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Evaluation of dynamic passive pedestrian detection

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ABSTRACT

Dynamic passive pedestrian detection (DPPD) has the potential to enhance the operational efficiency and safety of signalized intersections by cancelling unnecessary pedestrian service calls or extending the pedestrian phase to allow a pedestrian to safely finish crossing the street. This paper examines the accuracy and reliability of two thermal sensors and one optical sensor for DPPD at one mid-block crossing location and one signalized intersection in Washington County, Oregon. Results indicate the average accuracy rate for the thermal sensors was 89% at the signalized intersection and 82% at the mid-block location. The most common inaccurate detection types for the thermal sensors were Late, Held, and Miss calls. Average accuracy rate for the optical sensor was 26% at the signalized intersection and 83% at the mid-block location. The most common error types for the optical sensors were Spotty, Late, and Miss calls. False detections most often occurred for both sensors when vehicles and bicycles in the roadway crossed into the detection zones. Weather and lighting conditions affected thermal sensor accuracy, while only pedestrian type affected optical sensor accuracy. Pedestrian curbside waiting habits, jaywalking, and implications for sensor selection, deployment, and development are discussed.

1. Introduction

Most actuated traffic signals currently rely on pushbutton cues to initiate a pedestrian phase, which cannot be modified or cancelled once the service call is placed. If a pedestrian decides not to cross or to jaywalk, the continuation of the pedestrian phase can incur unnecessary delay for other intersection users. If the pedestrian needs more time to cross than the signal provides, the onset of the conflicting vehicular phase can jeopardize that pedestrian's safety. Dynamic passive pedestrian detection (DPPD) has the potential to enhance the operational efficiency and safety of signalized intersections with pedestrian call extension or cancellation functionality. Pedestrian call extensions extend the phase time for a pedestrian crossing if a pedestrian is detected in the crosswalk at the termination of the programmed walk time. A 2001 Federal Highway Administration evaluation of a pedestrian call extension system observed a 50% reduction in the percentage of pedestrians still in the crosswalk at the onset of the conflicting vehicular phase, suggesting safety benefits (Hughes et al., 2001). Fig. 1 illustrates this functionality.

Pedestrian call cancellation functionality would allow the signal controller to cancel a pedestrian call if the pedestrian activates a pedestrian push button, then leaves the curb detection zone and does not re-enter any detection zone for the same crossing in a given amount of time. Pedestrian call cancellation is not intended to truncate crossing time for "fast" pedestrians. Fig. 2 illustrates this functionality.

Relatively little research has assessed the viability of sensor technology for widespread deployment, an important first step towards implementing pedestrian call cancellation and extension. Similarly, little official guidance for sensor deployment exists. The goal of this study is to evaluate the DPPD potential of two thermal sensors and one optical sensor at one mid-block crossing location and one signalized intersection in Washington County, Oregon, where Washington County would ultimately like to deploy pedestrian call extension and cancellation functionality. Two research questions were developed to guide the research:

Research Question 1: What is the accuracy of current optical and thermal sensors to dynamically and passively detect a pedestrian throughout the entire crossing movement in varying pedestrian, weather, and lighting conditions?

Research Question 2: What unidentified or unexplained issues must be considered before dynamic passive detection is deployed for call extension or cancellation?

Data on pedestrian waiting habits in the curb zone and jaywalking was also collected to support both research questions. The researchers hope this work will help inform sensor design, selection, and

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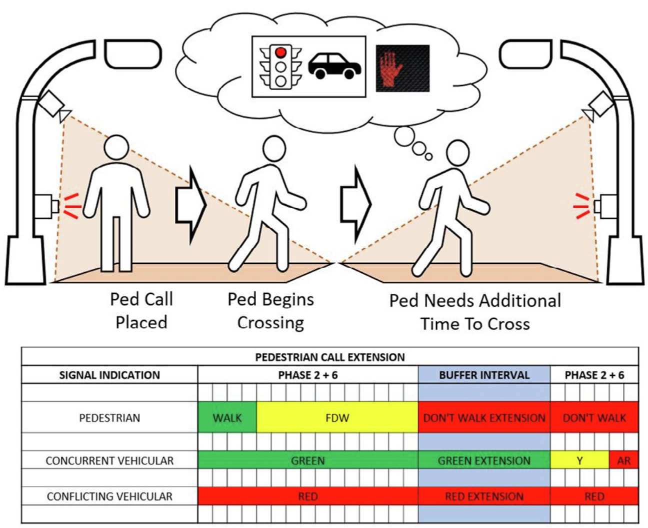

Fig. 1. Pedestrian Call Extension.

