Smart Safe Intersections That Protect Vulnerable Road Users

Overview and Results

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Area X.O, an autonomous test facility in Ottawa, Canada, conducted a comprehensive two-year study commissioned by Transport Canada. This research aimed to explore the integration of machine vision systems and infrastructure-to-vehicle communications to enhance the safety of interactions between connected autonomous vehicles (CAVs) and vulnerable road users (VRUs) at intersections. The study encompassed various VRU safety scenarios in private and public environments, yielding valuable insights for the secure deployment of these technologies. Area X.O compiled a meticulous 290-page report, detailing the research methodology, test results, key findings, recommendations, and future steps. This whitepaper offers a condensed overview of this report.

Introduction

The safe adoption of connected and autonomous vehicles (CAVs) and other smart mobility solutions demands a comprehensive assessment on how their underlying technologies perform, communicate, analyze, make decisions, act, and maintain safety in dynamic urban environments. It is particularly important when dealing with vulnerable road users (VRUs) – non-vehicular users that include pedestrians (adults and children), cyclists, and persons with disabilities or reduced mobility. According to Transport Canada, nearly 14,000 pedestrian collisions occurred in Canada between 2018 and 2019, while Statistics Canada data shows that between 2006 and 2017, an average of 54 cyclists died each year from vehicle collisions. Similarly, statistics compiled by the National Highway Traffic Safety Administration in the United States indicate that VRU fatalities have grown from 16 percent of all accidents to 20 percent in 2020. The significant proportion of fatalities between motorized vehicles and VRUs, combined with urban planning trends that are increasing pedestrian and cyclist traffic, underscore the need for further research into smart mobility technologies and CAVs to protect this segment of society.

Project Overview

Conducted through Transport Canada's Enhanced Road Safety Transfer Payment Program (ERSTPP), Area X.O researched how machine vision systems combined with infrastructure-to-vehicle communications could create safer interactions between CAVs and VRUs at intersections. The research team conducted a comprehensive two-year study of VRU safety scenarios in private and public environments to further our understanding on the safe deployment of these technologies.

The Area X.O team collaborated with more than eight partners, both in Canada and internationally. These included government agencies such as the National Resource Council (NRC) and the City of Ottawa, the University of Warwick for assessments and baselines using their Safety Pool Scenario Database, and the World Economic Forum through their Safe Driving Initiative framework. We also forged partnerships with prominent Silicon Valley companies such as Deepen AI, as well as several Canadian-based small-to-medium businesses with expertise in the smart mobility sector.

Once the project was completed, we compiled a comprehensive 290-page report for Transport Canada. This report meticulously details every aspect of our research, testing methodology, test results and collected data, along with our findings, insights, recommendations, and future steps. The insights garnered from this undertaking hold significant potential to shape the development of Canadian policy and regulatory frameworks as facilitated by Transport Canada. We aim to share these outcomes with the global community to support similar developments in other countries. As a condensed overview of our work, this whitepaper offers a high-level summary of our efforts.

Background

The fundamental question the team sought to answer was: can infrastructure sensors and V2X communications at city intersections make a measurable improvement to VRU safety? In other words, could intersection sensors be better at detecting VRUs compared to the vehicle, especially in time-critical road safety scenarios? Could advance warning from these sensors significantly increase the time available for a vehicle to react? To evaluate the real-world performance of an intersection sensor suite for VRU safety, the research team performed the following steps:

1) Studied the operational design domain (ODD) for traffic intersections to develop VRU safety test requirements in alignment with the World Economic Forum (WEF) Safe Drive Initiative.
2) Installed infrastructure sensors at a private and public four-way intersection, with a roadside unit (RSU) to transmit V2X messages that indicate VRU presence.
3) Tested and assessed state-of-the-art machine vision learning algorithms against large, diverse, and realistic datasets to advance road safety applications.
4) Outfitted an autonomous vehicle to receive V2X messages and automatically brake in the presence of VRUs, even in occlusion scenarios.
5) Conceptualized, implemented, and analyzed a set of safety scenarios that broadly cover VRU type, speed, vehicle manoeuvres, and vehicle occlusion.

