Field Evaluation and Design Implications of an Infrastructure-Assisted Gap Detection System for Pedestrians with Vision Loss at Roundabouts

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Abstract

Pedestrians with vision loss (PWVL) encounter challenges at unsignalized roundabouts because continuous traffic flow, curved vehicle trajectories, environmental noise, and inconsistent driver yielding can make crossing opportunities difficult to assess. This study presents the field evaluation and continued development of an infrastructure-assisted Smart Gap System that uses roadside sensing to detect and track vehicles and provide real-time information about the traffic condition at a pedestrian crosswalk.

The theoretical basis of the system remains the temporal relationship between vehicle time-to-arrival (TTA) and the time required by a pedestrian to complete the crossing. Field testing, however, showed that a multilane crossing opportunity may develop progressively rather than appear as one instantaneous roadway-wide gap. The operational framework was therefore refined by dividing the monitored approach into individual traffic lanes and the crosswalk into corresponding conflict segments.

Each lane is linked to its associated crosswalk segment, allowing the system to represent three crossing states: No Gap, Partial Gap, and Full Gap. These states are communicated through dynamic visual indications and four audible messages: “Vehicles approaching,” “Wait,” “Partial gap. Use caution,” and “Gap detected. Use caution.”

Field and video-based testing were conducted using municipal and independent camera configurations. An approach-zone sensitivity experiment evaluated eight system-estimated monitoring lengths from 26.2 to 83.7 m. Warning lead time increased substantially as the monitored length increased toward approximately 55 m, but little additional benefit was observed beyond approximately 55–58 m. Approximately 57 m was therefore retained as a provisional nominal setting for the tested site and camera configuration. Live Milesight diagnostics produced a mean internal processing delay of approximately 62.2 ms, while simultaneous comparison of the direct camera view and Smart Gap display indicated an observable offset of approximately 0.2 s. A preliminary video-reviewed performance evaluation of nine events produced four true positives, four true negatives, one false positive, and no false negatives, corresponding to 88.9% accuracy and 80.0% precision for Full Gap versus Not Full Gap classification.

The results demonstrate the feasibility of lane- and crosswalk-segment-based real-time gap assessment while highlighting the importance of monitoring-zone geometry, low-latency sensing, site-specific calibration, and qualitative PWVL field feedback. The PWVL field visit indicated that the system functioned as supplementary traffic information rather than a replacement for natural auditory judgment.

1. Introduction

Roundabouts are widely implemented for their ability to reduce severe vehicular collisions through lower operating speeds and fewer high-severity conflict points [1–3]. Despite these safety benefits, accessibility remains a critical challenge for pedestrians with vision loss (PWVL). At unsignalized roundabouts, pedestrians must rely on gap acceptance, which involves assessing the time available between approaching vehicles, and on driver yielding behaviour to determine acceptable crossing opportunities [4–7].

At roundabouts, continuous vehicle circulation, curved approach trajectories, and variability in driver yielding behaviour introduce significant uncertainty in identifying acceptable gaps. These challenges are exacerbated for PWVL due to reduced access to visual information and limitations in auditory perception under complex traffic conditions [8–10].

Furthermore, existing geometric and surface-based treatments, such as crosswalk setback, splitter islands, and tactile or auditory features shown in Figure 1, provide only partial accessibility support and do not convey real-time traffic conditions or reduce uncertainty in gap identification [4, 7].



Figure 1: A photograph taken by the research team showing Rectangular Rapid Flashing Beacon (RRFB) with the Accessible Pedestrian Signal (APS) that audibly says "Amber light is flashing; vehicles may not stop immediately."

Following the recommendations of the FHWA (2006) [11] and NCHRP Report 674 [12], a mechanical accessibility treatment was implemented during the early stages of this research. Specifically, sound strips (Figure 2) were installed and demonstrated promising preliminary results [13].



Figure 2: Fully Installed Strips on Redwood Avenue West going Westbound [13].

Although the sound-strip treatment demonstrated promising preliminary results [13], it remained a passive solution and did not provide real-time information about approaching traffic. Recent advances in

sensing and intelligent transportation systems now enable infrastructure-assisted solutions capable of providing real-time crossing guidance [14–16].

This study evaluates the field deployment and progressive refinement of an infrastructure-assisted gap detection system at a roundabout. The objectives are to: (1) examine how crossing opportunities can be represented across individual traffic lanes and crosswalk conflict segments; (2) evaluate the influence of upstream monitoring-zone length on warning performance; (3) quantify live-system latency and preliminary classification performance; and (4) identify geometric and implementation considerations relevant to future infrastructure-assisted pedestrian guidance systems; and (5) document qualitative PWVL field feedback on system use under real traffic conditions.

2. System Framework

The theoretical temporal requirement for an adequate crossing opportunity is represented by the relationship between vehicle time-to-arrival (TTA) and pedestrian crossing time (TPED), as shown in Eq. 1.

$$TTA > TPED + t_b \quad (1)$$

Where, t_b is a safety buffer that accounts for uncertainties in vehicle detection, speed estimation, pedestrian reaction variability, and system latency. A buffer of 1 s is adopted in this study as a conservative modelling assumption.

Vehicle time-to-arrival is defined using Eq. 2.

$$TTA = \frac{D}{V} \quad (2)$$

Where, D is the distance from the vehicle to the crosswalk conflict point and V is the estimated vehicle speed.