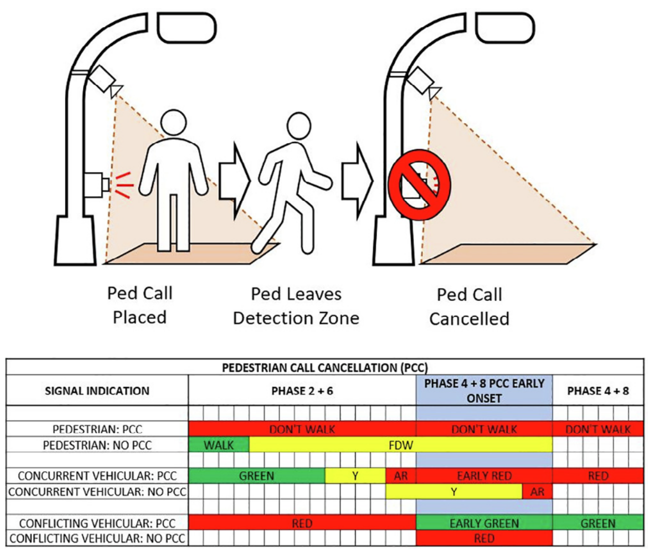

Fig. 2. Pedestrian Call Cancellation.

deployment and provide a framework for further analysis of new sensor technologies.

2. Literature review

Pedestrian detection has undergone considerable development in recent years, yet little guidance for its deployment exists in the United States (US). The Manual on Uniform Traffic Control Devices (MUTCD) states "passive pedestrian detection *may* be used to automatically adjust the pedestrian clearance time" (FHWA, 2009). The National Cooperative Highway Research Program (NCHRP) Signal Timing Manual (Second Edition), the Public Rights of Way Accessibility Guidelines (PROWAG), and the Americans with Disabilities Act Accessibility Guidelines (ADAAG) provide no additional guidance (National Cooperative Highway Research Program, 2015; U.S. Architectural and Transportation Barriers Compliance Board, 2011; 2002). State level documents like the Oregon Department of Transportation (ODOT) Signal Design Manual and Traffic Signal Policy and Guidelines specify only that a mechanism for pedestrian detection should be provided at crosswalks (Oregon Department of Transportation, 2020, 2017).

Outside the US, perhaps the most well-known application of dynamic passive pedestrian detection is the Pedestrian User-Friendly INtelligent (PUFFIN) crossing. Employed in the UK, Canada, and several other countries, the PUFFIN crossing is a signalized pushbutton-actuated crossing which performs pedestrian call cancellation and extension/truncation functions to improve efficiency and pedestrian safety. This functionality typically employs two sensor types: pressure-sensitive mats and radar. The pressure-sensitive mats monitor the curb zone; the pedestrian must stand on the mat to maintain detection. Radar sensors monitor the full crossing and are typically positioned at diagonal ends of the crossing; they can alert the signal controller to lengthen or shorten the pedestrian phase depending on the presence of a pedestrian in the crosswalk (FHWA, 1999; FWHA, 2001; Manston, 2011). Studies have shown that these crossings increase pedestrian compliance and reduce pedestrian-vehicle conflicts (FWHA, 2001; Hughes et al., 2001). However, the detection mechanisms employed are not perfect, and companies have historically struggled to provide curb zone detection with good pedestrian coverage and accuracy under a variety of weather and lighting conditions (FHWA, 1999; Manston, 2011).

