.

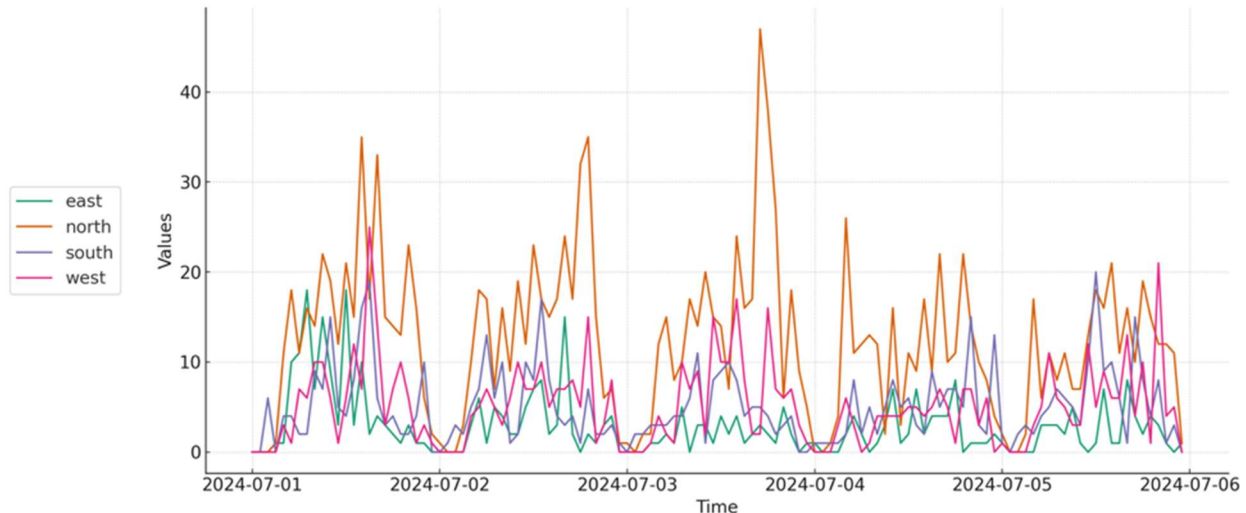


Figure 41 Pedestrian and bicycle combined counts for pedestrians and bicyclists over a six-day period by direction of travel. The count is the hourly count.

Accuracy of Vehicle Count Detection

The ability of the proposed system to accurately detect vehicles. We will measure the system's detection accuracy by comparing the number of true positives, true negatives, false positives, and false negatives against ground truth data.

Main result:

The sensor accurately detects vehicles.

- Vehicle detection was manually verified with the following statistics: 100% true positives, 2.7% false positives, 0% false negatives. All false positives are attributed to vehicles pulling trailers.
- The sensor is also able to count buses as a subclassification of the large vehicle type.

Approach:

We brought a temporary video camera (used only for count validation; cameras are not part of our deployed system) to the intersection at 26th and Clarksville. The video data was manually annotated to count vehicles passing through the intersection. The lidar vehicle counts from the same period were also analyzed. *Figure 42* visualizes the setup. On the top, the live data from the sensor is shown, with vehicles in blue and a visible pedestrian in yellow. The numbers visible in the image are the cumulative outflows of the intersection in each direction. The bottom shows the corresponding frame from the dash camera, where vehicles and a pedestrian are visible.

Findings:

First, we present the accuracy results. In our validation dataset, there are 318 vehicles counted from human annotation, and 329 vehicles counted from LIDAR sensor observation. Each of the 318 true positives are counted, with 11 false positives, and no false negatives. Investigation showed the false positives have two sources. Nine false positives were counted from vehicle trailers, where a truck or large vehicle was towing a trailer or flat bed. Two of the false positives were created from erroneous classification of light reflections from moving busses, effectively tricking the lidar sensor into seeing a large moving reflective point cloud. The reflection-based false positives are eliminated when requiring the threshold for classification confidence be above 75% within the perception software. These findings have been relayed to the lidar manufacturer for incorporation into successive software versions. Indeed, a major upgrade in perception software accuracy across multiple modes of travel is planned for release in 2025.

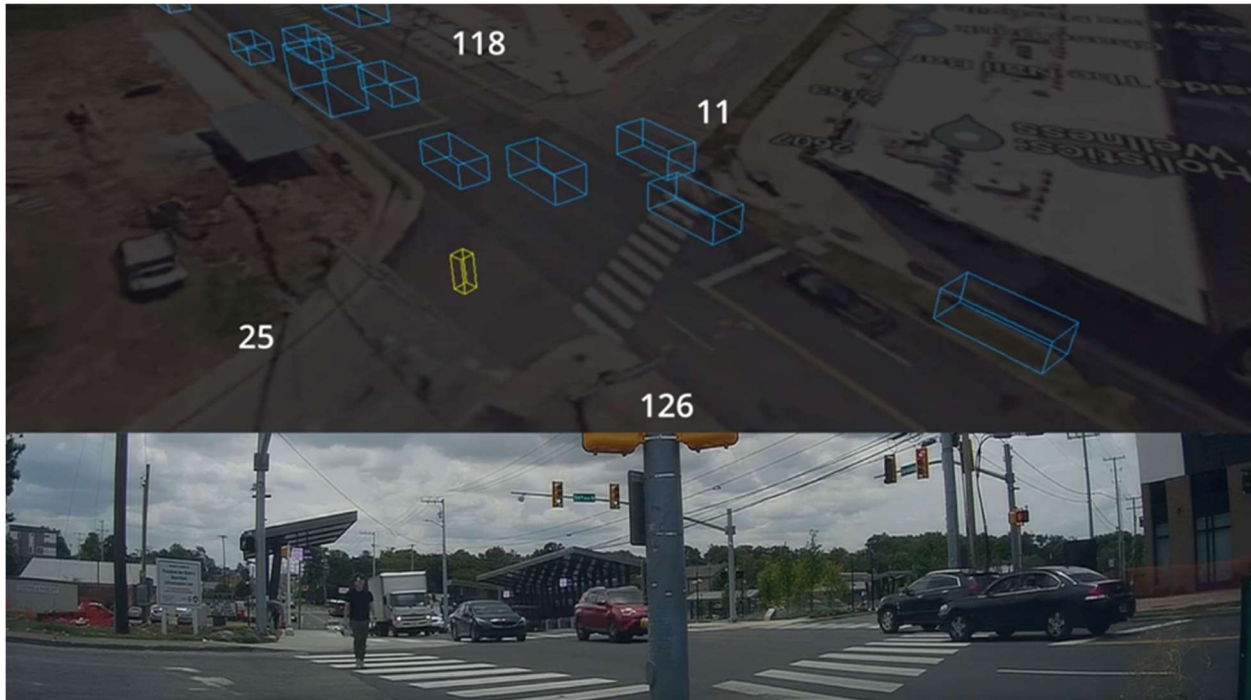


Figure 42 Screenshot from recording of dashcam video (collected and managed by Vanderbilt) and bounding boxes rendered from the lidar sensors. Yellow box shows the location of the pedestrian. Blue boxes show the location of the vehicles. Numbers are from the status of ground truth cumulative vehicle egress counts (manually annotated).

Using the data collected from Blue City, we are also able to provide timeseries analysis, for example by turning movement. Figure 43 shows all vehicles during the week of July 1, 2024, at Clarksville and 26th Ave. traveling eastbound on Clarksville Pike. The counts by movement type, i.e., Eastbound left turn (EBLT), eastbound through (EBST), and eastbound right turn (SBRT), are shown. The majority of vehicles travel straight through the intersection. A similar plot is shown for the movement breakdown on 26th Ave for vehicles in the southbound direction in Figure 44.

The sensor is also able to subclassify large vehicles, which includes a bus subclassification. To illustrate this feature, Figure 45 shows the bus frequency by movement direction across the intersection for the same week. Reduced service on the 4th of July is visible from the data.

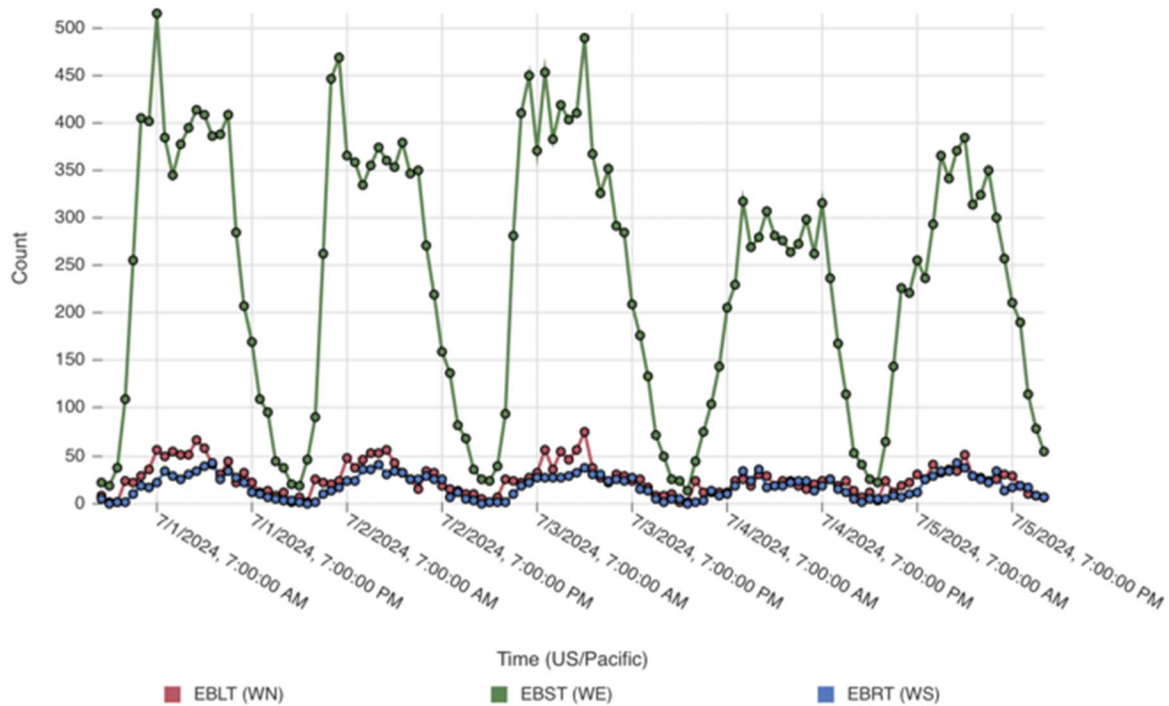


Figure 43 Total vehicle counts for eastbound direction (inbound morning rush hour), separated by turning movement. Eastbound left turn (EBLT), eastbound through (EBST), and eastbound right turn (EBRT) are shown for the week of July 1, 2024.

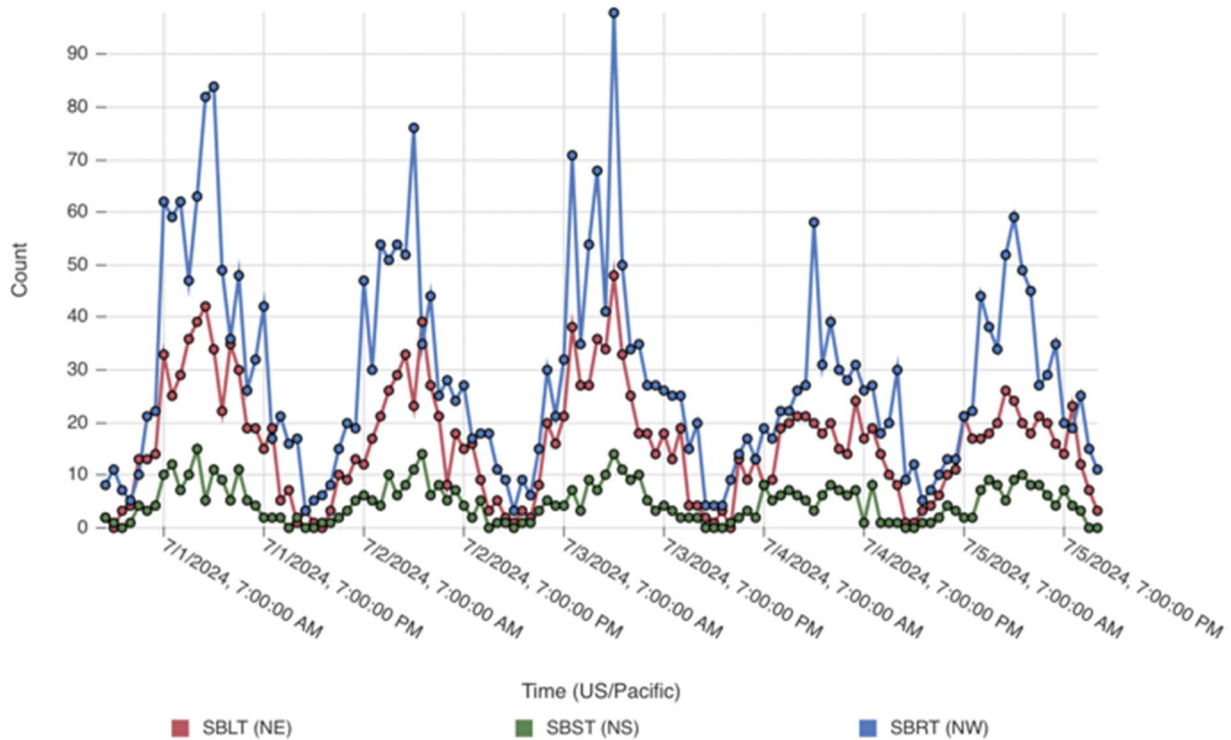


Figure 44 Total vehicle counts for southbound direction, separated by turning movement. Southbound left turn (SBLT), southbound through (SBST), and southbound right turn (SBRT) are shown for the week of July 1, 2024.

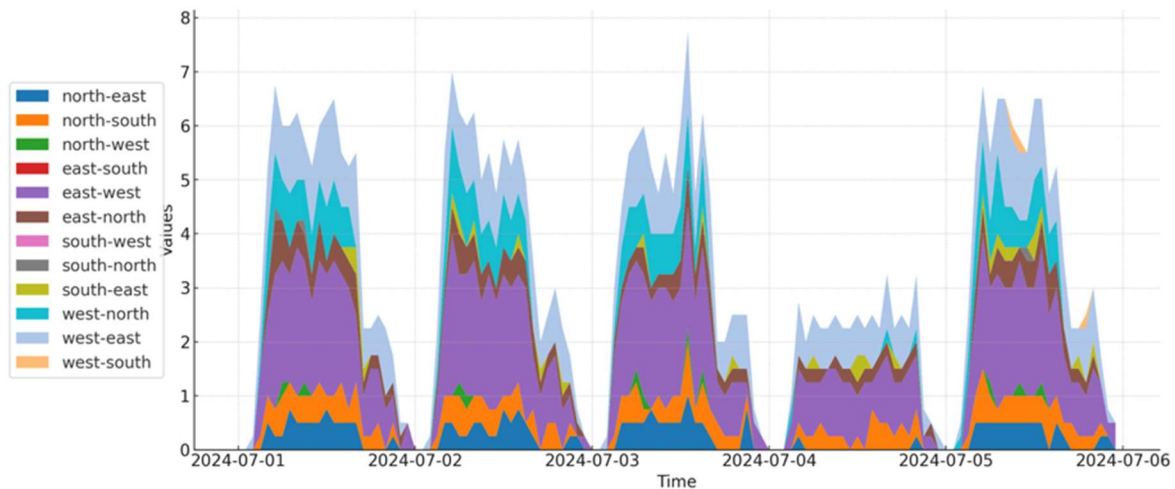


Figure 45 The sensor is also able to subclassify large vehicles, which includes a bus subclassification. Bus frequency, separated by direction movement across the intersection, is shown for the week of July 1-5, 2024.