Pedestrian crossing time is given by Eq. 3.

$$TPED = t_d + \frac{L}{v_p} \quad (3)$$

Where, t_d is pedestrian decision time, L is crossing distance, and v_p is walking speed. A conservative walking speed of 1.2 m/s and a decision time of approximately 2 s are adopted [17, 18].

The Smart Gap System processes live video to detect and track vehicles within user-defined roadway regions. Detected vehicles are associated with monitored traffic lanes and corresponding crosswalk segments. Vehicle movement direction, yielding behaviour, and crosswalk conflict are then evaluated to determine the operational state of each segment. Vehicle speed and time-to-arrival (TTA) continue to be calculated and retained for analysis; however, TTA does not independently govern the current lane state, crosswalk-segment state, visual display, or audible advisory.

The system records vehicle position, movement direction, speed, TTA, lane state, crosswalk-segment state, and the resulting advisory outputs for subsequent technical evaluation. The operational lane- and crosswalk-segment framework is described below.

2.1 Temporal Gap Theory and Operational Gap Assessment

The TTA–TPED relationship provides the theoretical temporal basis for describing an adequate crossing opportunity. Conceptually, sufficient temporal opportunity exists when an approaching vehicle is expected to reach the crosswalk after the pedestrian has had sufficient time to complete the crossing, including the selected uncertainty buffer.

During subsequent field development, including initial volunteer testing, it became apparent that the temporal relationship alone did not provide a sufficiently stable representation of the changing conditions at a multilane crossing. Vehicles in adjacent lanes did not necessarily respond simultaneously. A vehicle in one lane could slow or yield while another vehicle continued approaching. The crossing opportunity therefore developed progressively rather than changing directly from traffic present to a complete gap.

This observation did not invalidate the TTA–TPED framework. Instead, the system was supplemented with a lane- and crosswalk-segment-based operational framework that provides a more stable real-time interpretation of the theoretical crossing opportunity.

2.1.1 Lane and Crosswalk-Segment Readiness

A parent vehicle-approach polygon is divided according to the number of relevant traffic lanes. The corresponding pedestrian crosswalk is divided into the same number of conflict segments, and each approach lane is linked to its corresponding crosswalk segment. This allows the traffic condition affecting each portion of the crossing to be evaluated independently.

For each required crosswalk segment i, readiness is represented in Eq. 4 as:

$$R_i = \begin{cases} 1, & \text{segment } i \text{ is ready} \\ 0, & \text{segment } i \text{ is not ready} \end{cases} \quad (4)$$

where R_i represents the readiness of crosswalk segment i.

The total number of ready segments is shown in Eq. 5:

$$R = \sum_{i=1}^{N} R_i \quad (5)$$

where:

- R= number of ready crosswalk segments; and
- N= total number of required crosswalk segments.

The overall gap state, G, is then represented in Eq. 6 as:

$$G = \begin{cases} \text{No Gap}, & R = 0 \\ \text{Partial Gap}, & 0 < R < N \\ \text{Full Gap}, & R = N \end{cases} \quad (6)$$

A segment is considered ready when the traffic condition in its matched lane satisfies the implemented non-threatening conditions, such as the lane being clear, a relevant vehicle establishing a credible yield, or the relevant vehicle no longer threatening the crosswalk.

A vehicle occupying or encroaching upon the parent crosswalk overrides favourable segment conditions and returns the overall state to No Gap.

2.1.2 Visual and Audible Interpretation

The graphical interface provides a dynamic representation of the same gap state. Under a No-Gap condition, the affected crossing is displayed in red. During a Partial Gap, ready crosswalk segments are displayed in green while unresolved segments remain red, and the parent crossing is represented in yellow. A Full Gap is represented when all required crosswalk segments are green.

The three analytical gap states are communicated through four audible messages shown in the table below.

Table 1. Mapping of Gap States to Audible Information

Gap state	Audible information
No Gap	“Vehicles approaching.”
Partial Gap	“Wait.” or “Partial gap. Use caution.”
Full Gap	“Gap detected. Use caution.”

The Partial-Gap state may therefore produce either “Wait.” or “Partial gap. Use caution.” depending on pedestrian activation and the current advisory context. The four spoken messages do not represent four mathematical gap states.

The advisory wording communicates the observed traffic condition rather than directing the pedestrian to cross. The visual and audio interfaces are therefore two representations of the same underlying traffic-state assessment.

2.1.3 Audio-State Synchronization

During testing, traffic conditions could change while an earlier audio message was still being spoken or waiting within the speech system. The audio architecture was therefore refined so that an authoritative change in traffic state can supersede obsolete speech. The speech cooldown remains responsible for limiting unnecessary repetition, but it does not prevent the system from communicating a changed traffic condition. This refinement improves consistency between the visual gap state and the audible information.

3. Study Design and Data Collection

Field deployment was conducted at a roundabout in Thunder Bay, Ontario shown in Figure 3, with a combination of single-lane and multi-lane approaches across its legs. Two sensing configurations were evaluated:

- Municipal configuration: infrastructure-mounted camera with restricted access and observable latency; and
- Independent configuration: mobile camera system with direct real-time streaming capability.