The majority of prior studies evaluating DPPD technologies have examined the accuracy of infrared and radar systems by classifying pedestrian detection observations as valid, missed, or false. While no studies identified one system that works well in all scenarios, all studies concur that the systems require further development before full scale adoption would be warranted. In an early study on DPPD, Beckwith and Hunter-Zaworski (1998) evaluated short and long-range ultrasonic, passive infrared, and Doppler radar systems for accuracy performing DPPD at unsignalized intersections in Portland, Oregon. The researchers found that the infrared sensors had a good short-range detection rate, but a limited detection zone range. The Doppler radar was most effective at detecting pedestrians more than 30 feet away and had a detection zone wide enough to detect pedestrians across the full width of the crossing, but could only detect moving pedestrians (Beckwith and Hunter-Zaworski, 1998). A 2007 Texas Transportation Institute study also evaluated microwave radar and infrared sensors for DPPD in curb and crosswalk zones; both systems demonstrated error rates between 20% and 30%. The most frequently observed detection errors occurred when vehicles stopped within the crosswalk and triggered the detection zone. In the curb area, sensors also had difficulty detecting pedestrians that stood still. The researchers determined the systems were not reliable enough for implementation (Turner et al., 2007). Finally, Montufar and Foord (2011) examined infrared, infrared-video combined, and microwave systems at below-freezing temperatures using metrics of sensitivity (number of valid calls divided by number of pedestrians) and selectivity (number of accurately detected pedestrians divided by number of times detection occurred). Their analysis found that the infrared, infrared-video combined, and microwave systems had average sensitivities of 97%, 86%, and 62% and average selectivities of 14%, 43%, and 22%, respectively. The researchers concluded that sensor selectivity must be improved prior to deployment (Montufar and Foord, 2011).

A variety of factors can affect the accuracy of a sensor in the field. Klein (2020) identifies mounting height, detection range, occlusions, and sensitivity to wind, lighting conditions, and weather conditions as important considerations for sensor selection and deployment (Klein, 2020). A 2011 report investigating the state of detection technologies for PUFFIN crossings specifically states that a successful sensor system should perform well in all light conditions, be insensitive to shadowing, require minimal maintenance, should monitor the desired range, should detect static pedestrians, and should not rely on pedestrian action (Manston, 2011).

Prior studies unanimously describe DPPD sensor technologies as "promising"—with further technological development. However, recent years have seen the introduction of new detection technology such that DPPD systems deserve reconsideration. This work evaluates two new systems for DPPD to encourage further improvement of this technology for call extension and cancellation applications.

3. Methodology

This study assesses the accuracy of optical and thermal sensors for DPPD using video detection data at one mid-block and one signalized intersection location in Washington County, Oregon. Researchers categorized detector performance for each pedestrian crossing observation across several independent variables. The detection software, hardware, deployment process, and analysis process are discussed in this section.

3.1. Test locations

Engineers for Washington County, Oregon identified one mid-block and one intersection location for testing. These locations were candidates for Washington County's deployment of future DPPD systems. The signalized intersection location was Scholls Ferry Road and Nimbus Avenue. The major and minor street crossing widths are approximately 120 ft and 90 ft, respectively. All sidewalks are approximately five ft wide; crosswalks are approximately nine ft wide. The site experiences relatively low pedestrian volumes, with most of the pedestrian trips related to nearby employment centers. The mid-block location was Evergreen Parkway and Rock Creek Trail, a signalized crossing that serves the Rock Creek Trail system in Hillsboro, Oregon. The street crossing width is approximately 70 ft, comprised of two 30 ft crossings. The trail, sidewalks, and crosswalks have widths of approximately 12 ft, six ft, and ten ft, respectively. The site experiences relatively high pedestrian and bicycle volumes, with most trips related to recreation.