Signal Actuation Accuracy

The ability of the proposed ITS lidar system to accurately detect vehicles present in a detection zone or at a stop bar is critical for successful and accurate signal actuation. This requirement expands the capabilities of ITS lidar from a data collection instrument to include roadway/signal operations at and beyond the capabilities of existing technologies. This report describes ITS lidar detection accuracy by validating against ground truth data.

Main result:

The lidar accurately detects vehicles in signal approach actuation zones and at stop bars.

- Vehicle presence in actuation zones was manually verified with the following statistics: 100% true positives, 0% false positives, 0% false negatives. This translates to every vehicle in the study period correctly detected.
- The system is also able to measure if vehicles are completely stopped at a stop bar, as opposed to a rolling stop or a stop occurring past the stop bar.

Approach:

A temporary video camera was installed at the intersection of 26th Ave N and Clarksville Pike (used only for count validation; cameras are not part of the deployed ITS lidar system). The video data was manually annotated to count vehicles at a stop bar and lidar vehicle counts and behavior data from the same period was compared. Figure 42 depicts the setup of the camera and corresponding lidar data. On the top, the live data from the sensor is shown, with vehicles in blue and a visible pedestrian in yellow. The bottom shows the corresponding frame from the camera, where vehicles and a pedestrian are visible.

A positive presence detection is defined as an instance where a vehicle is present in the detection zone behind the stop bar, and the lidar system detects that any number of vehicles occupy this same zone. Measures of interest are the number of true positives, true negatives, false positives, and false negatives, determined by comparison to ground truth data.

Findings:

In our video validation dataset, there are 168 vehicles manually annotated. The lidar system correctly detects the presence of each of these 168 vehicles. The 168 true positives occur with no false positives and no false negatives. Investigation showed that there was never an instance where a vehicle was present at a stop bar and not detected, nor was there a moment when a stop bar detection occurs without a vehicle. Note that in some cases of vehicles towing trailers, the trailer is detected as an object; these instances were not included in the statistics since trailers would normally count towards intersection actuation (e.g., with inductive loop detection).

Detection Range

Detection range is the distance at which the system can accurately detect road users. It is essential that the system can provide detection over the entirety of the region-of-interest.

Main result:

The effective sensor range of the Ouster OS1 is 80 m. This aligns with the reported range of 80 m in the manufacturer's documentation.

Approach:

We consider the detection accuracy for each class type detected by the sensor. The classifications considered are: {vehicle, large vehicle, person, bicycle}.

Specifically, we plot the class confidence as a function of distance. We do this for each class detected by the sensor. For clarity we limit our analysis to 100,000 points captured in early July 2024. Note a single detection is a detection of an object in a lidar return. For example, a single vehicle observed in a single sensor for 1 second generates 10 detections, since the sensor operates at 10 Hz.

For interpretation, it is important to note that more frequent high-quality detections are expected closer to the sensor. This is due to two factors. The first factor is that more points are returned on each object as the object is closer to the sensor. The second factor is that all objects are expected to be present near the sensor for longer periods of time. Vehicles wait at red lights to clear the intersection, pedestrians wait to cross the intersection, etc. Consequently, we expect more total observations near the sensor compared to further from the sensor.

Findings:

The following figures (Figure 46, Figure 47, Figure 48, Figure 49) show the main results for the person, bicycle, vehicle, and large vehicle detection classes. In each figure we show on the left a plot containing 100,000 detections, and on the right the density plot indicating the density of the data in each area. Across the four classes, we see high quality detections are observed out to 80 meters. Smaller objects (bicycles, persons) have few detections with class confidence above 80 meters and above 0.8 class confidence score (higher is better). On the other hand, vehicles and large vehicles have higher class confidences at larger ranges, sometimes exceeding 80 meters.

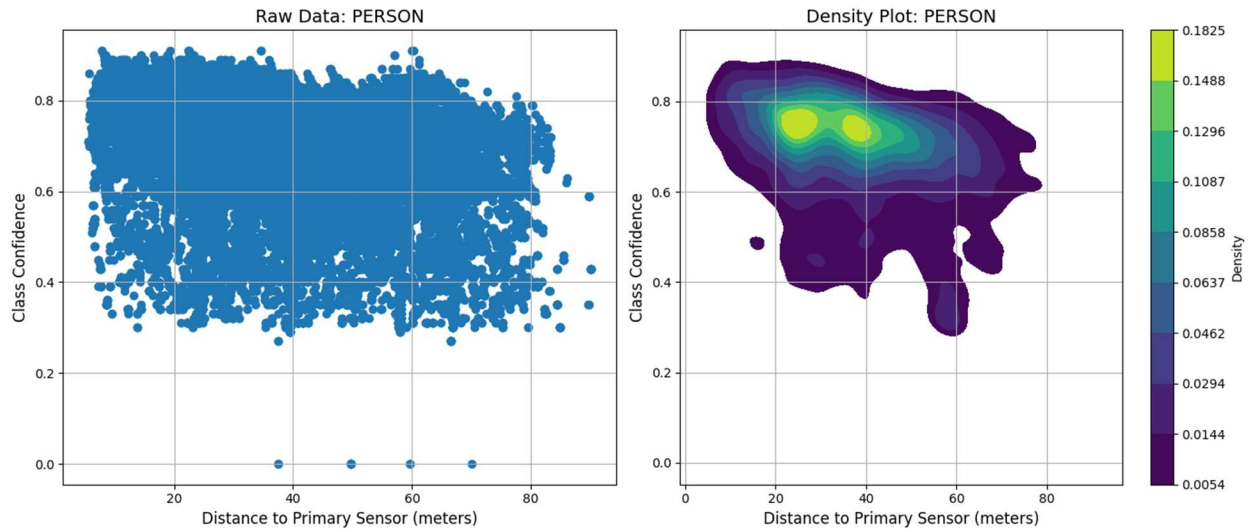


Figure 46 Class confidence of all “person” detections. Left figure. Plot of 100,000 observations comparing the distance to the sensor in meters (x axis) to the class confidence of the “person” detection. Right figure. Plot of the density of 100,000 observations confidence of the “person” detection. Right figure. Plot of the density of 100,000 observations comparing the distance to the sensor in meters (x axis) to the class confidence of the “person” detection.

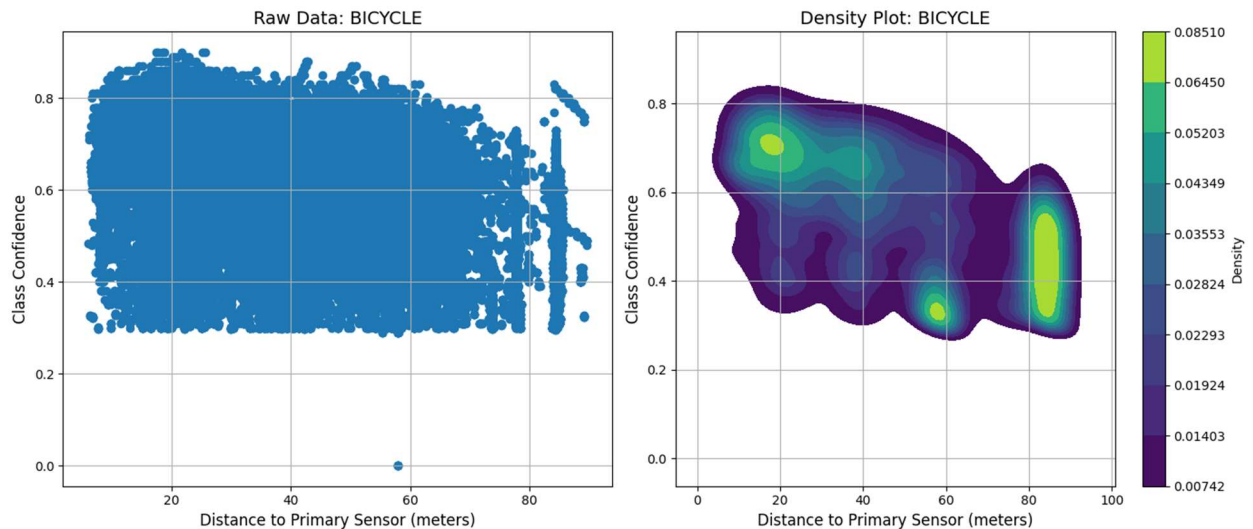


Figure 47 Class confidence of all “bicycle” detections. Left figure. Plot of 100,000 observations comparing the distance to the sensor in meters (x axis) to the class confidence of the “bicycle” detection. Right figure. Plot of the density of 100,000 observations comparing the distance to the sensor in meters (x axis) to the class confidence of the “bicycle” detection.

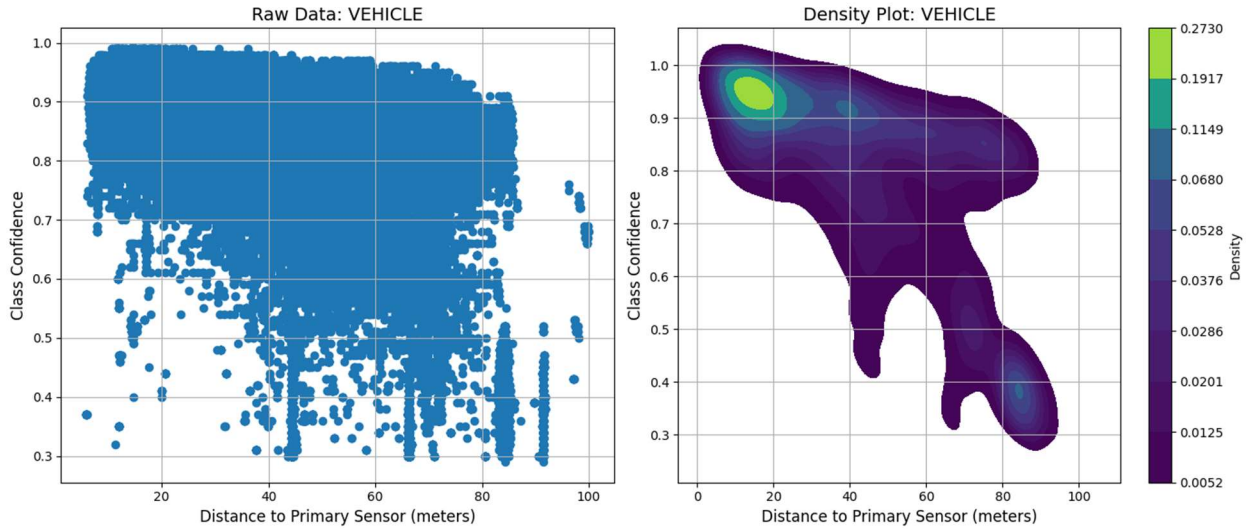


Figure 48 Class confidence of all “vehicle” detections. Left figure. Plot of 100,000 observations comparing the distance to the sensor in meters (x axis) to the class confidence of the “vehicle” detection. Right figure. Plot of the density of 100,000 observations comparing the distance to the sensor in meters (x axis) to the class confidence of the “vehicle” detection.

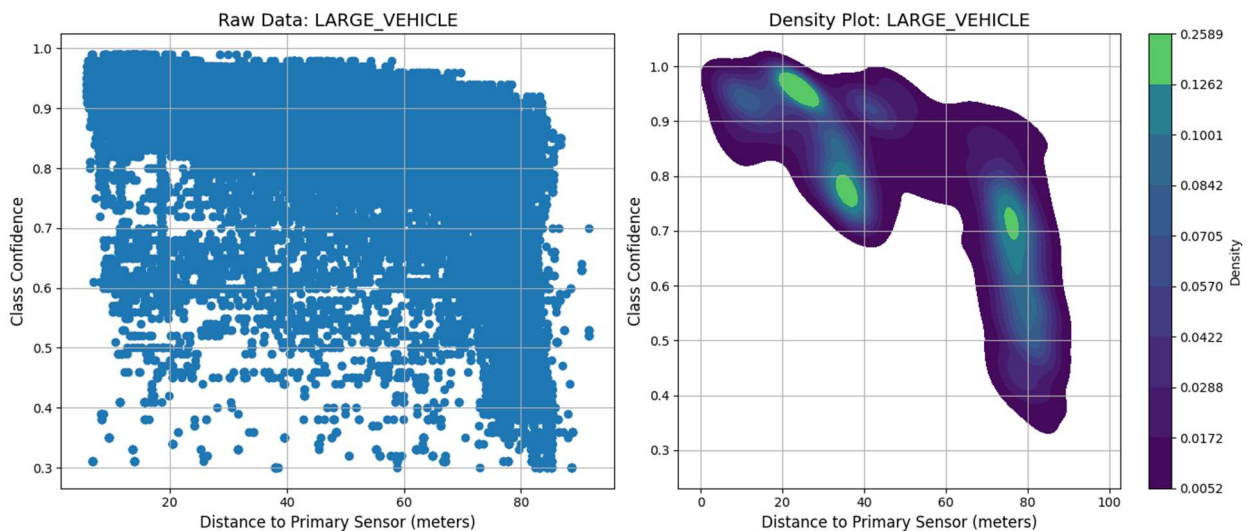


Figure 49 Class confidence of all “large vehicle” detections. Left figure. Plot of 100,000 observations comparing the distance to the sensor in meters (x axis) to the class confidence of the “large vehicle” detection. Right figure. Plot of the density of 100,000 observations comparing the distance to the sensor in meters (x axis) to the class confidence of the “large vehicle” detection.

Detection Latency

Detection latency measures the time it takes for the proposed system to identify and react to an event. A shorter latency is crucial to minimize the risk of accidents. We aim to achieve

near real-time detection, and any delays should be minimized during the proof-of-concept or prototype stage.

Main result:

The latency is negligible and appropriate for real-time actuation.

Approach:

The observed latency is the difference between the time the pedestrian enters the intersection and the time the light flashes accounting for the fact that the pedestrian was detected. Because of the difficulty of measuring sub-second timing delays, we took an experimental approach for validation. We created a temporary field setup that illuminated a beacon when a pedestrian entered the crosswalk to test the latency. The beacon flashed whenever a pedestrian entered one of the four crosswalks at the intersection. Figure 50 shows the detection zones that are used to separate pedestrians on the sidewalk from pedestrians in the crosswalk.