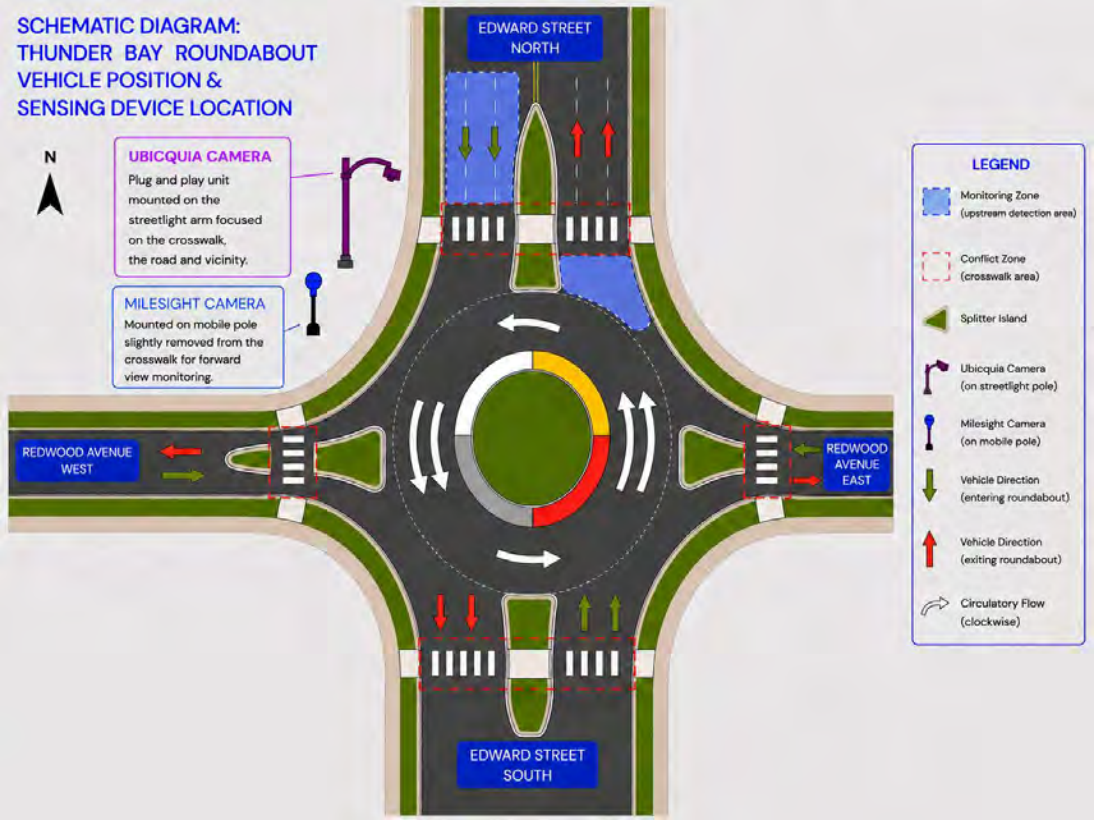


Figure 3: Roundabout intersection at Edward Street and Redwood Avenue in Thunder Bay. Actual circulatory traffic moves counterclockwise.

Calibration was performed by mapping image coordinates to real-world distances using visible roadway features such as crosswalk markings and lane boundaries. Regions of interest and conflict zones were defined through a graphical user interface, ensuring alignment between detection regions and physical roadway geometry.

3.1 Approach-Zone Length Sensitivity Test

A sensitivity experiment was conducted to examine how far upstream the system should monitor approaching vehicles. Eight progressively longer approach polygons were evaluated using the same recorded roadway sequence while the Smart Gap System settings were held constant across all runs. The system-estimated longitudinal extents were 26.2, 36.3, 39.3, 55.1, 57.4, 58.0, 69.8, and 83.7 m.

The metre values were derived from the image-based calibration and saved polygon geometry and should therefore be interpreted as system-estimated distances rather than survey-grade roadway measurements.

Warning lead time was defined as the elapsed time between the first applicable audible caution associated with the approaching vehicle and the time at which the same vehicle reached the crosswalk. Because the application recordings were not all equal in duration, total detection or audio-event counts were not compared. Instead, the same physical roadway event present within the common portion of all eight recordings was matched using the source-video sequence and time. The table below shows details recorded from the test.

Table 2. Monitoring-Zone Length Sensitivity Test

Configuration	System-estimated approach length (m)	Warning lead time (s)
L1	26.2	2.4
L2	36.3	2.8
L3	39.3	3.5

L4	55.1	5.5
L5	57.4	5.6
L6	58.0	6.0
L7	69.8	5.8
L8	83.7	5.5

3.2 Real-Time Processing Latency Verification

Real-time processing performance was evaluated during direct Milesight RTSP operation using latency diagnostics recorded by the Smart Gap System. The exported timing fields included frame age, object-detection inference time, display delay, and the combined internal video-processing delay. Descriptive statistics were calculated for the evaluated live run, including the median, mean, 95th percentile, and maximum observed delay. A separate side-by-side visual comparison of the direct Milesight live view and processed Smart Gap display was used to estimate the broader observable live-view-to-application offset. The internal diagnostic measurements and the visual offset are reported separately because they represent different measures of system responsiveness

3.3 Preliminary Video-Based Classification Evaluation

A preliminary event-level classification assessment was conducted using nine reviewed roadway events. Video recordings served as the ground-truth reference, while the corresponding system CSV records were used to determine the Smart Gap state at the representative event time. Because the operational system produces three states, but the objective of this preliminary calculation was specifically to evaluate Full-Gap identification, Full Gap was defined as the positive class and both Partial Gap and No Gap were grouped as Not Full Gap. Each event was then classified as a true positive, true negative, false positive, or false negative

3.4 External Video Stress Test

An external recorded roadway video from Sarasota, Florida, was used as a stress test of the lane/segment framework under a substantially different visual and traffic environment. The test examined vehicle detection, lane/segment association, spatial filtering, and transitions among No Gap, Partial Gap, and Full Gap. This test was not treated as an independent field deployment.