3.2. Detection software

Due to crossing length, two curb zones and two or three crosswalk zones were defined for each crossing in the detection software for individual evaluation. Fig. 3 shows the crossing layout and detection zones. Fig. 4 shows activated and non-activated zones for both detection systems at the two test locations. Because detection outcomes varied based on the direction that a pedestrian entered a zone, zones were classified as "Arriving" or "Departing" based on the pedestrian's travel direction. The curb zone and first crosswalk zones from which the pedestrian began their crossing were departing zones, while the last crosswalk zones and end curb zone were arriving zones.

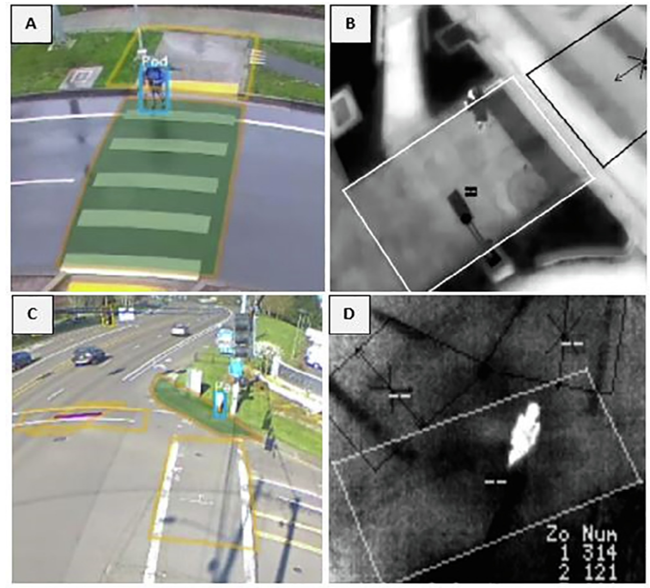

Fig. 4. Positive Detection for Optical Sensor at Mid-Block Crossing (A), High-Resolution Thermal Sensor at Mid-Block Crossing (B), Optical Sensor at Signalized Intersection (C), and Low-Resolution Thermal Sensor at Signalized Intersection (D).

3.3. Detection hardware

Optical and thermal detection systems were selected for testing based on availability and recent advances in their technological capabilities. Optical sensors capture video data of the surrounding environment and can detect pedestrians in the video data using image-based processing algorithms. Thermal sensors detect pedestrians using emitted heat signatures in the roadway environment. The particular thermal sensors used in this study operated in the long-wave section of the infrared spectrum. As shown in Fig. 4D, thermal sensor images appear on a grayscale: hot areas are represented in bright white, while the coolest areas are represented in black. Both systems analyzed for this study are marketed for multimodal presence detection and for counting pedestrians, bicycles, and vehicles. The sensors were not connected to the signal controllers and could not affect the signal timing at either test location.

Both the High-Res and Low-Res thermal sensors can source power from either a Broadband over Power Line (BPL) or Power over Ethernet (PoE) connection. The BPL source is used if multiple sensors are

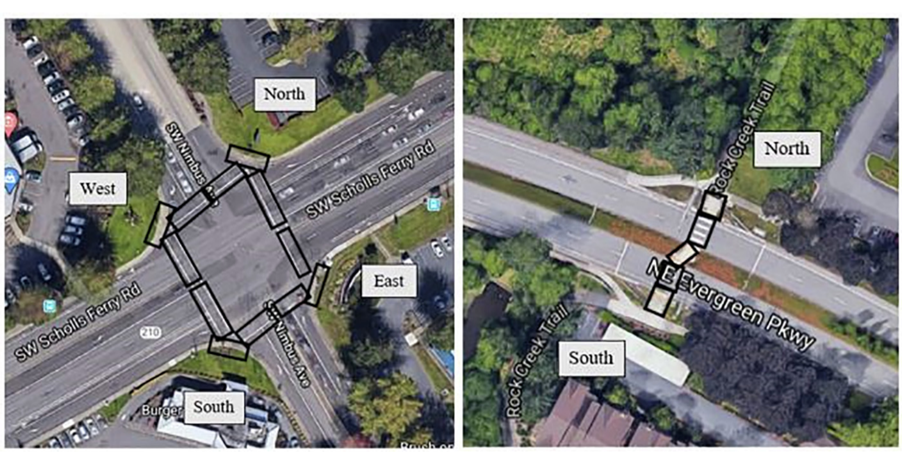

Fig. 3. Aerial images and detection zones for Scholls Ferry Road and Nimbus Avenue (Left); Evergreen Parkway and Rock Creek Trail (Right).

installed at the same location. The PoE source is used if the sensor is stand-alone or replacing an IP camera, and requires one CAT5e cable. The power draw for these sensors is less than five watts. The optical sensor uses a PoE connection.