Figure 50 Pedestrian detection zones are configured in lidar software and linked to channels on a digital input/output device that can control or trigger equipment such as signal controllers or lighting.



Figure 51 The LADDMS team performed a live field validation (on the sidewalk of 26th Ave. and Clarksville Pike) of the pedestrian detection to in crosswalks for Director Stan Caldwell to demonstrate the negligible latency of the detection for real-time applications.

Findings:

The system can distinguish between a pedestrian on the sidewalk compared to a pedestrian in the crosswalk in real-time. We validated the quality of detection with 2 days of testing on the flashing beacon. The accuracy was demonstrated live during Director Stan Caldwell's visit to Nashville in Spring 2024, see Figure 64.

Distance and Speed Estimation Accuracy

The system should accurately estimate the distance and speed of pedestrians and VRUs. This information is vital for assessing the potential threat and triggering timely alerts or safety measures. The accuracy of these estimations will be measured against ground truth data.

Main result:

The sensor reports accurate speeds and positions.

- We confirmed the positional accuracy of trajectories are within the noise floor of GPS.
- We confirmed the speed accuracy is within 1 m/s of an instrumented Toyota Rav4 from which we can directly observe the vehicle speed from the vehicle's own onboard sensors (accessed via the CAN).
- We confirmed the ability to generate comparisons of the average speeds of vehicles on each approach.

Approach:

To validate the positional and velocity accuracy of the trajectory data obtained from lidar, we performed a comparison of the reported data to the data obtained from Vanderbilt University's Toyota Rav4 research vehicle. The vehicle, shown in Figure 52, is equipped with custom CAN decoding software and hardware that allows access to onboard measurements from the vehicle's stock systems. For example, the vehicle speed (used for cruise control) is directly recorded. The vehicle is also instrumented with a GPS sensor which obtains 3-5 m positional accuracy in clear sky conditions. We drove the vehicle through the intersection to compare the instrumented runs to the recorded lidar data.

We also validate the ability to use the speed data for comparisons in the BlueCity software.



Figure 52 Vanderbilt University Rav4 instrumented with CAN decoding capabilities. We use the vehicle (shown here as used by the Traffic and Autonomous Vehicles undergraduate class offered at Vanderbilt by LADDMS partners Prof. Work and Sprinkle) to validate the lidar installation by driving through the intersection and comparing the speed as reported in the lidar with the speed recorded directly from the vehicle.

Findings:

The main results are shown in Figure 53 and Figure 54. Figure 53 shows all three vehicle trajectories recorded at the same time as our instrumented vehicle drive, plotted in the lidar local coordinate system (which has a zero, zero coordinate in the middle of the intersection).

The orange trajectory from the lidar corresponds to our instrumented vehicle's trajectory in black. Given that the GPS positional error is expected to be larger than lidar (and moreover it is highly correlated in time, so a positional error from one second to the next occurs roughly in a similar magnitude and direction), we simply apply a best fit of the positional data to align the trajectories. Visually there is good agreement on the positions reported from the GPS and those reported from lidar.

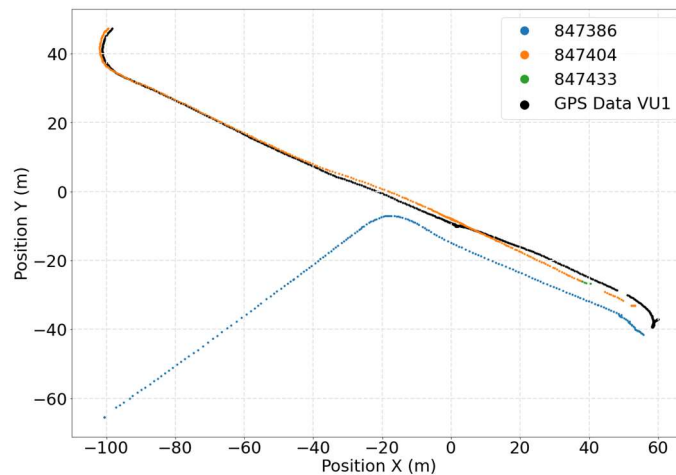


Figure 53 We have also validated the trajectory of the vehicle by overlaying the lidar data with our Rav4 trajectory. All vehicle trajectories collected at the same time as our vehicle are shown. The ID numbers in the legend correspond to the Object_ID from the Ouster lidar sensor tracking. The orange trajectory is our vehicle as seen by the lidar. The black trajectory is our GPS position. The difference in positions can be traced to GPS positional error, confirming we have high quality position data available to us from the lidar.

The sensor manufacturer, Ouster, reports sub 1cm accuracy on the range performance. There are also many qualitative assessments from the project team looking at data in real-time as well as in video data recordings for pedestrian and vehicle counts that allow us to conclude that the sensor produces accurate positional data below the noise floor of GPS.

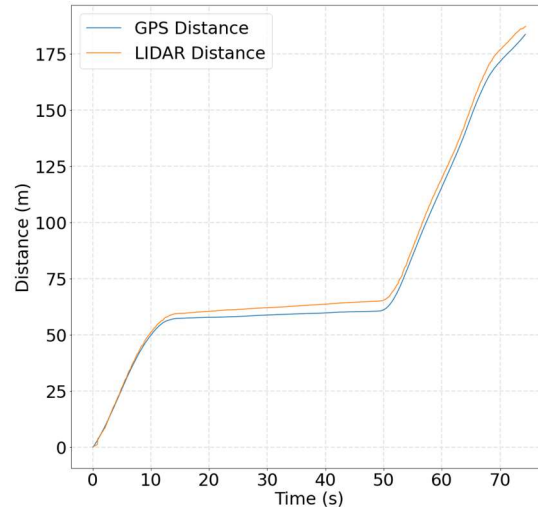


Figure 54 shows the cumulative sum of the distance travelled by the test vehicle as measured by an onboard GPS sensor and by the lidar sensors. The lidar is shown to over-estimate the distance travelled by under 2% in comparison to the GPS sensor.

Next, we compare the cumulative sum of the distance traveled by the test vehicle using GPS and lidar, as shown in Figure 54. The cumulative distance as a function of time of both the lidar trajectory and the GPS trajectory have good agreement. On this trajectory, the GPS cumulative distance and the lidar cumulative distance differ by less than 2% of the total distance traveled.

We next compare the velocity of the CAN data recorded from the vehicle (roughly, it allows us to read the speed data that the onboard systems such as the stock adaptive cruise control also use), with the lidar speed data. Figure 55 shows the velocity timeseries, including a large portion of time at which the vehicle is stopped at the traffic signal. The lidar is consistently faster than the CAN data but by a relatively small amount. The root mean squared error between the two speed estimates is 0.802 m/s, with a standard deviation of 0.632 m/s. The cause of the small discrepancy is unknown at this time but may be due to different data smoothing approaches used in the GPS receiver compared to what is used by the lidar.

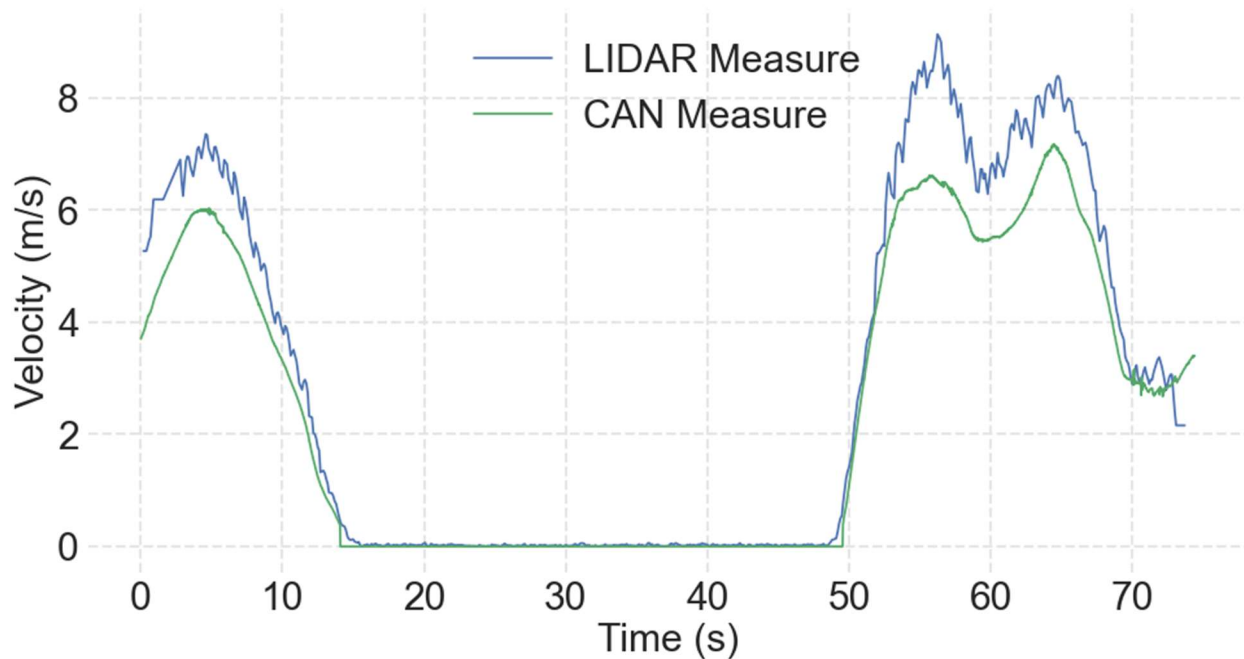


Figure 55 shows the velocity timeseries of the instrumented vehicle relative to the lidar. We see that the lidar has a slight bias to be faster than the data recorded from the vehicle CAN, and the average error of 0.802 m/s root mean squared error, with a standard deviation of 0.632 m/s.

With valid speed data being recorded, we can then look at speed patterns over longer periods of time. Figure 56 displays the hourly average speed along each approach, which shows faster average speeds are observed on the main road (Clarksville Pike). Note this plot shows the average of all vehicles through the intersection, which includes the time when the vehicle is stopped at the intersection. Figure 57 shows a different way to visualize the speed data which is integrated into Blue City software. Blue City allows generating a box plot showing the distribution of vehicle speeds at each approach.

In more detailed analysis such as the one provided for our super-speeders intervention validation reported above, it is beneficial to consider speed statistics along each trajectory of each vehicle.

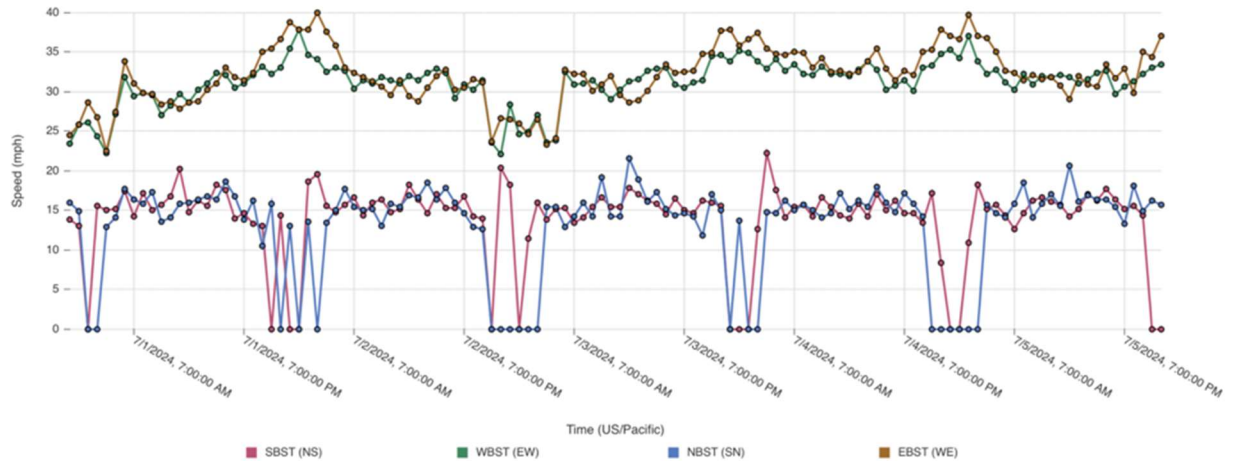


Figure 56 Average hourly speed of all vehicles traversing the intersection of Clarksville Ave and 26th Ave. during the week of August 1. The eastbound through (EBST) and westbound through (WBST) movements have average speeds that are 10-15 mph faster than the minor street (26th Ave; shown as northbound through (NBST) and westbound through (WBST)).

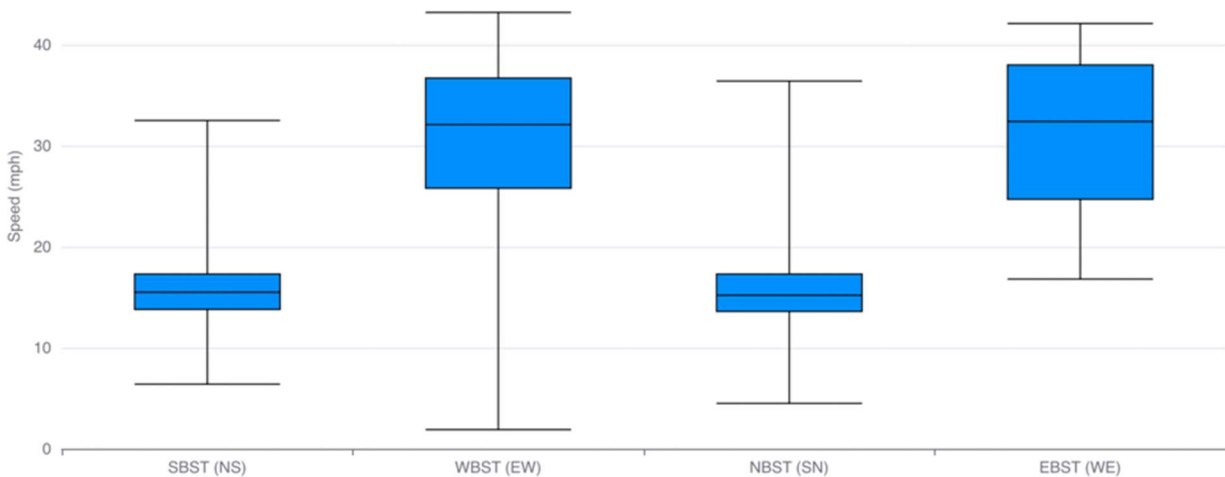


Figure 57 Distribution of vehicle speeds shown as a quartile box plot, separated by direction of straight-through movements.

Environmental Robustness

The system's performance should be evaluated under various environmental conditions, including adverse weather (e.g., rain, snow, fog), low-light conditions, and variable traffic densities. Robustness in adverse conditions is a critical factor for the system's real-world utility.

Main result:

Based on the available data we have, the preliminary data on the system shows that it is robust. The system achieved a 99.93% uptime when it received power to run.

Approach: We explored the total number of object detections from the 26th and Clarksville intersection over a span of a month. The data patterns are periodic, showing a large number of detections during the day and a decrease in object detections at night. Periods where no data is received are noted as outages.