3.5 PWVL Field Feedback Evaluation

A qualitative field feedback session was conducted with pedestrians with vision loss at the study roundabout. The purpose was to observe how participants interpreted traffic conditions with and without Smart Gap audio and to identify practical deployment issues under real roadway conditions. The feedback was treated as qualitative field evidence rather than a controlled behavioural effectiveness study.

4. Results

The results are provided in the following sections

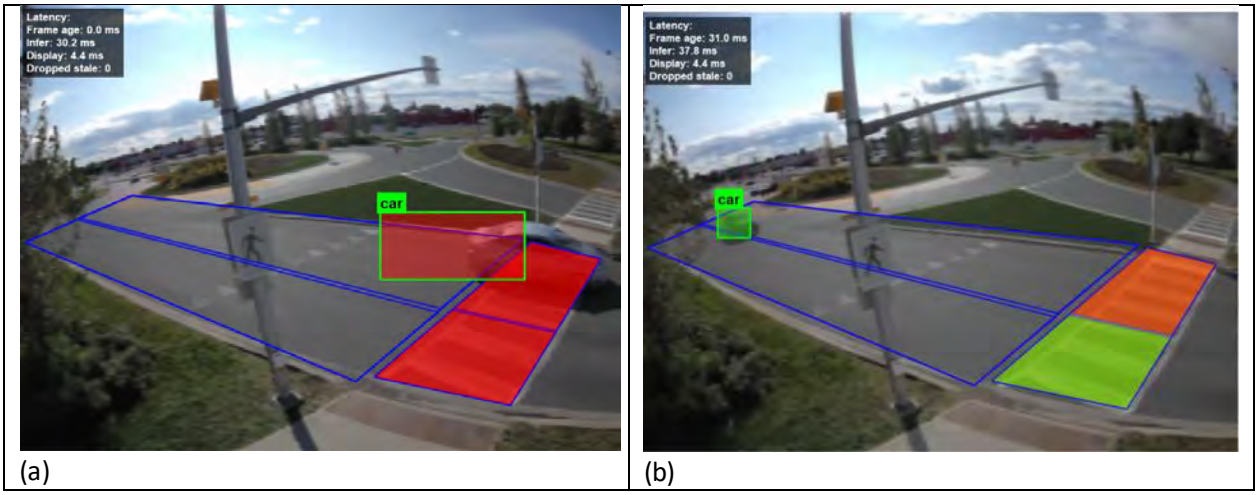
4.1 Progressive Lane-Based Gap Formation

Initial field testing demonstrated that traffic conditions in adjacent lanes could change independently. One vehicle could establish a credible yield while another lane remained influenced by approaching traffic. The lane/crosswalk-segment framework allowed this intermediate condition to be represented as a Partial Gap rather than forcing the entire crossing into a binary gap/no-gap state.

For a two-lane crossing, the resulting progression (Figure 4) can be represented conceptually as:

No Gap → Partial Gap → Full Gap

The progression is not necessarily one-directional. The appearance of new relevant traffic, renewed vehicle movement, or crosswalk occupancy can return the crossing from Full Gap or Partial Gap to a more restrictive state. This behaviour allows the system to represent the development and loss of a crossing opportunity dynamically.



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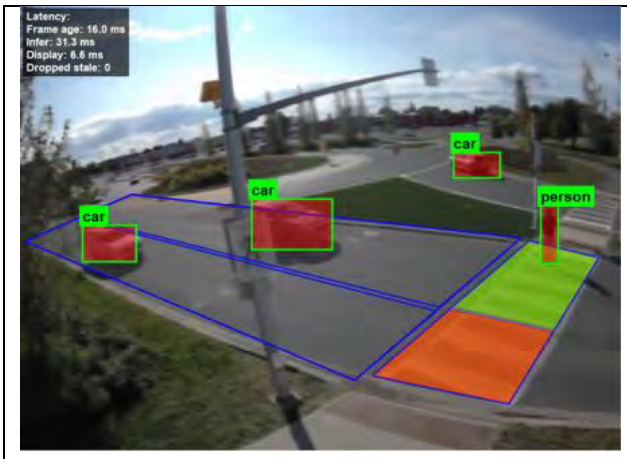

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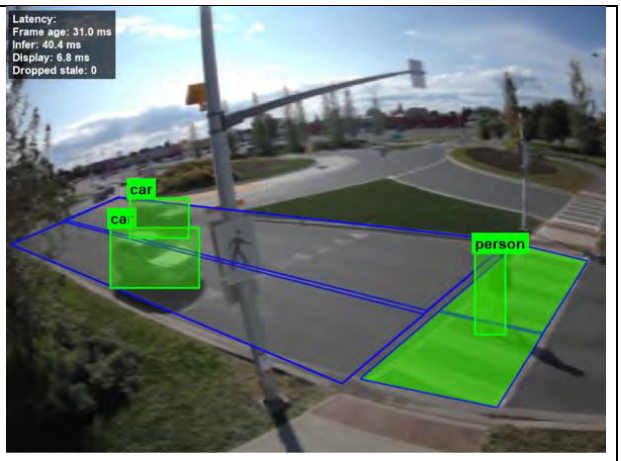


(d)

Figure 4. Progressive Smart Gap states: (a) No Gap; (b) Partial Gap without pedestrian activation; (c) Partial Gap with pedestrian activation; and (d) Full Gap.