3.3.1. Thermal sensors

This study assessed a high-resolution (High-Res) and low-resolution (Low-Res) thermal sensor. The High-Res sensor has a 640 × 480 pixel resolution with a 90 degree horizontal view, 69 degree vertical view, and 30 fps frame rate. The sensor is rated for a detection distance of up to 100 ft. The Low-Res sensor has a 160 × 120 pixel resolution with a 95 degree horizontal view and nine fps frame rate. The sensor is rated for a detection distance of up to 40 ft for pedestrians and 65 ft for bicycles and vehicles. Both sensors can differentiate between pedestrians, bicycles, and vehicles. The manufacturer recommends one sensor per intersection corner for complete intersection coverage and an installation height no higher than 30 ft from the ground for the High-Res sensor and 20 ft for the Low-Res sensor. At the signalized intersection location, two High-Res thermal sensors were mounted approximately 25 ft high on signal poles above the east and south corners of the intersection and two Low-Res thermal sensors were mounted approximately 17 ft high on signal poles above the north and west corners of the intersection. At the mid-block location, one High-Res thermal sensor was mounted approximately 29 ft high on a signal pole above the north side of the crossing and one Low-Res thermal sensor was mounted approximately 12 ft high on a signal pole above the south side of the crossing. With this configuration, the High-Res and Low-Res sensors each monitored half the crossing zones.

3.3.2. Optical sensor

The Optical Sensor is a 4 K resolution, fish eye lens camera with a 182 degree horizontal view, 176 degree vertical view, and 15 fps frame rate. The sensor can differentiate between pedestrians, bicycles, light vehicles, single-unit trucks, articulated trucks, and buses. Two cameras are recommended for larger intersections, while one sensor is sufficient for smaller intersections. The recommended camera installation height is at least 30 ft on a traffic pole nearest the controller cabinet. With this configuration, the cameras are rated to have a tracking radius of up to 190 ft. At the signalized intersection location, two optical sensors were mounted approximately 26 ft high on signal poles above the west and south corners of the intersection. At the mid-block location, one optical sensor was mounted approximately 26 ft high on an extension pole attached to the mast arm over the westbound lane.

3.4. Detection system deployment

The sensor manufacturers installed and calibrated the thermal and optical sensors at both locations between Spring 2019 and Fall 2019. A preliminary analysis revealed none of the crosswalk zones at the signalized intersection monitored by the optical sensor were detecting pedestrians in the arriving direction due to a directional filter setting. This setting could not be changed prior to final analysis, so data collected from the arriving direction of a crosswalk zone at the signalized intersection was excluded from analysis. The preliminary analysis also revealed that three crosswalk zones monitored by the thermal sensors at the signalized intersection were longer than all other crosswalk zones; zone accuracy here was lower due to Late detections. The vendor recommended shortening the zone lengths to match the others, however, Washington County desired to test the detection distance limits of the sensor, so the zone lengths were not changed. Following the preliminary analysis, the manufactures further calibrated the sensors between January and mid-March, after which researchers performed a final analysis of the data.

3.5. Data analysis

Video files recorded between the end of March 2020 and early May 2020 were analyzed for this study. Few pedestrian crossings were observed at the signalized intersection during this time, likely due to statewide stay-at-home orders related to the COVID-19 pandemic. The mid-block location experienced little to no disruption in pedestrian activity—potentially due to recreation-related crossings. A total of 512 unique observations were recorded between the two sites—1,024 observations between the two sensor systems. Table 1 shows the distribution of observations by pedestrian type, weather, lighting conditions, and location.