Main results:

The main result is shown in Figure 58. Two outages are shown in grey near the period of 6/29/2024. The first visible outage occurred for 17 hours and was due to the intersection losing all power during a severe storm. After power was restored, the system came back online. A second smaller outage occurred approximately 2 days later. This outage took the sensor offline for an unexpected cause. Excluding the outage due to no power, we calculated a 99.93% uptime for the sensor.

In future analysis we will perform more assessments, e.g., in cold weather. The lidar manufacturer reports good performance in inclement weather. Informally we have observed good performance in rain and in nighttime settings, although a quantitative analysis is needed to fully validate our anecdotal observations.

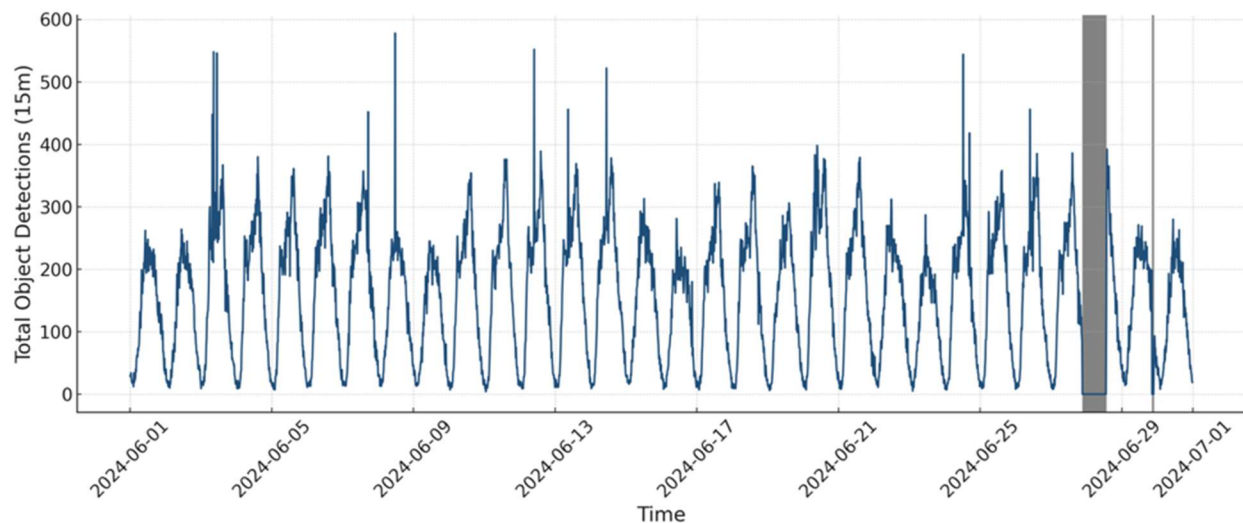


Figure 58 Total object detections for the month of June, 2024, showing two periods of sensor data outage in grey. The larger outage was a 17-hour outage due to the intersection losing power during severe weather. Discounting this month, total sensor uptime was 99.93%.

Near-miss timeseries

The ability to measure near-miss events over time allows continuous monitoring and tracking of safety along the corridor.

Main results:

The sensor accurately records near-misses using the post encroachment time criterion, allowing quantification of safety concerns that were previously impossible to measure with traditional methods available to NDOT. See also *Near-miss accuracy reported earlier in Section 2*.

Approach:

We validated individual near-miss events earlier in the report, and here report the temporal evolution of the near-miss events as reported in the Blue City software. Near-misses are again quantified using the *post encroachment time* (PET). The Blue City software automatically tabulates the number of events with PET within a threshold (the magnitude is reported, rather than a signed value as used previously in the report).

Findings:

As shown in Figure 59, the number of near-misses between vehicles and non-vehicles (defined as post encroachment time of less than 2 seconds) is 20.1 near-misses/day, with a standard deviation of 6.6 near-misses per day. The analysis was conducted over an 86-day window from April through July 2024. We further plot the PET frequency between 0 and 2 seconds in Figure 60 for improved readability. Finally, Figure 61 and Figure 62 show that it is possible to inspect individual near-miss events using Blue City, in a comparable approach to what is reported in earlier sections. This demonstrates scalability of the near-miss analysis used in the report, because it is a plug-and-play feature in Ouster's Blue City Software.

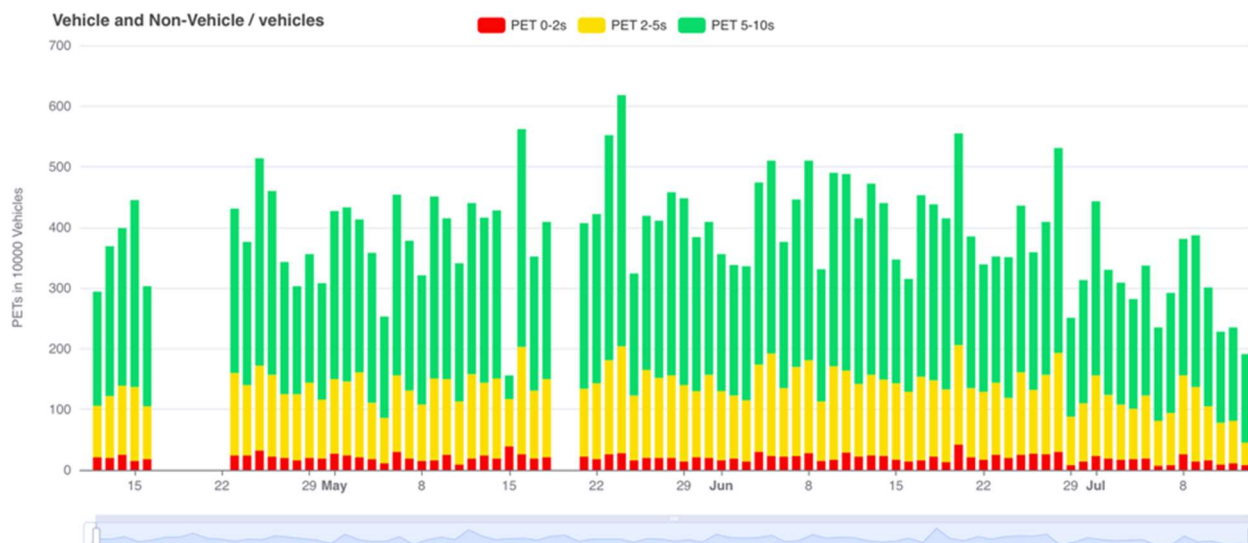


Figure 59 The PET of the lidar installation at 26th Ave. and Clarksville Ave. from April 15 – July 13. Red indicates PET values between vehicles and non-vehicles between 0-2 seconds, yellow indicates PET values between 2-5 seconds, and green indicates PET between 5-10 seconds. The data outages April 16-22 and May 19-20 were due to planned work on networking and communication reconfigurations.

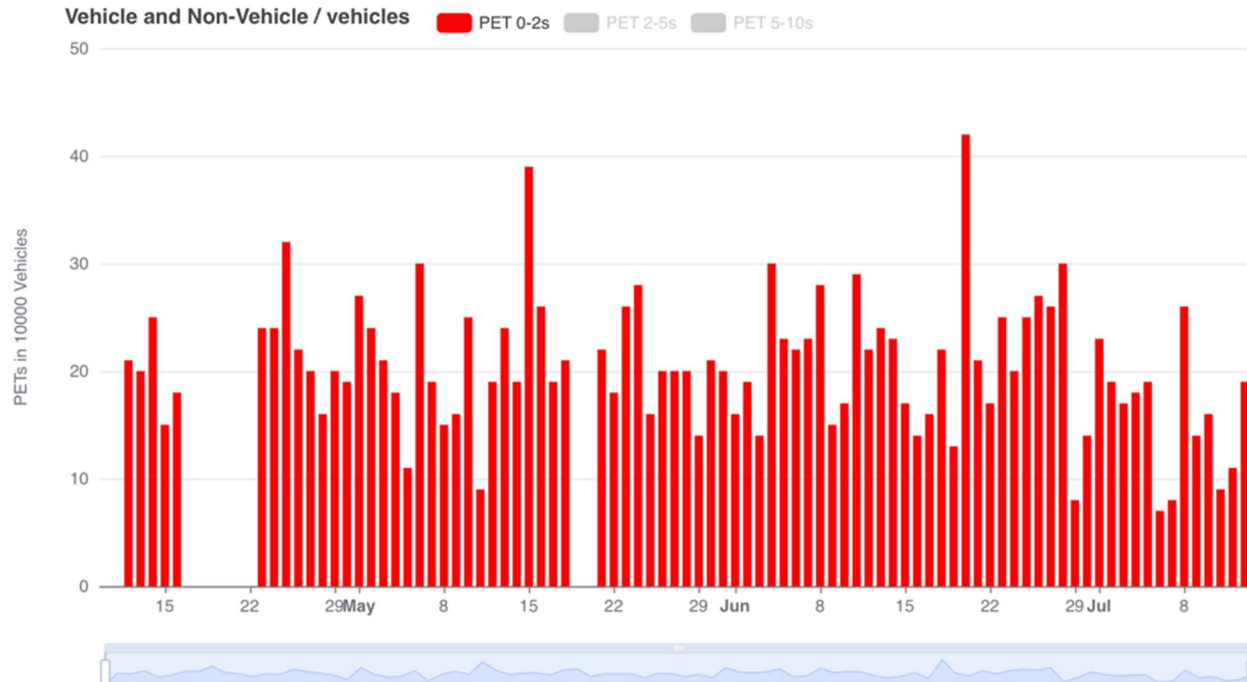


Figure 60 The PET of the lidar installation at 26th Ave. and Clarksville Ave. from April 15 – July 13. The number of near-misses between vehicles and non-vehicles (defined as post encroachment time of less than 2 seconds) is 20.1 near-misses/day, with a standard deviation of 6.6 near-misses per day.

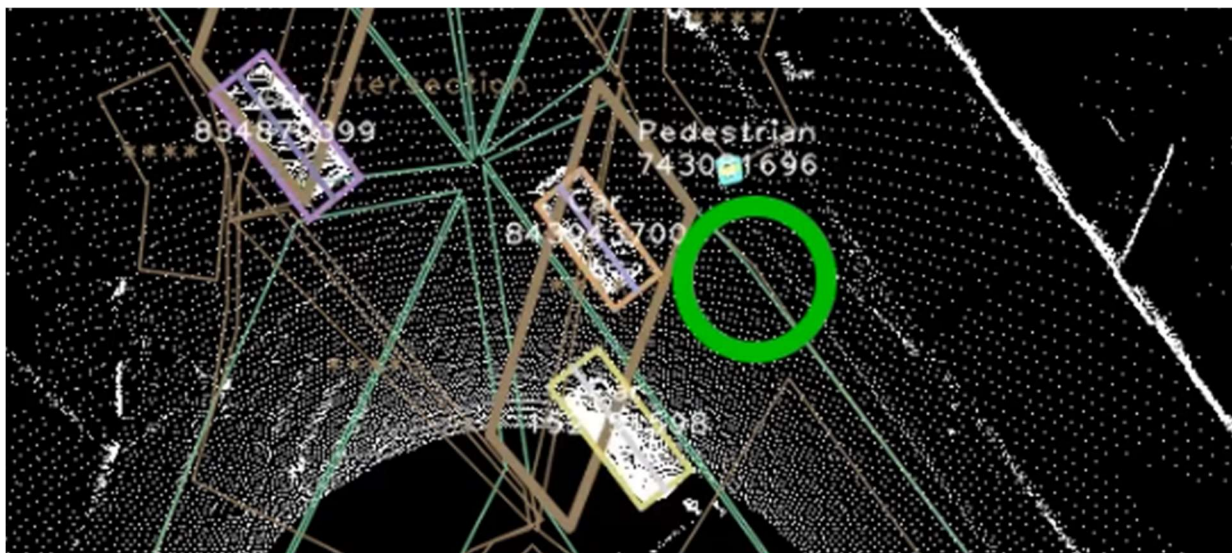


Figure 61 Single frame from a near-miss (PET < 2 sec) observed at 11:59PM on July 13, 2024. The green circle indicates a region where the pedestrian trajectory ID 743081696 will have a low PET with vehicle trajectory ID 554026880 not yet visible in the scene). See the following figure for a detailed time evolution. Individual replay of low PET events allows validation of the detected events.

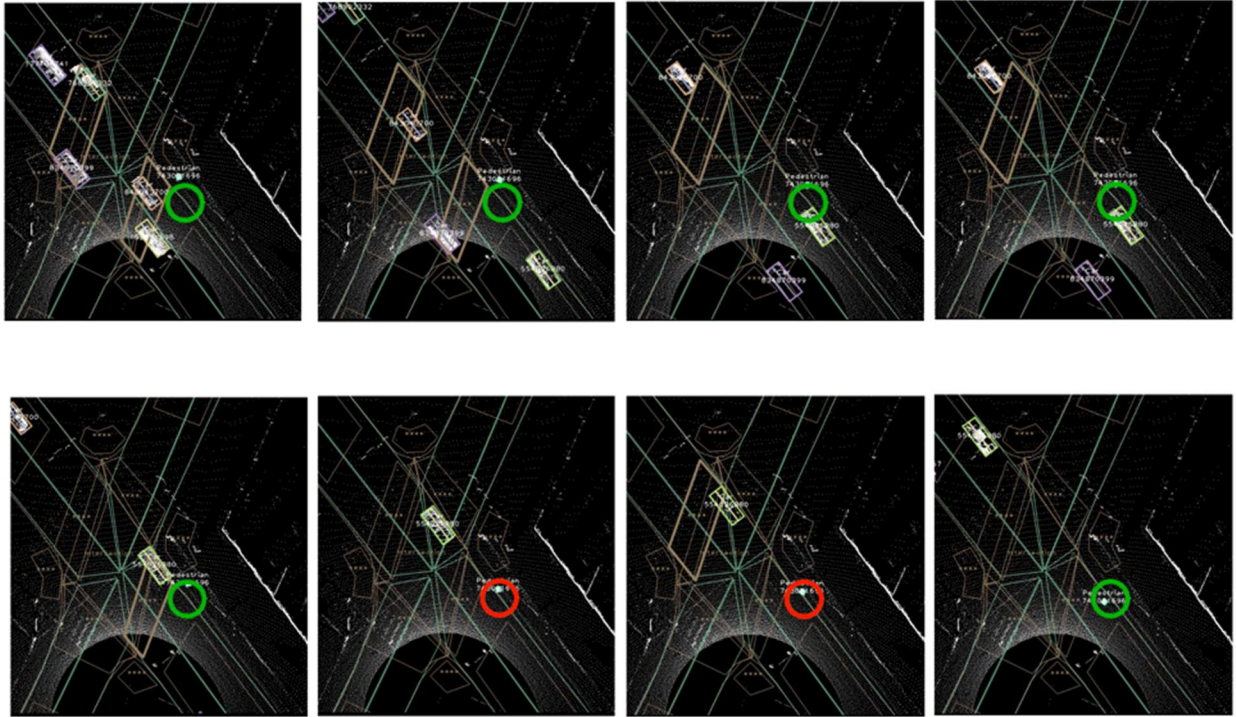


Figure 62 Individual frames over a 5 second interval from a near-miss observed at 11:59 PM on July 13, 2024. The circle indicates the location of the $PET < 2$ near-miss (the circle is red during the low PET interval). In this instance, the pedestrian immediately follows the vehicle.