4.2 Monitoring-Zone Length

Warning performance improved substantially as the monitoring zone was extended from approximately 26 m toward approximately 55 m. Warning lead time increased from 2.4 s at 26.2 m to 5.5 s at 55.1 m and reached 6.0 s at 58.0 m.

Extending the zone farther upstream did not produce a corresponding increase in warning time. The 69.8 m and 83.7 m configurations produced warning lead times of 5.8 and 5.5 s, respectively. These results indicate diminishing returns beyond approximately 55–58 m for the tested site and camera configuration.

Approximately 55 m is therefore interpreted as the minimum effective extent observed in this preliminary experiment, while approximately 57 m was selected as a provisional nominal setting for subsequent testing. These values are specific to the tested geometry, camera position, image calibration, field of view, and detection configuration and should not be interpreted as universal roundabout design values.

4.3 Real-Time Processing Latency

Real-time latency was evaluated using the direct Milesight camera configuration and the system's exported timing diagnostics. The mean internal video-processing pipeline delay was approximately 62.2 ms, while the median was approximately 59.4 ms. The 95th-percentile delay was approximately 101.7 ms, and the maximum observed value was approximately 149.7 ms. No substantial frame-backlog problem was observed during the evaluated run.

A separate simultaneous visual comparison of the direct Milesight live view and the processed Smart Gap display indicated an observable application/display offset of approximately 0.2 s (200 ms). This

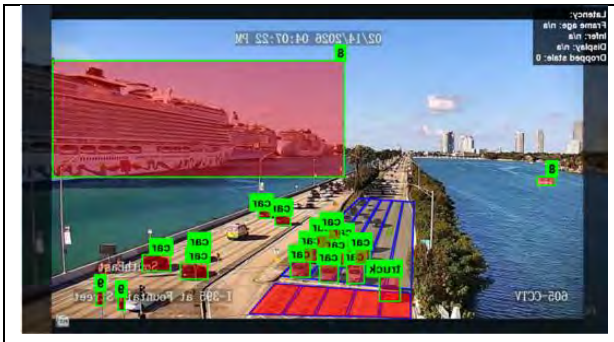
value represents a broader practical comparison than the internal software-processing measurements and is therefore reported separately.

The results indicate sub-second system responsiveness under the evaluated configuration. Latency is treated as a technical performance measure rather than a variable controlling the No-Gap, Partial-Gap, or Full-Gap logic.

4.4 External Video Stress Test

To examine whether the lane/segment framework could operate under a substantially different roadway scene, as shown in Figure 5, the system was also applied to external vehicle-only video from Sarasota, Florida. This was an external-video stress test rather than a second field deployment.

The test was used to examine multi-lane detection, lane/segment association, and No-Gap/Partial-Gap/Full-Gap transitions under a different roadway environment. Detections occurring outside the configured roadway conflict zones did not govern the crossing state, illustrating the importance of spatial filtering and lane/crosswalk association in preventing irrelevant detections from controlling the advisory logic.



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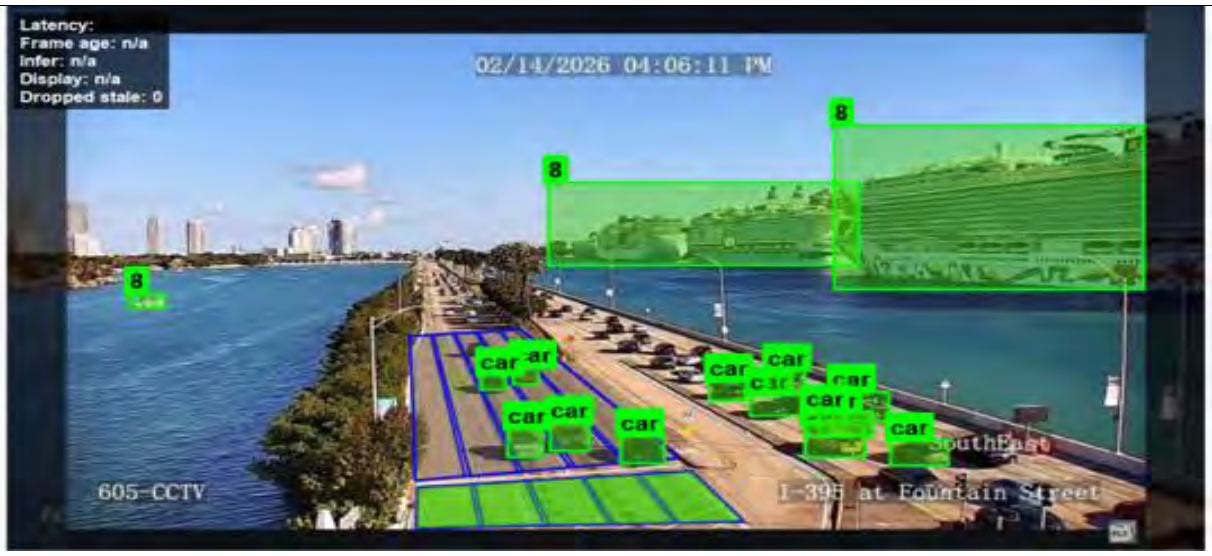

(c)

Figure 5. External-video stress test using roadway footage from a Florida Department of Transportation (FDOT) YouTube video: (a) No Gap; (b) Partial Gap; and (c) Full Gap. Source: Florida Department of Transportation (FDOT), YouTube.