Project Outset

At the start of the project, the team developed 28 VRU safety scenarios that covered a diversity of VRU types, vehicle speeds, and occlusions by following test procedures outlined in ISO 22737, Euro NCAP 2020, ISO 19237, ISO 22078, and SAE J2945. To ensure testing would occur within a controlled, repeatable, and safe environment, the team used a four-way intersection in a closed track at the Area X.O smart mobility test and research facility in Ottawa. The team outfitted the intersection's infrastructure poles with the necessary sensors (visual, thermal, lidar) as well as roadside "edge" compute platforms to run the machine vision algorithms and send V2X messages. They also equipped Area X.O's dedicated autonomous test vehicle (a 2020 Lexus RX 450h SUV) with additional sensors (inertial motion, lidar, cameras, and radar), C-V2X technology, and an edge-compute drive-by-wire platform to process messages and initiate braking as required. The final piece was the installation of a track and control system for adult, cyclist, and child Euro NCAP test dummies. Area X.O also coordinated with the City of Ottawa and directed the installation of the equivalent infrastructure equipment – sensors, roadside compute platforms, and V2X communication modules – at the Kanata public smart intersection to create a duplicate public setup for collaborative industry trials as well as future research and testing.

Data Collection, Review and Analysis

Area X.O employed a rigorous and systematic approach that validated the combined use of these technologies in a series of real-world deployment scenarios. Here's what we did and the lessons we learned.

Machine Vision and Deep Learning – Investigation

We reviewed current state-of-the-art literature in the machine vision field for techniques that could be used to detect VRUs from cameras mounted on infrastructure poles at street intersections. The team evaluated classical algorithms as well as many deep learning algorithms (such as R-CNN, Fast R-CNN, Faster R-CNN, R-FCN, Mask R-CNN, Cascade R-CNN, SSD, and many variants of YOLO) based on their expected performance over VRU images. The team also examined several public image datasets (Caltech Pedestrian, CityPersons, EuroCity, TJU-DHD, TDC8, LLVIP, VisDrone) for their suitability in training the deep learning models.

The team validated the most promising algorithms with real-life intersection camera footage from the City of Ottawa. Using this footage to train, refine, and validate the VRU detection deep learning models, the team correlated their results with controlled CAV-VRU test performance at the Area X.O private test facility. This work helped the team understand the opportunities to improve existing deep learning algorithms for VRU detection and classification, particularly in inclement weather and challenging visibility conditions.

Machine Vision and Deep Learning – Results

The team had several observations upon completing the machine vision research and testing.

- While many datasets exist for intelligent transportation systems (ITS), those that specifically include areas necessary for public deployment, such as children, polemounted images, mobility-challenged VRUs, and active weather are scant to non-existent. Real-world VRU safety solutions will require more comprehensive datasets.

- Overall performance of the VRU detection model worked well for the adult and cyclist VRU types but not for the child. Indeed, smaller individuals pushed the bounds of the system, especially when on the far side of the crosswalk at a distance from the camera. This highlights the need to maximize the resolution of infrastructure-installed cameras.
- As expected, detection performance during daylight was better than at night. While nighttime VRU recognition was improved by using thermal cameras, our model was trained with a standard visual image dataset and the algorithms struggled to consistently recognize VRUs within thermal images. Specific thermal images for training would likely result in better performance, as would the use of sensor fusion techniques.
- VRU occlusion – where the view of the pedestrian is blocked by cars or other road users – is a challenge that infrastructure-based detection and notification aims to solve. While roadside infrastructure has a different vantage point for distinguishing VRUs than the vehicles approaching an intersection, VRU occlusion by vehicles also remains a challenge for a roadside system depending on the camera installation location. Properly detecting VRUs despite occluding objects may require additional methodologies and multiple inputs to construct a correct internal representation of the environment. Additionally, rigorous evaluation of VRU path- and behaviour-predicting algorithms could help provide solution robustness for timely VRU detection while minimizing false positives.
- An unexpected result was that winter scenes had a slight performance improvement. This is because the presence of snow seemed to provide better contrast between the VRUs and the roadway than non-winter scenes.