Accuracy of Pedestrian and Vulnerable Roadway Users (VRU) Detection:

The ability of the proposed system to accurately detect vulnerable roadway users (VRUs). We will measure the system's detection accuracy by comparing the number of true positives, true negatives, false positives, and false negatives against ground truth data.

Main result: The sensor data can detect out of crosswalk events, but the cloud software must be properly calibrated to enable validation. We reported on the accuracy of pedestrian detection in an earlier section of this report.

Approach: To determine the validity of the out of crosswalk events, we use the Blue City software to visualize and count out of crosswalk events. We selected a single day of out of crosswalk events, and manually verified the first 20 events.

Findings:

The Blue City software allows direct visualization of hotspots of out-of-crosswalk events (Figure 63), as well as the ability to visualize individual trajectories (Figure 64). Because the point cloud for out of crosswalk events is saved in Blue City, it makes validation of out of crosswalk events easy to manually check.

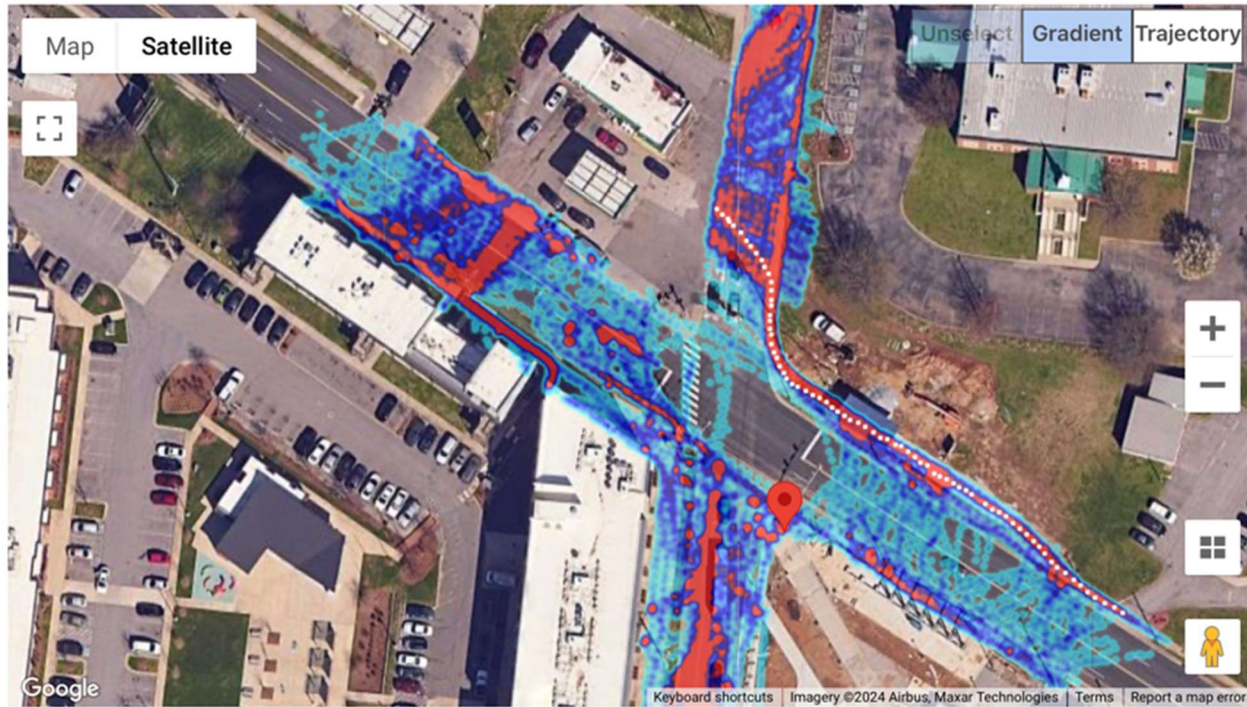


Figure 63 All of the out-of-crosswalk detections by density on a single day (July 12, 2024). Each trajectory corresponds to an out of crosswalk event that can be played back with lidar point clouds through the blue city software (see Figure 64 below).



Figure 64 Out of crosswalk event log at 26th and Clarksville Pike. Individual inspection of each trajectory and playback of conditions during the event are possible. Frequent crossings of Clarksville Pike west of the intersection and 26th Ave north of the intersection are due to nearby residents visiting convenience stores.

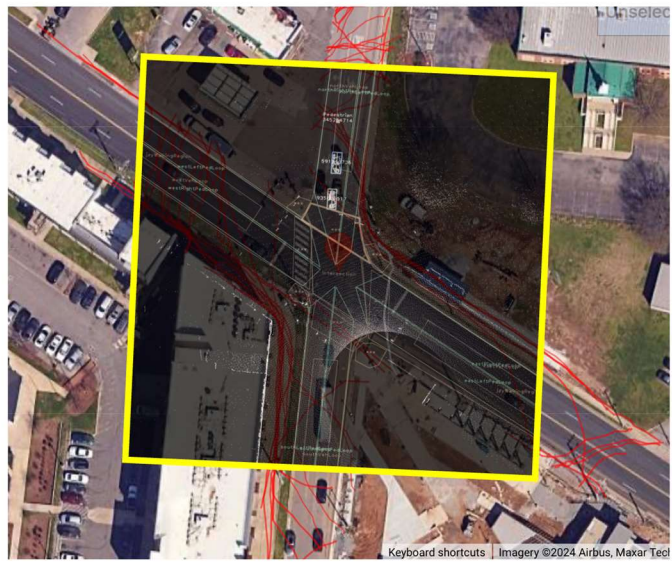
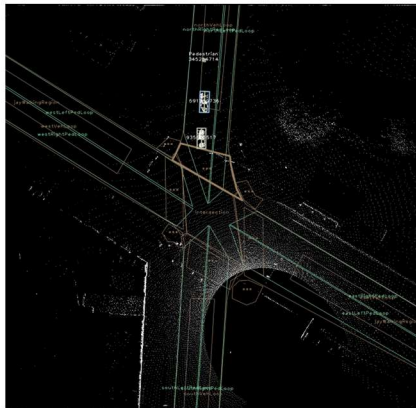


Figure 65 Illustration of the playback feature in BlueCity software. The left shows the field of view of the out of crosswalk lidar point cloud playback feature, used to validate out of crosswalk events. The right figure shows the BlueCity map with out of crosswalk trajectories from July 28, 2024, shown in red. The yellow box surrounds the approximate field of view of the recording.

Out of the 20 events we replayed, eleven visualizations clearly contained a pedestrian crossing or in the roadway at a non-crosswalk location. The remaining nine visualizations contained no pedestrians, which is the result of a software setting (explained next).

We further inspected the data as shown in Figure 65. The left image shows a single frame from the lidar point cloud replay feature. On the right, the same image is overlaid on the visualization of the trajectories for the given day. From the overlay on the right, it is clear that some reported out of crosswalk events (red trajectories) cannot be visualized in the playback without adjusting the configuration of the recorded field of view. This is because the crossing occurs outside of the yellow box, where the replay feature works.

Based on this insight, we conclude the likely cause of the nine visualizations containing no pedestrians is due to the field of view setting. We are coordinating with Ouster to improve the configuration that will allow improved validation within Blue City. Because the lidar unit also makes the raw trajectory data available, we are still able to validate out of crosswalk events corridor-wide from outside of the Blue City software, as we did for our out-of-crosswalk intervention reported earlier in the report.

Test Scenarios and Datasets:

To assess performance comprehensively, a diverse set of test scenarios and datasets will be employed. These may include urban and suburban environments, different road types, and scenarios involving pedestrians, bicyclists, motorcyclists, and other VRUs. Real-world data will be collected and analyzed to ensure the system's performance aligns with real-world traffic situations.

Main result:

The system is able to analyze pedestrian safety at each of the eight install locations which differ in geometry and speed limit and works in daytime and nighttime.

Approach:

To demonstrate the performance of the complete system, we look at out of crosswalk events throughout the corridor. Here the analysis is based on the raw trajectory data that is available through the edge compute units. We count all out of crosswalk events that occur within 25 m of the crosswalk at signalized intersections (labeled as out of crosswalk event at a signalized intersection) and compare to all out of crosswalk events that occur more than 25 m from the crosswalk at signalized intersections (labeled as midblock out of crosswalk event). All out of crosswalk events at non-signalized intersections are labeled as midblock out of crosswalk events.

Findings:

The results of the corridor-wide analysis for a single day are shown in Figure 66. On the left we observe 954 out of crosswalk events occurring near signalized intersection crosswalks, and 658 at midblock settings. When separated by time of day, we find that 25% of the 954 out of crosswalk events at signalized intersections occur at night. Exploring the midblock out of crosswalk events, we see that 30% of the events occur at night. This confirms the system is working in a variety of contexts and also highlights a new potential safety concern, which is crossings occurring in nighttime hours in the dark.

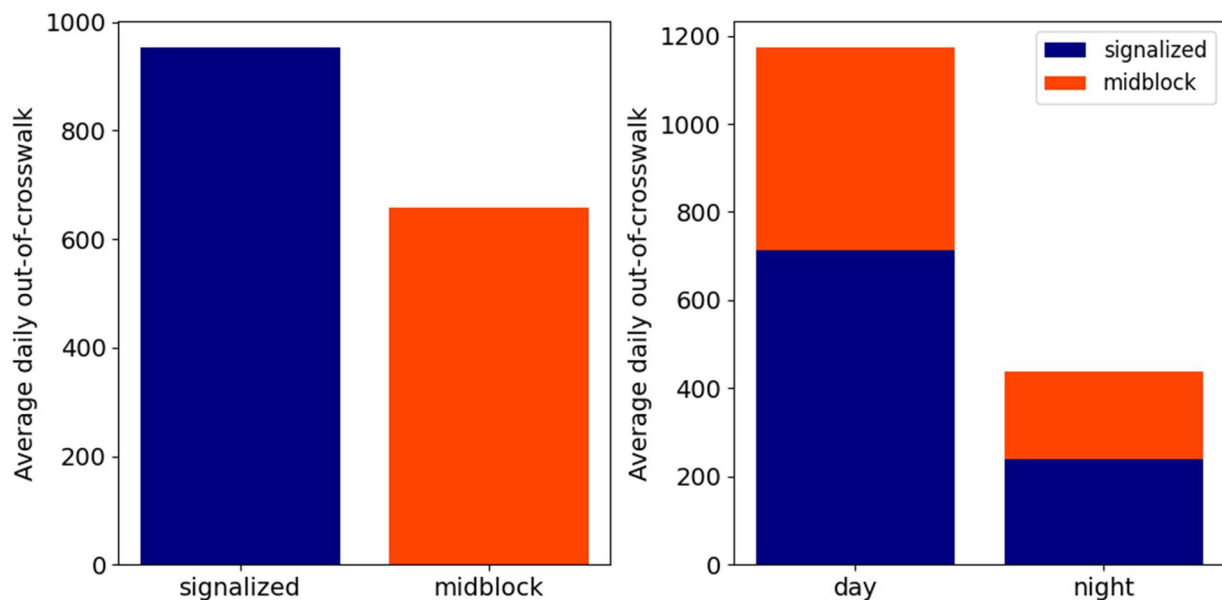


Figure 66 Left Out of crosswalk events occurring within 25 m of a signalized intersection crosswalk compared to all midblock crossings (either at midblock locations or further than 25 m from the signalized intersection)

crosswalk). A large number of crossings occur at midblock locations). Right Comparison of the same out of crosswalk data, visualized by daytime and nighttime.

Sensitivity Analysis:

The system's sensitivity to parameter variations and sensor configuration will be studied. This analysis will help optimize the system's design and parameters for specific use cases and environments. This will provide a framework for large-scale deployment.

Main result: The out of crosswalk pedestrian activity varies substantially by location, and the count depends on how the zones are drawn.

Approach:

To assess the sensitivity of out of crosswalk events to location and to how the out-of-crosswalk zones are configured, we explore out of crosswalk data for the period of July 24-26, 2024. We start with a conservative estimate of the location of the roadway, drawn in GIS software to aid interpretation of the trajectory data. We then expand the zone by 1 meter in all directions, and 2 meters in all directions (still within the roadway) to observe how the pedestrian counts out of the crosswalk change.

Findings:

The baseline conservative out of crosswalk data is shown in Figure 67. and shows out of crosswalk events by location. Location F has a large number of out-of-crosswalk events (642) dominates the out of crosswalk events (39% of the corridor total). This matches with informal field observation; the intersection has a lot of pedestrian activity in general.

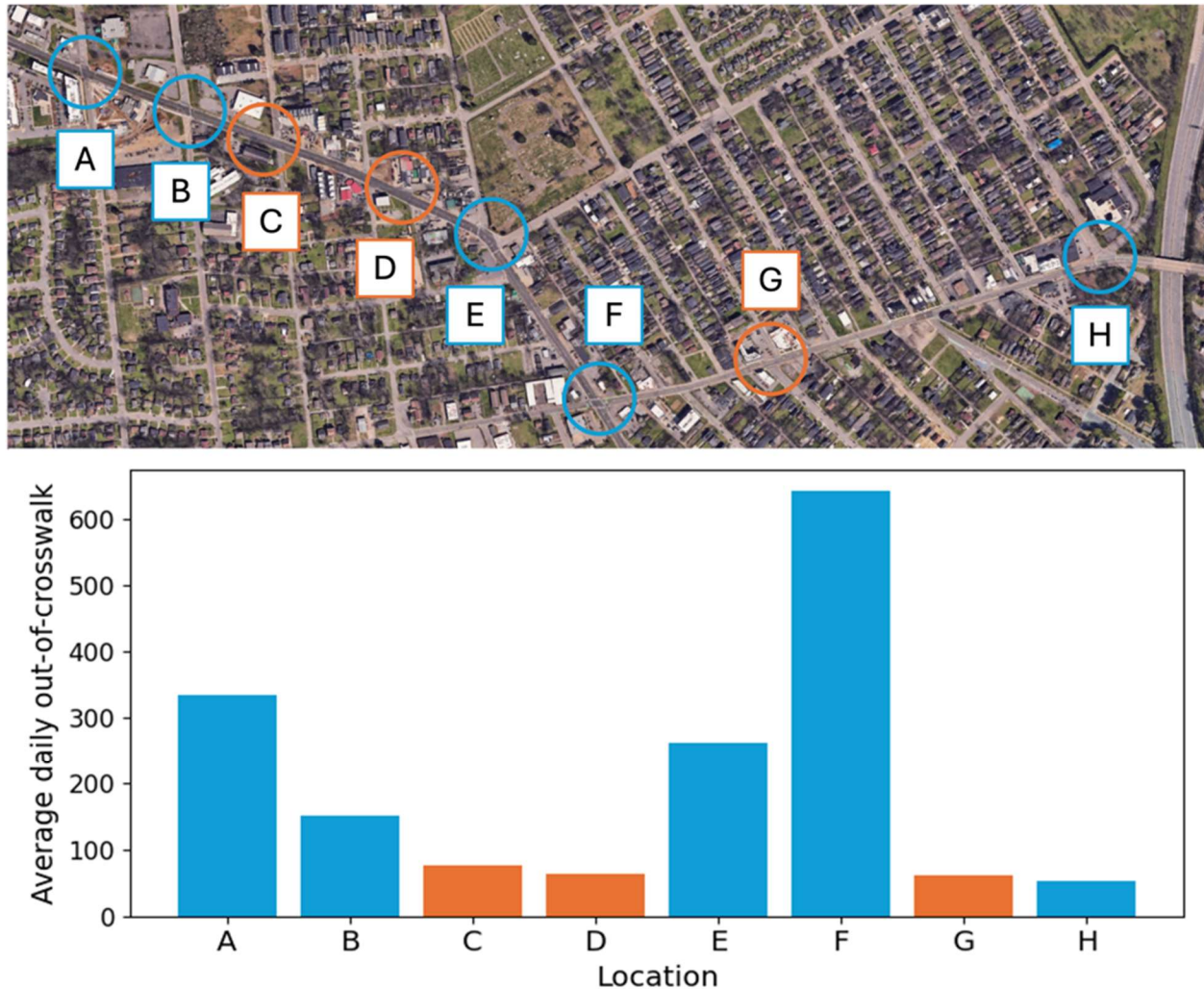


Figure 67. Out of crosswalk data for each of the eight installation locations from July 24-26, 2024. The top shows the locations in North Nashville labeled A-H. Midblock locations are colored in orange, while signalized intersections appear in blue.