4.5 Preliminary Classification Performance

A preliminary event-level performance evaluation was conducted using nine video-reviewed events. The corresponding video clips were used as the ground-truth reference, while the system CSV records were used to identify the application state at the representative event time.

Because the operational system contains three states—No Gap, Partial Gap, and Full Gap—a binary classification was used specifically to evaluate Full-Gap identification. Full Gap was defined as the positive class, while both Partial Gap and No Gap were grouped as Not Full Gap and treated as the negative class. Partial-Gap observations were therefore retained in the analysis rather than excluded.

Of the nine evaluated events, four were true positives, four were true negatives, one was a false positive, and none were false negatives.

At this preliminary stage, Eq. 7 and Eq. 8 show a measure of the system's accuracy and precision.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \times 100 = \frac{4 + 4}{4 + 4 + 1 + 0} \times 100 = 88.9\% \quad (7)$$

And therefore,

$$Precision = \frac{TP}{TP + FP} \times 100 = \frac{4}{4 + 1} \times 100 = 80.0\%$$

(8)

Accuracy therefore indicates that the system state agreed with the video-based ground truth in eight of the nine reviewed events. Precision indicates that four of the five Full-Gap classifications were confirmed as Full Gap in the corresponding video. Because the sample is small, these values are reported as preliminary performance measures.

4.6 PWVL Field Feedback

The PWVL field feedback indicated that participants used the Smart Gap audio as supplementary information together with natural vehicle sound. On the inbound approach, the audio helped some participants interpret traffic conditions more quickly. Muted trials suggested that participants could still assess traffic using natural sound, but sometimes required more time.

The field visit also identified practical limitations. Warning timing was especially important on the exit side of the roundabout, where the short distance between the circulatory roadway and the crosswalk reduced advance warning time. Multiple vehicles increased interpretation difficulty, and RRFB/APS sounds sometimes interfered with Smart Gap audio. Non-yielding drivers remained an external source of uncertainty. These findings suggest that practical usefulness depends not only on detection performance, but also on roadway geometry, warning distance, traffic complexity, competing sounds, and driver behaviour.

5. Geometric Design Implications

The findings from this study highlight the important role of geometric design in enabling the effective deployment of infrastructure-assisted pedestrian safety systems at roundabouts. In particular, elements such as crosswalk placement, approach geometry, and splitter island design directly influence both driver behaviour and sensing performance.

Crosswalk setback influences pedestrian visibility, driver yielding opportunities, and the sensing horizon available to the system. The appropriate setback therefore has both geometric and sensing implications and should be considered together with roadway geometry and sensor placement. This relationship is consistent with established roundabout guidance emphasizing the importance of crosswalk placement, visibility, and yielding behaviour [2, 4].

Splitter islands support staged crossings, reduce pedestrian exposure, and simplify detection. By dividing the crossing into two stages, the system can evaluate each direction independently, reducing the

complexity of gap assessment. They also provide consistent reference points for defining crosswalk conflict zones.

Approach geometry significantly affects detection performance. Inbound approaches generally provide sufficient upstream distance for monitoring, while exit approaches are constrained by proximity to the circulatory roadway. This reduces the available observation history for vehicle tracking, direction assessment, yielding recognition, and gap-state stabilization. For exit approaches, geometric constraints limit the available distance between the circulatory roadway and the crosswalk, reducing the feasible monitoring zone length and introducing a structural limitation on system performance. These findings are consistent with previous observations in mechanical accessibility treatments, where insufficient upstream distance reduced effectiveness [13].

The monitoring-zone sensitivity experiment further demonstrates that increased monitoring distance does not provide unlimited benefit. For the tested configuration, useful warning performance largely plateaued once the system-estimated monitoring extent reached approximately 55–58 m. This range is not a universal geometric standard; it is specific to the tested site, camera position, field of view, detection capability, and calibration. The broader design implication is therefore that monitoring zones should be calibrated to site geometry and sensing performance rather than assigned a fixed nominal distance.

6. Infrastructure Implementation Considerations

The system has been designed to be deployable as a sensor-agnostic edge-processing unit integrated with roadside sensing infrastructure.

For a typical deployment, the system requires:

- a sensing device (camera, radar, or LiDAR);
- continuous electrical power supply;
- low-latency data transmission;
- an edge-processing unit (“brain box”);
- a calibration interface for defining monitoring zones;
- a pedestrian feedback interface.

The current pedestrian feedback interface uses a roadside loudspeaker. The spoken messages communicate the detected traffic condition without instructing the pedestrian to cross. Future implementations could examine alternative accessible output interfaces, but such alternatives were not evaluated in the present study.

Deployment must be performed at the level of individual crosswalks, as each approach has unique geometric constraints. Monitoring zones are configured via a graphical user interface and must be aligned with roadway geometry.

Maintenance requirements include ongoing sensor alignment, periodic recalibration, communication reliability, and performance under environmental conditions.

From an implementation perspective, the system architecture separates sensing, processing, and user interaction components. The sensing layer captures raw data, the processing layer performs detection and gap evaluation, and the output layer delivers feedback to the pedestrian.

In addition, a sensor-agnostic architecture offers flexibility in deployment, enabling agencies to select sensing technologies based on available infrastructure and budget constraints. However, regardless of sensor type, the system requires consistent data quality and low-latency transmission to function effectively.