RF Communications Fabric

The project team achieved vehicle-to-infrastructure (V2I) communication to and between vehicles at line-of-sight by using cellular V2X (C-V2X) communication technologies. Since any experimental solution requires reliable V2X message communication, we carefully tested the radio frequency (RF) at 5.91 GHz (channel 183), the centre of the C-V2X spectrum. The team performed this testing at the Area X.O intersection where the actual test scenarios occurred and did not measure any interference when using the C-V2X protocol.

CAV Collision Avoidance – Testing

To ensure there was a controlled and safe environment during all tests, the project team performed autonomous vehicle testing exclusively at the Area X.O private test track. This provided sufficient time to properly set up each test scenario according to their respective operational design domain requirements. The team repeatedly positioned the test CAV and occluding vehicles into predetermined positions, and carefully monitored and performed several runs to confirm results. It also allowed the team to use a motion controlled VRU test dummy so as not to endanger anyone should the vehicle fail to come to a complete stop in time.

Area X.O used its private intersection with machine vision sensors, image detection algorithms, and C-V2X technologies along with its autonomous Lexus to test the 28 VRU safety scenarios (mentioned earlier) to exercise end-to-end scenarios for different speeds, different types of VRUs (adult, child, and cyclist), different types of manoeuvres (straight through, turning right, turning left), occlusions (such as cars waiting in the intersection performing left turns or other cars on the roadway), and special cases (false positives and lane closures). If the machine vision sensors detected a VRU within the intersection or intended CAV path, it would trigger a notification to the RSU, which would broadcast the V2X safety message regarding VRU presence to the CAV. The CAV platform would then perform the appropriate safety manoeuvre - in other words, apply the brakes and avoid a potential collision.

The team recorded relevant environmental conditions, test infrastructure setup parameters, V2X communications scheme, CAV behaviour, and stopping distances during the various VRU safety scenarios.

CAV Collision Avoidance – Results

Once the testing was successfully complete, the team was left with a number of observations.

- The end-to-end testing using machine vision and V2X technologies was very successful at detecting VRUs under the defined conditions. On average, this significantly increased the time between the object and event detection and response (OEDR). It also increased the potential time to collision, thereby allowing the vehicle to stop significantly before the VRU impact point, increasing the VRU’s safety envelope.
- The test system occasionally detected people that were not within the intersection and reported them as VRUs to the oncoming test vehicle. While the vehicle properly ignored them, a robust system would need to reject VRUs more carefully outside the region of interest to prevent false VRU alerts and to preserve bandwidth for actual VRUs.
- The thermal cameras used in the tests showed blooming (visual artifacts) under bright sunlight that rendered images unsuitable for VRU detection. Anti-blooming techniques

(such as shields) should be applied to thermal cameras in future test scenarios and infrastructure installations.

- VRUs are difficult to detect in some circumstances, and manual braking was still necessary in some tests. As a result, consistently reliable detection of VRUs will likely require measures beyond just camera inputs such as in-road sensors, crosswalk indicators, V2V message propagation, or traffic intersections' signal phase and timing (SPaT) operation.
- The test vehicle stopping distance when the VRU entered the crosswalk from the far side of the vehicle was twice the distance from the tests when the VRU entered the crosswalk from the near side. This highlights how critical time is in such VRU safety scenarios, especially as we look to accommodate higher vehicle and VRU speeds.

These observations validate the need for further testing and evaluation of emerging connected and mobility solutions to accelerate their path to widespread maturity and adoption.

Impacts and Lessons Learned

This project identified many insights for future test and real-world scenarios in the same operational design domain (ODD) found at typical municipal intersections. This includes recommended functional performance metrics for SAE's Automated Vehicle Safety Consortium (AVSC): Time-To-Collision (TTC), Safety Envelope, Object and Event Detection and Response (OEDR), and False Positive Rate. The team also developed a behavioral competency evaluation framework for measuring CAV performance regarding VRU safety. These metrics and frameworks can help guide future work in creating smarter and safer intersections.