To understand the sensitivity of the counts as a function of the size of the zone, we proceed to increase the area that defines the out-of-crosswalk area (Figure 68). As the area increases by 1 m at each intersection, we see the out of crosswalk events increase by 39.1% across the corridor. As the area increases by 2 m, we see the out of crosswalk events increases by 66.8%. We note that all areas remain within the roadway, so it highlights that a consistent approach to the definition of out of crosswalk area is important for comparable results across intersections (as we have done).

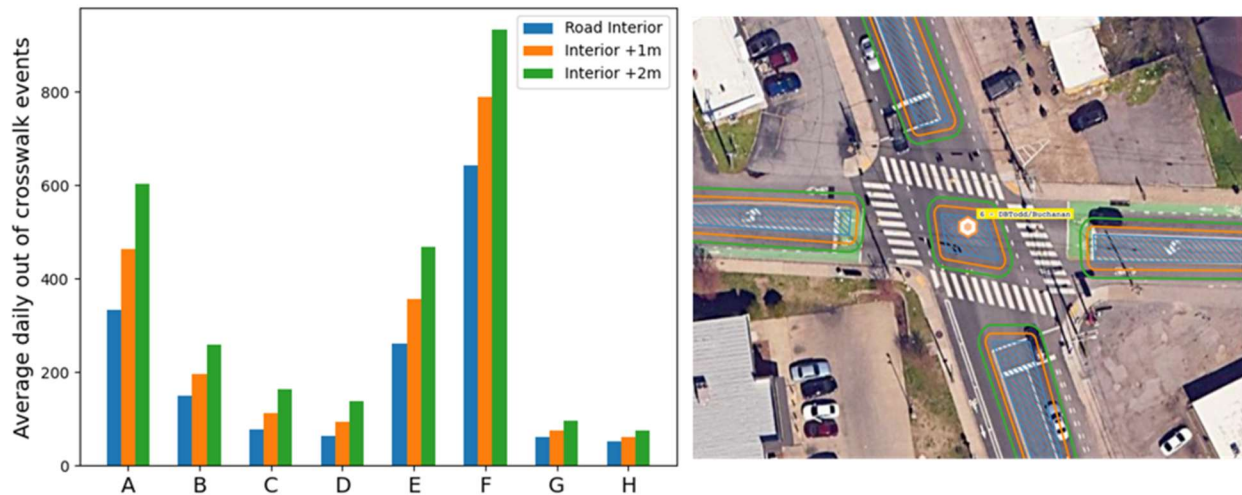


Figure 68. Left: average out of crosswalk events for each of the eight locations as a function of the shape of the area defining the out of crosswalk area. Right: A zoom in of intersection F shows the road interior in blue, the expanded interior (+1 m) in orange, and the expanded interior (+2 m) in green).

Original expectations and progress on goals

Our project has exceeded original expectations. The deployment provides more complete data than any other corridor in Nashville, and the project is allowing us to discover issues that are not possible along any other corridor in Nashville. We have expanded beyond our original scope to add partners, win additional funding (a new grant from *Tennessee Department of Economic and Community Development* was recently announced), and invest local funds to expand to additional signals not currently part of our Stage I project.

We provide a summary table of our original goals and our progress to meet them in Stage I in Table 69 below.

Category	Goal	Met?
Safety and Reliability	Expand Safety Measures	Yes, by providing count data on non-motorized road users
Safety and Reliability	Support Vision Zero	Yes, by enabling evaluation of interventions
Safety and Reliability	Improve Crash Data Collection and Quality	Yes, through near-miss detection
Safety and Reliability	Analyze and Assess	yes, enabled discovery of significant out of crosswalk events and excessive speeding

Safety and Reliability	Protect Vulnerable Users	Yes, by allowing safety concerns to be monitored and interventions to be data driven
Resiliency	Improve Reliability of the Transportation System	Yes, through successful integration of the sensors with signal control infrastructure
Resiliency	Improve Cybersecurity	Yes, through involvement of Metro ITS as a partner.
Partnerships	Effectively Engage Community	Yes, through early community engagement activities
Partnerships	Foster Collaborations with the Private Sector	Yes, through collaboration with Ouster
Partnerships	Demonstrate Leadership and Organizational Capacity	Yes, by growing an expanding team of experts
Integration	Safety and Technology Expansion	Yes, by integrating the sensor into the TMC
Integration	Improve EMS Response and Preparedness	Yes, indirectly. The data can support incident detection as a future capability
Integration	Improvement of Transportation System Status Quo	Yes, the project supports NDOT's departmental priorities on safety
Workforce Development	Promote Local Workforce Dev.	Yes, through engagement with TSU students and workers at Stansell, NABCO
Workforce Development	Increase Knowledge and Skills	Yes, through research and practitioner exchanges & student engagement
Workforce Development	Increase Univ. NDOT collaboration	Yes, through weekly (minimum) meetings

Table 69 Summary of goals and progress.

Stage 1 demonstrated improvement

Safety and reliability.

We demonstrated the ability to detect safety issues that were previously not quantified or unknown.

- **Speeding.** Residents in our community engagement identified speeding as an issue. We are able to quantify speeding vehicles using the sensors that are installed. See our results described above in which we reduced the share of vehicles traveling 40 mph in a 25-mph zone and 60 mph in a 40-mph zone by 35% and 30% respectively.

- Near-miss detection. The blue city platform we purchased from ouster directly computes near-miss events. We manually validated the findings by inspecting 68 near-miss events.
- Out of crosswalk intervention performance. On Clarksville Pike, we identified significant out of crosswalk events in a specific area. To test the proof of concept of intervention, we talked to community members, added a temporary fence, and retimed the signal. We reduced the share of out of crosswalk events by 75%, and observed the events shifted to an unexpected location.

Resiliency

We improved resiliency of the signal system. During a storm on the weekend of July 4, we identified anomalous trajectories observed at 26th and Clarksville. Using the data, we were able to detect the signal was in flash. A request to the signal shop allowed the signal to be reset so that it returned to normal operation before it was called into hub Nashville (our community input system). This demonstrates the ability of the sensor network to improve the resiliency of the traffic signal control system to extreme weather-related events.

Partnerships

The project, led by NDOT, included the following founding project partners: Tennessee State University, Vanderbilt University, and University of Tennessee Chattanooga. As Stage I evolved, the project team expanded. The Stage I project partners has grown to include Metro (Nashville local government) Information Technology Services (Metro ITS), Ouster, the manufacturer of the lidar sensors, AECOM, a consulting company assisting with design and project management, Austin Peay University, located in Clarksville, TN, and the City of Clarksville, TN.

Our partnership with AP and Clarksville was funded through the *Transportation Network Growth Opportunity* (TNGO) initiative, under *Tennessee Department of Economic and Community Development* (TNECD) and in partnership with Launch Tennessee and Team Tennessee, is an economic development tool designed to connect statewide research assets, communities and talent to spark new research and innovation in this sector.



The goal of TNGO is Economic development tool used to connect and leverage research and innovation assets statewide. The initiative focuses on making Tennessee the No. 1 destination in the Southeast for mobility R&D investment.

Integration

Our live viewer (located at <http://ndot-laddms.mogi.io>), is now integrated into our Traffic Management Center. We are in the process of reviewing our standard signal detection equipment to consider the benefits of installing lidar as an alternative detection technology. This will enable us to automatically collect critical data on peds and other vulnerable road users at signalized intersections beyond those funded through SMART grant activities.

Workforce development

We held 3 training sessions (one at Vanderbilt, one at Stansell Electric Company, and one at NABCO Electric Company), resulting in 26 staff trainings. NABCO is affiliated with the International Brotherhood of Electrical Workers. NABCO and Stansell are the two largest signal maintenance contractors in middle Tennessee.

Part 3 of 6: Anticipated Costs and Benefits of At-Scale Implementation

Expected impacts of at-scale implementation

Safety and Reliability

Our project will improve the safety of the transportation network for all roadway users with increased focus on pedestrians, bicyclists, and other vulnerable users. Additionally, we will improve emergency response. We expect to rapidly assess problematic safety issues along the corridor, and deploy interventions designed to proactively improve safety. We will rapidly assess interventions and use the findings to improve the effectiveness of Metro's Vision Zero Implementation.

Resiliency

We will increase the reliability and resiliency of the transportation system, focusing on data management and security through our collaboration with Metro Information Technology Services. The Nolensville Pike installations will occur on a recently upgraded fiber network, which will provide improved robustness to cyberattacks through the deployment of intermediate distribution frames on the network. Monitoring of near-misses and deploying interventions to prevent crashes will keep the transportation network connected and responsive.

Partnerships

We will expand the project benefits by collaborating with Ouster, the manufacturer, to scale the most promising technologies beyond the project.

Integration

The system will be integrated with the Traffic Management Center, and we expect to integrate with other systems such as the transit network. Near-miss information and high-quality traffic information will also benefit emergency responders.

Workforce development

Our Stage II system will prototype a new method of cross agency collaboration. Led by NDOT, we will purchase 10 additional lidar units and transfer them to interested agencies to install the devices in other communities. Our project team members will train local workforce to configure and install devices, use the BlueCity software, and analyze and interpret the data. We will continue to learn from those who live, work, play, and visit in the community to more effectively deliver a valuable community project.

We will continue to expand our training activities with local signal maintenance contractors, traffic management staff, as well as provide educational opportunities through our university partners.

Stage 2 Expected System Costs

Stage I

Our Stage 1 cost breakdown is as follows. Our hardware cost (lidar) retails for \$41,600. This includes 2 Ouster OS 1 128 channel lidar units, an edge compute unit for processing the data at the intersection, the mounting brackets for the lidar units, a power over Ethernet converter, a one-year warranty, and a one-year subscription to the BlueCity cloud software that is optional (i.e., no vendor lock-in) but has initially worked well for real-time analysis. The lidar and edge compute box are shown in Figure 71.

The installation costs are approximately \$22,300 for each intersection installation, and approximately \$20,000 for each mid-block location. This includes labor for the installation, as well as additional equipment to support the installation (Figure 70). The specific equipment includes a CISCO Meraki MG 51 cellular modem and corresponding dual patch antenna, a six-port gigabit POE industrial rated managed network switch, input-output card, cabinet, cabling, wiring, and power supplies for all devices.

The design, testing, and integration costs of Stage I for the 8 locations are approximately \$200k.



Figure 70 Left. Typical installation includes a small additional cabinet attached to the main signal control cabinet. Right. Cabinet includes the edge computer power supplies, and a network switch.



Figure 71 Stage I equipment includes an edge computer (left) a lidar sensor center, and a power supply (right). Photo taken in Stansell Electric Company Conference Room prior to deployment.

Stage II

Our stage II estimated costs are based on realized costs in Stage II as well as efficiencies we expect in areas such as design, testing, integration, and installation. Our hardware costs will decrease in some areas (accounting for volume purchasing) and increase in other areas (purchasing higher quality cabinets to house equipment). All costs reported below are the result of coordination with existing Stage I parties (Stansell, Ouster, AECOM, University partners) who are all committed to ensuring the success from Stage I is carried over to an at scale implementation.

The estimated costs for stage II are as follows. We estimate lidar OS1 devices, edge compute units, brackets, BlueCity license, and warranty will land at \$4.0M. This accounts for equipment for all installation sites identified in State II, plus an additional 10 units for our workforce development activities. We anticipate reduced unit costs for hardware due to the volume order, and an increase in the cost of the warranty, which we are extending to 10 years, up from 1 year in stage I. The total hardware cost accounts for these increases and decreases and results in a lower total cost per installation compared to our realized Stage I prices.

The installation work is estimated at approximately \$2.1M, which accounts for reduced per-site costs for installation due familiarity with the installation process gained in stage I. We will remove some hardware (cellular modems on Nolensville Pike are not necessary, due to the existing fiber network), but upgrade some equipment (We plan to use a more robust cabinet).

Our system design, equipment testing, integration costs are budgeted at \$1M and accounts for the increased number of installation sites, and a lower per-site cost for the work accounting for efficiencies learned in stage I and efficiencies due to the volume of work.

Our final budget for a at scale stage II implementation is estimated at \$10M. This accounts for additional activities such as data management, evaluation of the project, evaluation of safety interventions, workforce development activities, community impact and community engagement activities, research and technology transfer activities to scale the most promising aspects of the project. Further information is provided in a Budget Narrative with our Stage II proposal.

Status quo

The status quo for intersection detection within NDOT is to use radar-based detection. On a typical four-way intersection, four radar sensors are installed. The cost of the radar retails around \$20,000 per device or \$80,000 per intersection. Volume discounting can reduce the final price. Assuming the lidar sensors and radar sensors offer similar detection capabilities (an apples-to-apples test was outside the scope of our Stage I grant), the lidar solution is approximately 25% cheaper on a hardware basis. Assuming estimated pricing for 10-year warranty for lidar (retail price includes a 1-year warranty), the price of lidar is approximately 10% cheaper. The standard radar installation for NDOT does not generate pedestrian counts or bicycle counts that are accessible to TMC staff. The lidar unit offers these capabilities through direct integration with the edge compute box, or through the BlueCity software, which has an annual software license fee per intersection.

Considering the status quo radar installation, we deem lidar to be competitive in cost. A detailed cost analysis will require carefully factoring operating and maintenance costs which will evolve as more familiarity with lidar and its long-term performance is understood in later stages of the project.