Installation considerations include ensuring clear line-of-sight coverage of the monitoring zone, stable sensor mounting, and protection of equipment from environmental conditions. In cold climates, snow accumulation and reduced visibility may affect both detection accuracy and system reliability, requiring periodic maintenance and recalibration [2].

The need for crosswalk-specific configuration implies that large-scale deployment must consider the effort required for calibration and maintenance across multiple locations. However, using a graphical interface to define detection zones simplifies this process and allows adjustments without physical modifications to infrastructure.

These considerations indicate that successful deployment depends on coordinated design of sensing, communication, and processing systems rather than independent component selection.

The prototype evolved from an initial mobile field configuration (Figure 6) toward an infrastructure-oriented arrangement combining roadside sensing, local processing, and pedestrian-facing loudspeaker output. Direct Milesight video was adopted for low-latency field operation while preserving the ability to integrate with existing roadside infrastructure. The field configuration also allowed camera position, processing equipment, power, communication, and audio output to be adjusted during technical testing.

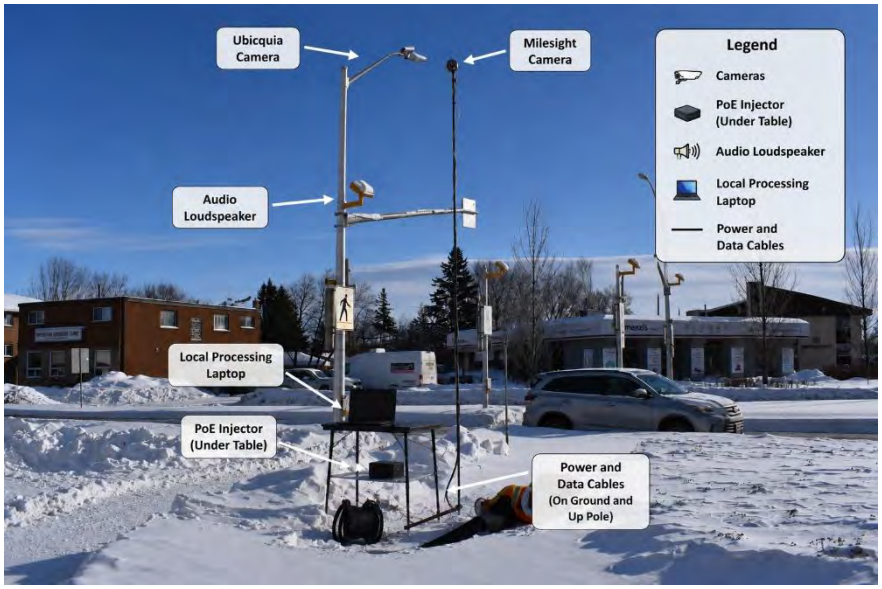

Figure 6: Smart Gap System field prototype configuration in Thunder Bay, Ontario.

Although the present evaluation focuses on roundabouts, the lane/segment architecture may have broader application to other pedestrian conflict environments. Potential applications include channelized turn lanes, conventional intersections, school-zone crossings, selected midblock or rural crossings, and locations where bicycles, scooters, e-bikes, automated vehicles, or other moving devices create pedestrian conflicts. These applications remain prospective and require site-specific validation.

7. Limitations

The primary field evaluation was conducted at one roundabout, and the monitoring-zone findings are specific to the tested roadway geometry, camera location, field of view, detection capability, and image-based calibration. The longitudinal monitoring distances are system-estimated rather than survey-grade measurements.

The preliminary classification-performance evaluation is based on only nine video-reviewed events and should not be interpreted as a final estimate of system accuracy. Additional ground-truth validation across larger traffic samples and different environmental conditions is required.

PWVL field feedback was collected during a limited qualitative field visit at one site. The findings should therefore be interpreted as operational and usability observations, not as proof of behavioural effectiveness or safety improvement.

The Sarasota evaluation used external recorded video and should be interpreted as a stress test of the lane/segment logic rather than an independent field deployment.

8. Conclusions

This study demonstrates the field feasibility of an infrastructure-assisted Smart Gap System that combines real-time vehicle detection with lane- and crosswalk-segment-based assessment of pedestrian crossing opportunities at an unsignalized roundabout.

The original TTA–TPED relationship remains useful for describing the theoretical temporal requirement of a crossing gap. Field development showed, however, that a multilane crossing opportunity may form progressively as conditions in individual traffic lanes change. The resulting lane/segment framework allows the system to represent No Gap, Partial Gap, and Full Gap states while maintaining crosswalk occupancy as an overriding restrictive condition.

Monitoring-zone sensitivity testing showed substantial improvement in pedestrian warning lead time as the system-estimated approach length increased toward approximately 55 m. Little additional benefit was observed beyond approximately 55–58 m for the tested configuration, and approximately 57 m was retained as a provisional nominal setting for subsequent testing at this site.

The direct Milesight configuration demonstrated sub-second responsiveness, with a mean internal processing delay of approximately 62.2 ms and an observed live-view-to-Smart-Gap display offset of approximately 0.2 s. A preliminary nine-event evaluation produced 88.9% accuracy and 80.0% precision for Full Gap versus Not Full Gap classification.