Relevant SAE Standards for VRU Safety

As additional assistance to future work in this area, the Area X.O team identified the relevant SAE standards that apply to this ODD:

- SAE J2945/9 – Vulnerable Road User Safety Message Minimum Performance Requirements
- SAE J2945/2 – Performance Requirements for V2V Safety Awareness
- SAE J2945/6 – Cooperative ACC Performance Requirements
- SAE J2945/8 – Cooperative Perception Systems (Work in Progress)
- SAE J3224_202208 – V2X Sensor-Sharing for Cooperative and Automated Driving
- SAE J2945/3 – Requirements for V2I Weather Applications
- SAE J2945/4 – Road Safety Applications (Work in Progress)

- SAE J2945/7 – Positioning Enhancements for V2X Systems (Work in Progress)
- SAE J3269 – Vehicular Precise Positioning System Reference Architecture
- SAE J3270 – Test Procedures for Precise Positioning Systems for Passenger Vehicles
- SAE J3186 – Application Protocol and Requirements for Manoeuvre Sharing and Coordinating Service

Impacts on Canadian Policy and Regulation

The research team also identified several potential impacts to transportation regulation and policy in Canada in the following publications:

- *Transport Canada: Guidelines for Testing Automated Driving Systems in Canada, Version 2.0, 2021, TP 15482E*
- *Transport Canada: Safety Assessment for Automated Driving Systems in Canada, January 2019, TP 15402E*
- *Transport Canada: Automated and Connected Vehicles Policy Framework for Canada, January 21, 2019, TP 15408E*
- *Canadian Council of Motor Transport Administrators: Canadian Jurisdictional Guidelines for the Safe Testing and Deployment of Vehicles Equipped with Automated Driving Systems, Version 2.0*
- *Transport Canada: Transport Canada's Vehicle Cyber Security Strategy, 2021, TP 15473E*

Public Road Infrastructure

Area X.O also worked with the City of Ottawa to outfit a public intersection in the west end of Ottawa with an identical portfolio of sensors and infrastructure equipment as that in the private intersection tests – visual and thermal cameras, lidar, V2X roadside units, roadside edge compute platforms, and other crucial environmental sensors. Since the installation mirrors the private Area X.O intersection equivalent, it allows small and medium-sized businesses (SMBs) and other organizations to migrate their testing from a fully controlled environment into the public domain much more easily.

The public installation improves the test infrastructure available to Canadian organizations, advances the development of smart mobility technologies, and provides a platform for further CAV technology research. For researchers in the smart mobility industry as well as municipal safety or transportation departments, it opens the capability to test various components and edge scenarios as the environment and public safety situation allows. And perhaps most importantly, it allows the long-term data collection of valuable real-life situations using actual municipal infrastructure.

Working with Smart Mobility SMBs

Components of the private and public infrastructure were used in select trials with SMBs developing CAV technology to validate the usability and effectiveness of the project's technology suite as well as providing opportunity for startups, scaleups, and other industry partners to work on researching, testing, and commercializing their technology. Fortran Traffic Systems and SmartCone Technologies completed trials that intersected and extended the main body of research outlined in this project, and Sensor Cortek improved the current and future usability of the public intersection equipment through a project extension.

Fortran Traffic Safety Awareness Solution

Fortran provides cities with transportation and traffic management solutions. As part of this research project, Fortran deployed its FLUX Glide technology in the test vehicle. This smart city mobility technology was developed to keep driver, cyclists, and pedestrians safe with a traffic-safety awareness and control app for smartphones. The technology supports real-time monitoring of data broadcasted by physical RSUs and even allows users to obtain similar pedestrian safety alerts from virtual RSUs in a secure fashion, when physical RSUs do not exist at intersection locations.

The Fortran project enabled the company to conduct a real-time assessment of their technology. They successfully completed their project that demonstrated tracking vehicles against pedestrians and cyclists in the travel path as well as showing audio and video alerts via their application if a crash was predicted to be imminent.