To mitigate the unknown technology risk, we have budgeted for a 10-year hardware warranty on the lidar units to ensure the expected life of the system aligns with existing widely deployed technologies.

Expected benefits

To estimate the potential benefits, we focus on the potential safety improvements. Note this is a preliminary estimated benefit analysis, a complete benefit cost analysis may offer

additional benefits beyond what is reported here. Our approach focuses on Nolensville Pike, which is the primary area of our Stage II implementation for simplicity of presentation. The base data reported here is extracted from the 2022 Nolensville Pike Study

Assumptions and Context

- *Project Scope:* Pedestrian safety improvements on Nolensville Pike, including enhanced crosswalks, pedestrian refuge islands, improved lighting, and traffic calming measures.
- *Objective:* Reduce pedestrian-related crashes and improve overall safety for all road users.

Baseline Crash Data (2014-2021, 7 years):

We summarize the baseline crash data over the 7-year period in the following table:

Category	Total Crashes	Fatal	Serious Injuries	Minor Injuries
Total Crashes	816	-	-	-
Total Pedestrian Crashes	62	11	13	37
Total Bicyclist Crashes	8	-	1	7
Driving Crashes (Non-Pedestrian/Bike)	746	-	31	667

The next table normalizes the crashes into crashes per year to aid in annual estimates of benefits.

Category	Total Crashes	Fatal	Serious Injuries	Minor Injuries
Total Crashes	116.57	-	-	-
Total Pedestrian Crashes	8.86	1.57	1.86	5.29
Total Bicyclist Crashes	1.14	-	0.14	1
Driving Crashes (Non-Pedestrian/Bike)	106.57	-	4.43	95.29

We use the following monetized values (2022 \$) from USDOT Guidance:

Crash Type	Monetized Value (2022 \$)
Fatal Crash	\$14,022,900
Serious Injury (A)	\$1,188,200
Minor Injury (B)	\$233,800
Possible Injury (C)	\$111,700
No Injury (O)	\$5,000
PDO Crash	\$9,100

Crash Type	Monetized Value (2022 \$)
Injury Crash	\$313,000

Next, we present the assumed crash reduction factors. For the pedestrian-related crashes, we assume a 20% reduction. This assumption is based on evidence from Vision Zero programs and similar pedestrian safety improvements in other cities, which have shown significant reductions in pedestrian crashes¹. For non-pedestrian crashes, we assume a 5% reduction. This lower reduction factor reflects the indirect benefits that pedestrian safety improvements might have on general traffic safety.

Next, we summarize the calculations for Annual Benefits:

Crash Type	Baseline (crash/yr)	Reduction	Value per Crash	Annual Benefit
Pedestrian Fatal Crashes	1.57	$1.57 \times 20\% = 0.314$	\$14,022,900	$0.314 \times 14,022,900 = \$4,405,194.60$
Non-Pedestrian Fatal Crashes	1	$1 \times 5\% = 0.05$	\$14,022,900	$0.05 \times 14,022,900 = \$701,145$
Pedestrian Serious Injury Crashes	1.86	$1.86 \times 20\% = 0.372$	\$1,188,200	$0.372 \times 1,188,200 = \$442,898.40$
Non-Pedestrian Serious Injury Crashes	4.43	$4.43 \times 5\% = 0.2215$	\$1,188,200	$0.2215 \times 1,188,200 = \$263,167.30$
Pedestrian Minor Injury Crashes	5.29	$5.29 \times 20\% = 1.058$	\$233,800	$1.058 \times 233,800 = \$247,200.40$
Non-Pedestrian Minor Injury Crashes	95.29	$95.29 \times 5\% = 4.7645$	\$233,800	$4.7645 \times 233,800 = \$1,113,227.10$
Pedestrian Crashes	8.86	$8.86 \times 20\% = 1.772$	\$313,000	$1.772 \times 313,000 = \$554,136$
Bicyclist Crashes	1.14	$1.14 \times 20\% = 0.228$	\$313,000	$0.228 \times 313,000 = \$71,364$

Summing across all crash types, we estimate the total annual safety benefit: \$7,798,332.80. Applying a 3.1% discount rate over a 10-year period, the estimated benefits are \$66.5M.

The estimated cost of our Stage II deployment is \$10M, accounting for hardware, software, design, deployment, outreach, workforce development, and other activities. Conservatively estimating the operations and maintenance at 7.5% annual cost rate of the

¹New York City DOT, New York City Streets are Safer and More Equitable After 10 Years Of Vision Zero, available at <https://www.nyc.gov/html/dot/html/pr2024/10-years-vision-zero.shtml>, accessed July 30, 2024.

upfront project cost, and accounting for a 10-year horizon with a discount rate of 3.1%, we estimate the combined cost at \$16.4M.

Considering the above analysis, the estimated benefit-cost ratio of the at-scale system is $\$66.5\text{M}/16.4\text{M}=4.0$.

Preliminary baseline data

We will continue to monitor our performance in stage one over the coming months to determine if the crash reduction benefits are larger or smaller than anticipated. Similarly, we will update our knowledge of the operations and maintenance cost as part of our baseline data. NDOT maintains crash data, and all data from Stage I is being maintained per our data management plan.

Proposed schedule

Our Stage I project is ahead of schedule thanks to the complete buy-in of community members, project partners, and local government leadership. In a single week in Stage I, we installed seven sensors, detected excessive speeding, deployed a successful intervention, and validated it. Our proposed schedule for Stage II is equally ambitious, but achievable by this project team.

Months 1-4:

- Stakeholder outreach begins, notice of project implementation to surrounding neighborhood organizations and businesses.
- Systems Engineering Analysis, site visits, preliminary plans
- Continue Stage I workforce training sessions/classes begin.

Months 5-8:

- NEPA review & utility coordination
- Plans, specifications, and estimates
- Lidar procurement
- Community engagement, workforce development activities, data infrastructure deployment

Months 9-18:

- Unit bench testing and lidar installation
- Subsystem/system testing & integration

Months 18-24:

- Burn in testing, data collection
- Community engagement

Months 24–36:

- Intervention deployment, data analysis, dissemination

A detailed schedule for Stage II is shown in Figure 72.

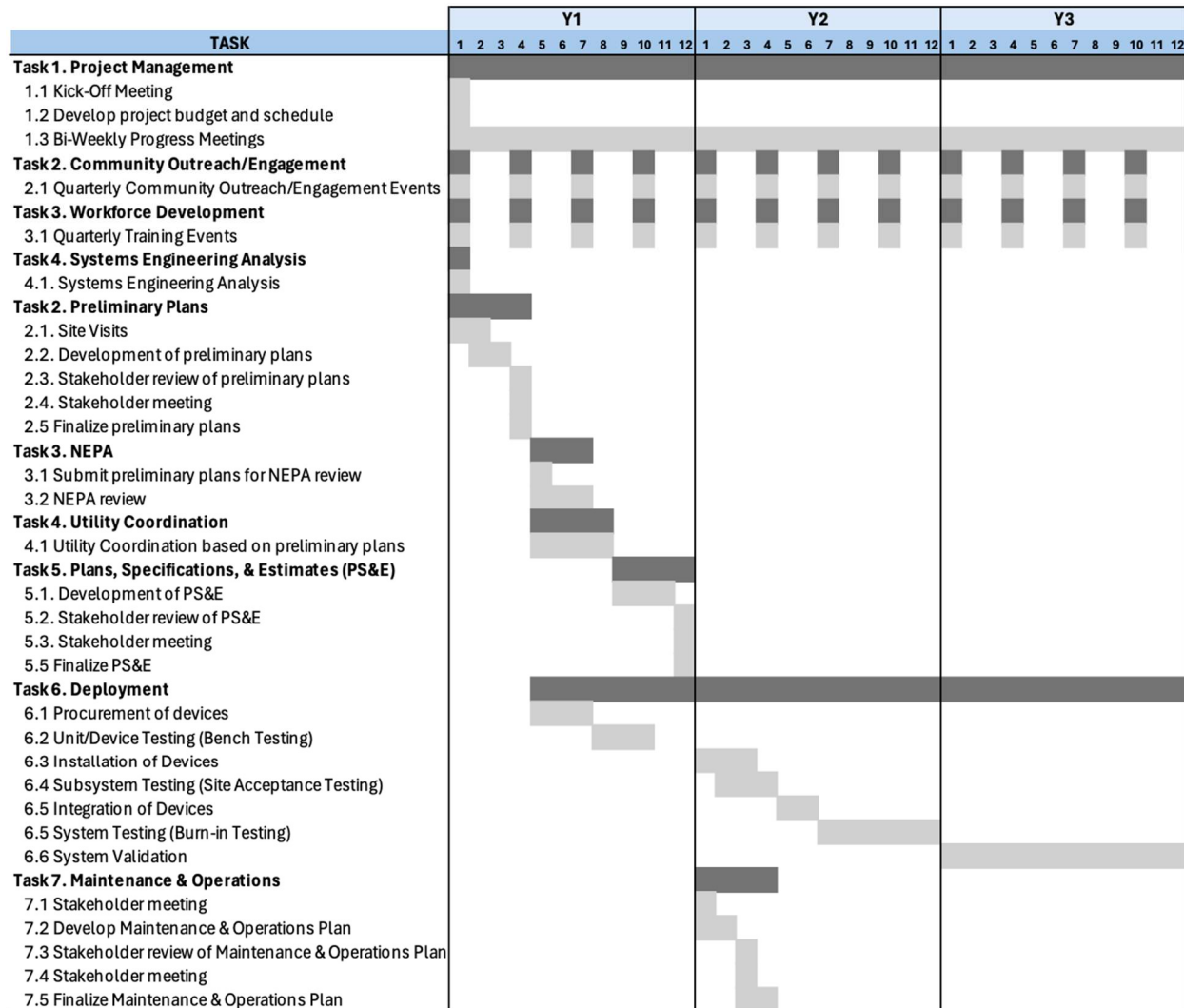


Figure 72. Overview of implementation schedule for Stage II.

Feasibility of Workplan

We confirm our system will be integrated with existing transportation systems, including transit. Based on our team’s extensive experience with ITS deployment, our schedule is ambitious but feasible.

Legal/regulatory. We are familiar with the NEPA process and are committed to avoid right of way and environmental impacts to expedite NEPA review and ensure a Categorical Exclusion designation. We will follow all applicable procurement policies and sole source requirements to procure Ouster Build America Buy American certified lidar units. We will

proceed with the justification process for Stage II equipment while this grant is under review.

Local utilities. We have a close working relationship with local utility agencies and we effectively engaged with them during our SMART Grant Phase I project. With our existing relationships with the local utility agencies, we will ensure early and frequent communication and coordination to guarantee the utility conflicts are addressed early and utilities such as power and communications are ready prior to installing devices in the field.

Partners. We will be working with the same contractors from the LADDMS Phase 1 project. We will ensure early and frequent coordination to guarantee equipment is procured, tested, and installed in a timely manner. Our project partners are critical our ability to meet the Phase II schedule milestones. We will build on and strengthen the partnerships developed in Phase I to guarantee we successfully complete Phase II project on schedule.

Supply chain. NDOT will directly procure lidar units from Ouster to reduce procurement delays. In Stage I, the project team identified a standard set of equipment needed for intersection and mid-block crossing installations, including cabinets, switches, and communications equipment. We are procuring devices early to allow bench testing and configuration while plans, specifications, and estimates are completed.

Stage I feasibility learnings

Our Stage I grant taught us several valuable lessons that have been accounted for in our schedule. First, community engagement is critical, and helped us avoid camera-based technologies that raised community privacy concerns. Second, direct collaboration with Ouster accelerated our staff and workforce trainings and allowed us to troubleshoot issues quickly. Third, we have established a direct collaboration with Metro ITS at the planning stage of this project to improve our ITS security posture on the at-scale implementation.

Plans for physical safety and cybersecurity

All project partners follow a safety-first culture. The project goal is to improve safety of all road users, and as a privacy preserving sensing project has minimal direct risks to public safety. NDOT is working with Metro ITS to deploy *intermediate distribution frames* to the Nolensville Pike fiber network by June 2025 for this project. The system will operate on NDOT's internal fiber network in accordance with NDOT's cybersecurity protocols.

Part 4 of 6: Challenges & Lessons Learned

We highlight the significant challenges, lessons learned, and recommendations based on our Stage I project.

Legal, Policy, and Regulatory Requirements (e.g., NEPA, BABA)

Challenge. We did not encounter any challenges related to legal, policy, or regulatory requirements.

Solution/lessons learned/recommendation. Our approach to avoid these challenges included the following.

- NEPA: We selected sites that are located within existing right of way and do not disturb the ground.
- BABA: We purchased Ouster lidar products, which are built in San Francisco. Ouster is Buy American and Buy America certified.

Procurement and Budget

Challenge. Purchasing devices from a new vendor on an aggressive procurement schedule.

Solution/lessons learned/recommendation. We coordinated directly with Ouster sales and engineering team to secure an accelerated equipment delivery. We used other funds to procure a first set of sensors through a university partner (later reused for education and workforce development activities) that allowed us to discover design, installation, and data management hurdles early. An on-call contractor was used to procure the remaining items. As part of this project, we have expanded procurement channels to include Southern Lighting and Traffic – an existing NDOT vendor – and direct equipment acquisition by NDOT.

Partnerships

Challenge. The project team did not include all critical project partners for installation at the start.

Solution/lessons learned/recommendation. We quickly expanded the project partners to include Metro Information Technology Services (responsible for cybersecurity policy for Nashville IT networks), Ouster (the lidar equipment manufacturer), Stansell Electric Company (the electrical contractor responsible for installing the devices), AECOM (responsible for project management and technical implementation support), and Nashville Electric Service (responsible for approving and inspecting new electrical service at mid-block installations).

Technology Suitability / Integration with Incumbent Systems

Challenge. Lidar sensors applied to intelligent transportation systems is not a mature technology domain, so there was very limited information about the quality of data we should expect.

Solution/lessons learned/recommendation. We procured our first sensor early, so that we could begin assessment of data quality and derivative analytics, as well as identify integration issues with time remaining in the project schedule to incorporate the lessons learned.

Data Governance

Challenge. The lidar units generate a significant amount of processed data. The edge compute unit creates bounding boxes from the point cloud data, which reduces the initial size, but the processed dataset still generates 50,000,000 raw object records per day (~20GB) system-wide (roughly 6.25M per installation location).

Solution/lessons learned/recommendation. We have created two data pipelines. The first pipeline leverages Ouster's commercially available Blue City cloud analytics platform. It is capable of providing near-miss detection (post encroachment time), as well as a variety of standard traffic signal performance measures. The second is a Vanderbilt University hosted data management computing cluster (2 PB raw capacity, significantly larger than the expected 300TB) to support research activities and exploratory analysis for the project partners.

Specifically, Vanderbilt runs a hybrid flash-hard disk database server cluster with 2PB raw capacity and the option to scale hard disk archival space to 8PB. Incoming network bandwidth to each of the three database servers is 50Gbps and each has 96 CPU cores and 768GB RAM in order to serve database queries on large datasets, simultaneously with incoming database write operations. This allows prototyping of new analysis approaches that are not yet available in the Ouster platform as well as multiple years of raw data storage. New analysis approaches will be licensed under a permissive open-source license to allow Ouster to integrate the developments into their commercial product which allows scalability to other projects.