These findings indicate that effective infrastructure-assisted pedestrian guidance depends on the coordinated design of sensing, roadway geometry, lane/crosswalk representation, low-latency processing, and accessible user communication. PWVL field feedback further indicated that successful deployment depends on both system performance and the roadway environment. Further work should expand ground-truth validation, examine additional sites and sensing configurations, and analyze the quantitative data collected during PWVL trials.

References

1. Retting, R. A., Persaud, B. N., Garder, P. E., and Lord, D. "Crash and Injury Reduction Following Installation of Roundabouts in the United States." *American Journal of Public Health*, 91(4): 628–631. (2001). DOI: 10.2105/AJPH.91.4.628.
2. Transportation Association of Canada (TAC). *Canadian Roundabout Design Guide*. Ottawa, ON: Transportation Association of Canada. (2017).
3. National Academies of Sciences, Engineering, and Medicine. *Roundabouts: An Informational Guide—Second Edition*. NCHRP Report 672. Washington, DC: The National Academies Press. (2010). DOI: 10.17226/22914.
4. Schroeder, B. J., and Rouphail, N. M. "Event-Based Modeling of Driver Yielding Behavior at Unsignalized Crosswalks." *Journal of Transportation Engineering*, 137(7): 455–465. (2011). DOI: 10.1061/(ASCE)TE.1943-5436.0000225.
5. Daniels, S., Brijs, T., Nuyts, E., and Wets, G. "Explaining Variation in Safety Performance of Roundabouts." *Accident Analysis & Prevention*, 42(2): 393–402. (2010). DOI: 10.1016/j.aap.2009.08.019.
6. Geruschat, D. R., and Hassan, S. E. "Driver Behavior in Yielding to Sighted and Blind Pedestrians at Roundabouts." *Journal of Visual Impairment & Blindness*, 99(5): 286–302. (2005). DOI: 10.1177/0145482X0509900504.
7. Schroeder, B. J., Rouphail, N. M., and Hughes, R. G. "Toward Roundabout Accessibility—Exploring the Operational Impact of Pedestrian Signalization Options at Modern Roundabouts." *Journal of Transportation Engineering*, 134(6): 262–271. (2008). DOI: 10.1061/(ASCE)0733-947X(2008)134:6(262).
8. Guth, D., Ashmead, D., Long, R., Wall, R., and Ponchillia, P. "Blind and Sighted Pedestrians' Judgments of Gaps in Traffic at Roundabouts." *Human Factors*, 47(2): 314–331. (2005). DOI: 10.1518/0018720054679533.
9. Ashmead, D. H., Guth, D., Wall, R. S., Long, R. G., and Ponchillia, P. E. "Street Crossing by Sighted and Blind Pedestrians at a Modern Roundabout." *Journal of Transportation Engineering*, 131(11): 812–821. (2005). DOI: 10.1061/(ASCE)0733-947X(2005)131:11(812).

10. Long, R. G., Guth, D. A., Ashmead, D. H., Emerson, R. W., and Ponchillia, P. E. "Modern Roundabouts: Access by Pedestrians Who Are Blind." *Journal of Visual Impairment & Blindness*, 99(10): 611–621. (2005). DOI: 10.1177/0145482X0509901005.
11. Inman, V. W., Davis, G. W., and Sauerburger, D. *Pedestrian Access to Roundabouts: Assessment of Motorists' Yielding to Visually Impaired Pedestrians and Potential Treatments to Improve Access*. Publication No. FHWA-HRT-05-080. Federal Highway Administration, U.S. Department of Transportation, McLean, VA. (2006).
12. Schroeder, B., Hughes, R., Rouphail, N., Cunningham, C., Salamati, K., Long, R., Guth, D., Emerson, R. W., Kim, D., Barlow, J., Bentzen, B. L., Rodegerdts, L., and Myers, E. *Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities*. NCHRP Report 674. Transportation Research Board, Washington, DC. (2011). DOI: 10.17226/14473.
13. Adeniran, O. A. *Identifying and Addressing Roundabout Accessibility Issues Confronting Persons with Vision Loss in Canada: A Pilot Study*. Master's thesis, Lakehead University, Thunder Bay, ON. (2023).
14. Barbaresso, J., Cordahi, G., Garcia, D., Hill, C., Jendzejec, A., and Wright, K. *USDOT's Intelligent Transportation Systems (ITS) Strategic Plan, 2015–2019*. Report No. FHWA-JPO-14-145. U.S. Department of Transportation, Intelligent Transportation Systems Joint Program Office, Washington, DC. (2014).
15. Harkey, D. L., Carter, D. L., Barlow, J. M., and Bentzen, B. L. *Accessible Pedestrian Signals: A Guide to Best Practice*. NCHRP Web-Only Document 117A. Transportation Research Board of the National Academies, Washington, DC. (2007).
16. Coifman, B., McCord, M., Mishalani, R. G., Iswalt, M., and Ji, Y. "Roadway Traffic Monitoring from an Unmanned Aerial Vehicle." *IEE Proceedings—Intelligent Transport Systems*, 153(1): 11–20. (2006). DOI: 10.1049/ip-its:20055014.
17. National Academies of Sciences, Engineering, and Medicine. *Improving Pedestrian Safety at Unsignalized Crossings*. NCHRP Report 562/TCRP Report 112. Washington, DC: The National Academies Press. (2006). DOI: 10.17226/13962.
18. Transportation Research Board. *Highway Capacity Manual, Sixth Edition: A Guide for Multimodal Mobility Analysis*. Washington, DC: The National Academies Press. (2016). DOI: 10.17226/24798.