SmartCone VRU Detection and Awareness Solution

SmartCone is an Ottawa-based technology ecosystem company that specializes in providing industrial internet of things (IIoT) solutions for transportation safety, pedestrian management, logistics, and more.

The Area X.O team worked with SmartCone to demonstrate how their smart mobility technologies can enhance VRU safety by detecting and notifying drivers and pedestrians via cellphone app. SmartCone technology was deployed at the private test track to signal the test vehicle of a pedestrian crossing the oncoming intersection. The company then created an app to act as an early warning notification system to warn the driver of a VRU ahead or crossing the intersection.

Sensor Cortek Data Collection and Analysis

The original project scope did not include data collection and analysis from the public intersection installation, a strong need that became evident after the review of existing public data sets. Thus, an addendum was created and funded by Transport Canada, and executed by Sensor Cortek in collaboration with Area X.O to maximize the usefulness of the public infrastructure equipment. This included:

- Developing a plan for data capture, data storage, and data management protocols for the public intersection
- Creating the necessary data capture and storage infrastructure
- Developing algorithms and models to analyze the data and identify critical use cases
- Identifying limitations of hardware, infrastructure, or process and developing refinements to accommodate them
- Developing a user-friendly dashboard for visualizing and accessing data and its analysis

This project was challenging due to the infrastructure's several high-bandwidth sensors (RGB, thermal, and lidar cameras), which captured 250GB of compressed data per hour. Edge device storage capacity, 4G network transmission speed, occasional network disconnects, processing power, and passive CPU cooling were all factors that required very careful data handling, compression, storage, and transfer and dictated some hardware architectural changes.

The team outlined a large number of critical use cases implicated in VRU safety, including jaywalking, running red lights, over-speeding, unexpected vehicle or pedestrian motion, cyclist lane position, and others. Sensor Cortek developed and trained AI software to detect and flag these critical cases, and created a dashboard that would allow filtering and sorting of the collected data and reviewing video footage surrounding any flagged event.

Future Steps, Considerations, and Scale

We believe the research conducted during this project shows that roadside VRU detection and V2X communication along with automated vehicle braking can positively impact the safety of VRUs at intersections and crosswalks. Thus, vehicles operating under autonomous control or with advanced driver assistance systems (ADAS) can be guided to stop even when they are unable to see a VRU, improving overall safety.

However, this research was purposefully done under controlled and optimal conditions. This shows the viability of a solution but not the full extent of what would be required for a real-world deployment. Further research is necessary to create a system that will operate consistently and correctly in the public sphere to protect a VRU under a wide variety of operating conditions.

Areas for continued research include the use of sensor fusion to improve consistent VRU detection under all conditions, limited-scale public tests to validate the reliability and safety improvements in real-life scenarios, simulation testing to more thoroughly flesh out corner cases, further industry collaboration to test the benefits of the trialed solution and see if it can be turned into commercial products, cybersecurity testing and hardening, diverse VRU-centric dataset development, and use of the public intersection data to augment those datasets.

Summary

It is our hope that the data, outcomes, and conclusions from this project will help the smart mobility industry, municipal planners, and transportation regulators gain insights and data needed to implement and deploy technology solutions at intersections for CAVs that better protect VRUs. Note that this whitepaper provides a very short high-level overview of the full report submitted to Transport Canada; for more information or specific details, please contact Area X.O at info@areaxo.com.

About Area X.O

Area X.O is an autonomous test facility that helps technology suppliers quickly bring their smart mobility innovations to market. As the only four-season R&D complex of its kind in North America with a private and public V2X test facility on city streets, it fuels the creation, commercialization, and adoption of breakthrough innovations that benefit communities, the economy, and the environment. Area X.O helps local, national, and global startups, SMEs, multinationals, and governments with critical support from partners like Transport Canada, Accenture, BlackBerry QNX, Ericsson, Microsoft, Nokia, and the Government of Ontario. For additional information, visit: AreaXO.com.