Workforce Capacity (e.g., impacts on jobs)

Challenge. As a new technology, no electrical nor ITS contractors available to NDOT had experience configuring and installing the sensors.

Solution/lesson learned/recommendation. We developed close collaboration with Stansell Electric Company workers. We began the collaboration with bench testing our first device, then later partnered on a technology demonstration at the ITS Tennessee Annual Meeting. Later, the project team developed a hands-on training program to increase the number of workers with knowledge of lidar, with help from Stansell and NABCO Electric Company (Figure 73).



Figure 73 We have developed workforce development activities to address the shortage of skilled electricians with experience with new lidar technology. Photo above with NABCO Electric Company (IBEW) Electricians.

Internal Project Coordination

Challenge. The 18-month timeline leaves very little slack time to recover from mistakes and to integrate lessons learned.

Solution/lesson learned/recommendation. The project team meets weekly and more frequently when challenges arise. Construction meetings with contractors and NDOT operations staff were held almost daily during peak construction periods.

Community Impact

Challenge. The 18-month timeline leaves very limited time to evaluate the impact of safety interventions using traditional evaluation processes.

Solution/lesson learned/recommendation. We created live visualization tools and a team of analysts to collect before/after data and quickly assess the impact of the interventions using the streaming data. Analysis measures can be computed in nearly real time to monitor performance.

Public Acceptance

Challenge. Our initial project design included cameras, which created privacy concerns with community members. (See news articles above at WKRN in March 2023 and June 2024 that initially focused on cameras and later only on Lidar).

Solution/lesson learned/recommendation. Our early community engagement allowed us to pivot away from cameras to a pure lidar solution.

Cybersecurity

Challenge. Integration of devices that are accessible over the internet create new avenues for cyber-attacks if integrated into the traffic signal system. The original IT network design for signal systems was not envisioned for this use case when it was designed.

Solution/lesson learned/recommendation. We brought in Metro ITS as a partner to design cybersecurity solutions. We have multiple avenues for appropriate installation depending on the site needs and state of the network. 1) Mid-block crossings do not create a risk for traffic signal systems because the sensor is not connected to critical signaling infrastructure at an intersection. 2) We can connect to signals through an SDLC adapter, allowing the lidar to be used for control of a single signalized intersection without merging network communications. 3) In future installations, we expect to install at locations where Metro ITS has already performed network upgrades that prevent vulnerabilities at a single intersection from compromising the entire network. 4) Metro ITS has agreed to do a complete security review of the Ouster sensor which may allow additional restrictions to be relaxed.

Part 5 of 6: Deployment Readiness

Deployment requirements

To achieve successful deployment at scale, several requirements must be met:

- High Injury Network: We will expand our focus on mid-block crossings in our at-scale implementation, since many of the safety issues occur at these locations. Focusing on our most unsafe streets will maximize our community impact.
- High Volume and Congestion: Targeting areas with high traffic volumes and congestion is important. These locations can greatly benefit from improved detection at our signalized intersection installations, offering additional opportunities to improve traffic flow while also improving safety.
- Good Communications Network: We will focus on areas with an upgraded fiber network or high-quality cellular data transmission. Effective data transmission and real-time monitoring from the TMC depend on these elements.
- Good Right of Way with No Ground Disturbance: This minimizes delays and reduces the complexity of the implementation process.

Key obstacles

One significant obstacle is the unprecedented scale of analyzing massive datasets to evaluate the impacts of an at-scale implementation. This project represents our first large-scale endeavor in this area. To address this challenge, we have established strong collaborations with TSU, UTC, and Vanderbilt, which possess the necessary expertise in managing and analyzing extensive data. Their involvement will be crucial in ensuring the robustness and accuracy of our data analysis efforts.

Another key obstacle is manpower. Our focus on increasing the skills of our existing staff members will allow us to meet the growing challenges facing Nashville as we rapidly address our safety and mobility challenges as the community continues to expand.

Additionally, network integration poses a potential challenge. To mitigate this, we have developed multiple integration pathways tailored to the varying states of the communication network infrastructure across different areas. This strategic approach allows for flexible and effective integration accounting for differences in the locations we plan to install devices in an at-scale implementation.

Strategies and demonstrated progress

To ensure the readiness of the project for at-scale implementation, we have developed and demonstrated several key strategies. One important aspect is the ability to prioritize possible

interventions from our Vision Zero toolbox effectively. Given the large number of potential interventions, it is essential to quickly deploy and evaluate the most impactful ones. This prioritization is needed because interventions vary widely in terms of cost, implementation speed, and benefits. Some are low-cost and fast to implement, while others require significant infrastructure changes but offer substantial benefits.

To manage this complexity, we will need to build on our existing data management approaches. Effective data management will enable us to assess and compare the potential safety and mobility impact of the project at a granular level.

A comprehensive evaluation plan is needed to quantify the impact of these interventions. This plan will need to build on our existing metrics for safety and mobility, ensuring that we can rigorously assess the effectiveness of each intervention. By continuously monitoring and evaluating the outcomes, we can refine our strategies and ensure that the most effective approaches are scaled up across the network.

Uncertainties and risks and mitigation plans

Legal, Policy, and Regulatory Requirements

Compliance with NEPA and Other Regulations: Plans that are not compliant with legal, policy, and regulatory requirements can add substantial project delays to correct these oversights.

Risk Mitigation Plan: Our plans for NEPA and BABA compliance are straightforward. Ouster products are Buy America Buy American compliant, and we adhere to all relevant procurement regulations. Since we are working within the existing right-of-way and not disturbing the ground, this should streamline NEPA compliance. By avoiding significant environmental impacts, we minimize the complexity and potential delays associated with regulatory approvals.

Procurement and Budget

Procurement and Budget Management: Managing procurement and budgeting for the project could pose challenges, including cost overruns and procurement delays.

Risk Mitigation Plan: NDOT will directly procure the necessary equipment and services, utilizing a sole source procurement approach. This standardized setup allows for predictable and consistent costs, effectively enabling a repeatable approach to design and budgeting. Additionally, we now have a reference design for both mid-blocks and intersections, further streamlining the procurement process and ensuring cost efficiency.

Partnerships

Description of the Risk/Uncertainty: There is a risk that not having the right partners may hinder our ability to move quickly and stage our at-scale activities correctly, potentially delaying project progress and effectiveness.

Risk Mitigation Plan: We have significantly expanded our partnerships to include groups that will be involved in helping the project design implement, deploy, and evaluate on a fast schedule. By leveraging these expanded partnerships, we ensure that we have the necessary resources, expertise, and support to advance the project efficiently. Additionally, we will continuously assess and refine our partnership strategy to ensure that we have the right partners in place to address emerging challenges and opportunities, allowing us to move quickly and stage our activities effectively.

Technology Suitability / Integration with Incumbent Systems

Compatibility with Existing Systems: There is a risk with new technology that it may not be compatible with existing traffic signal control systems, or traffic management center applications, leading to integration challenges.

Risk Mitigation Plan: We have developed a standard hardware stack (including Ouster sensors and edge compute box, plus a cabinet, switch, modem, and other electronics needed for fast installations) and a standard software stack (provided by Ouster, along with research grade software built through Ouster's hardware API), along with reference designs for intersections and mid-blocks. Our standardized testing procedures ensure that all components function correctly and reliably. Additionally, we have validated the ability to integrate with legacy traffic signal control systems through the SDLC protocol. Finally, because we have validated the data both through Ouster's proprietary software (Blue City), and through their open API, we have multiple long-term options available to avoid vendor "lock-in". This comprehensive approach ensures that our technology is suitable and can be seamlessly integrated with incumbent systems now and into the future.

Data Governance

Data Management and Security. There is a risk of data management challenges and potential security breaches during data transmission.

Risk Mitigation Plan: We have estimated the data rate of the at-scale system at 300TB. Our infrastructure can retain large amounts of data (we have 2 PB of storage with the capability to expand), ensuring we can store all traffic generated by the system. We transmit data from the sensor to our research partners using SSL with authentication tokens to ensure the data is not tampered with during transit. Additionally, we maintain a data management plan that outlines procedures for data retention, security, and governance, ensuring robust data management and security practices.

Workforce Capacity (e.g., impacts on jobs)

Skill Gaps and Workforce Readiness: There is a risk of skill gaps and inadequate workforce readiness to handle the new technology, which could hinder project implementation, sustainability, and generalizability beyond our own project.

Risk Mitigation Plan: We have established strong relationships with the electricians at Stansell Electric Company and Nabco Electric Company who install our systems, ensuring a reliable workforce. We are creating training programs for other agencies, partnering with the City of Clarksville and Austin Peay University (located in Clarksville TN) to expand our knowledge transfer. We are developing a visitor program that allows researchers to sit at the Traffic Management Center (TMC) and TMC staff to regularly visit our university partners, fostering knowledge exchange. We are inviting NDOT staff to guest lecture in transportation engineering classes at our partnering Universities. Furthermore, we will continue to offer workshops and training sessions at ITS Tennessee and other professional conferences, ensuring continuous skill development and workforce readiness.

Internal Project Coordination

Coordination and Scalability: Ineffective internal coordination and unclear roles and responsibilities could hinder project scalability and overall success.

Risk Mitigation Plan: We will continue to use our existing tools and meeting cadence, which have served us well in our Stage I effort. Additionally, we will refine roles and responsibilities within the team to allow for scalability. This refinement ensures that each team member understands their duties clearly, facilitating smoother project execution and enabling the project to scale effectively.

Community Impact

Effectiveness and Community Acceptance: There is a risk that community engagement activities may not effectively address community concerns or may fail to gain community acceptance.

Risk Mitigation Plan: We will continue our community engagement activities and follow up activities initiated in Stage 1. For Stage II, we will employ the same strategy, utilizing strategies from NDOT's Vision Zero toolbox. Additionally, we will validate these strategies with sensor data to ensure the approaches are not only theoretically sound but also effective in practice, as seen in the data and perceived by community members. This approach ensures that our community engagement efforts are data-driven and tailored to meet actual community needs and expectations.

Public Acceptance

Public Concerns About Technology: There is a risk that the public may have concerns about the use of new technology, particularly regarding privacy.

Risk Mitigation Plan: To address these concerns, we have engaged with community leaders, local media, government leaders, and community advocacy groups. Based on prior community feedback, we specifically selected LiDAR technology instead of video to mitigate privacy concerns. We will continue to engage with community partners throughout the project, maintaining an open dialogue and adjusting the project based on the feedback we receive to ensure it meets public expectations and addresses any concerns.

Cybersecurity

Data Security and Network Vulnerability: There is a risk of data breaches and network vulnerabilities due to the integration of new technologies and collaboration with multiple partners.

Risk Mitigation Plan: To address this risk, we have brought on Metro Information Technology Services as a partner to ensure robust cybersecurity measures are in place. We have established approved data use agreements between project partners and NDOT to govern data sharing and usage. As one part of a multi-pronged strategy, Metro ITS and NDOT have agreed to install intermediate distribution frames to allow better managed control over the network traffic on NDOT's fiber network to support this project. NDOT has hired Robert White as the new TSMO manager and Robert will lead this risk mitigation thrust in collaboration with Metro ITS. Robert is a public voting member on the following projects led by the Institute of Transportation Engineers (ITE) with the American Association of State Highway Transportation Officials (AASHTO), National Electrical Manufacturers Association (NEMA) and US DOT: ATC Cybersecurity; NTCIP 1211 Signal Control and Prioritization; NTCIP 1204 Environmental Sensor Station; Infrastructure Standard Security Implementation (ISSI).

Maintenance and operations

Limited Data on New Product: As this is a new product, there is limited data on its long-term performance and maintenance requirements.

Risk Mitigation Plan: We have collaborated with Ouster, who has had many intersections operational for six years with prior generation hardware. We are working with their 7th generation sensor. To mitigate risks, Ouster has extended the product warranty from one year (initial purchases) to ten years (at-scale implementation). This extended warranty ensures predictable costs for NDOT and aligns with industry standards for other traffic detection technologies. Additionally, market trends suggest that the hardware and extended warranty will be more cost-effective than the current purchased hardware.

Maintenance Requirements: The maintenance requirements for LiDAR installations are not yet fully integrated into NDOT's existing documentation.

Risk Mitigation Plan: NDOT is in the process of updating its maintenance documentation to account for LiDAR installations, particularly with regard to the expected cleaning schedule.

The recommended maintenance interval for LiDAR sensors is similar to that of cameras, ensuring that the maintenance process is straightforward and manageable.

Performance in Snow: We do not have firsthand experience with the system performance in snowy conditions.

Risk Mitigation Plan: Ouster has provided data from another installation that confirms satisfactory performance in snowy conditions. Furthermore, this is not a significant issue for Nashville, which typically experiences only one to two snowstorms per year.

Impact on workers

Impact on Workers: There is concern that the implementation of new technologies might negatively impact the availability of good-paying jobs.

Risk Mitigation Plan: As a sensing technology, there is not a significant risk of job displacement. Instead, our approach focuses on upskilling existing jobs. We work directly with electricians and have established partnerships with Stansell Electric Company and NABCO Electric Company. NABCO is affiliated with the International Brotherhood of Electrical Workers (IBEW). This collaboration ensures that workers receive the necessary training and support to adapt to new technologies, thereby harnessing beneficial impacts and mitigating any potential negative effects.

Part 6 of 6: Wrap-Up

Reflecting on the course of the project, did the proposed solution meet your expectations?

The proposed solution exceeded our expectations, achieving significant improvements in road safety and traffic management. The integration of lidar technology and real-time data dissemination proved effective in reducing incidents and enhancing overall efficiency. The system eliminates human intervention for field data collection.

Do you think you would make any notable changes to the proposed solution for at-scale implementation?

For at-scale implementation, several refinements could further optimize the solution. Firstly, improving the interoperability of the system with existing traffic management infrastructure across different jurisdictions would be essential. Secondly, expanding the training programs to ensure a broader and more comprehensive skill set among operators and maintenance personnel would enhance the system's reliability and effectiveness. Lastly, incorporating more robust data analytics capabilities would allow for better predictive insights and proactive measures.

What advice would you give to other communities embarking on the same path?

1. **Order materials early:** Early procurement allows for testing and integration familiarity, maintains project momentum, and helps avoid delays caused by supply chain disruptions.
2. **Build your partners early:** Establishing strong partnerships with key stakeholders, including local governments, educational institutions, and technology providers, is crucial for the project's success.
3. **Value your community participation:** Engaging the community and incorporating their feedback enhances the system's acceptance and effectiveness.
4. **Build your partnership with the manufacturer:** A strong relationship with technology manufacturers ensures better support, customization, and long-term sustainability of the system.
5. **Ensure good transportation infrastructure including telecommunications.** After working with community partners to identify dangerous/problem areas, check to make sure communication infrastructure is available to handle the data load.