Researchers recorded false calls and pedestrian crossings from the optical and thermal sensor videos. A pedestrian had to make a full crossing—not necessarily passing through all zones—for an observation to be recorded. Detector outcomes were evaluated by zone, not by crossing, so a single pedestrian observation could have multiple detector outcomes as the pedestrian passed through multiple zones. Detection outcome was categorized for each pedestrian observation as Valid, Spotty, Dropped, Held, Late, or Miss; definitions are shown in Table 2. The detection outcome was marked as N/A if a pedestrian never entered a detection zone—for example, if the pedestrian cut corners or walked outside the crosswalk.

Accuracy was computed as the number of Valid detections divided by the total number of Valid and inaccurate detections combined, shown by Eq. (1). All detection outcomes other than a Valid outcome were considered inaccurate. Inaccurate outcomes include Spotty, Dropped, Held, Late, and Miss outcomes.

$$Accuracy(\%) = \frac{Valid}{(Valid + innacurate)} x100\% \tag{1}$$

For each observation, pedestrian type, weather conditions, lighting conditions, and a variety of auxiliary data was recorded. Pedestrians were classified as one of three types: Typical, Cyclist, or Atypical. A Typical pedestrian reasonably conformed to the detection algorithm's expected pedestrian shape, which accounts for all body types, but does not account for large items attached to the pedestrian. A Cyclist was any person riding a bicycle. An Atypical pedestrian was someone whose general shape was different from the first two cases—for example, someone riding a scooter, pushing a stroller, sitting in a wheelchair, or using an umbrella. In addition, the number of pedestrians crossing per observation were recorded. If multiple pedestrians crossed the street together, this was considered a single observation.

Weather and lighting conditions were recorded using a condensed version of the classification scheme used in the Oregon Department of Transportation Motor Vehicle Traffic Crash Analysis and Code Manual (Oregon Department of Transportation, 2019) and the National Highway Traffic Safety Administration Fatality Analysis Reporting System (FARS) (National Highway Traffic Safety Administration, 2020). The

Table 1
Observation Distribution by Independent Conditions (3/21/20 – 5/7/20).

	Signalized Intersection	Mid-Block
Pedestrian Type		
Typical Pedestrians	97	283
Cyclist	2	112
Atypical Pedestrians	3	15
Weather Conditions		
Clear	57	327
Cloudy	22	35
Rain	23	48
Lighting Conditions		
Daylight	61	359
Twilight	21	25
Darkness	20	26
Total Observations	102	410

Table 2
Detection Outcome Definitions.

Detection	Definition
Valid	Pedestrian enters the zone, detection is initiated and held continuously, then dropped when pedestrian leaves. <1 s of delay in initiating or dropping the call.
Spotty	Pedestrian is in the zone, but the call is dropped for any perceivable duration and then reinstated.
Dropped	Pedestrian is still in the zone, but the call is dropped and not reinstated.
Held	Pedestrian leaves the zone, but the call is held for more than 1 s.
Late	Pedestrian enters the zone, but the zone is called at least 1 s late.
Miss	Pedestrian enters and leaves the zone without being detected.

classifications used for this study were Clear, Cloudy, Rain. Lighting condition classifications were Daylight, Darkness, and Twilight.

Researchers recorded the following auxiliary data: pedestrian waiting behavior, occlusions, pedestrian phase during which the pedestrian began crossing, crossing location of the pedestrian relative to the crosswalk, and pushbutton use. Pedestrians were classified as either Stationary (little movement within the detection zone while waiting to cross), Zone Movement (movement throughout the zone while waiting to cross), or Leaves Zone (pedestrian leaves the detection zone while waiting to cross). This information can inform the size at which curb detection zones need to be drawn to incorporate all pedestrian behaviors. Occlusions, which occurred when the sensor's view of the pedestrian was blocked, were recorded with notes as to the object that caused the occlusion, location, and duration of the occlusion. This information can help identify best practices for camera set-up and placement. The pedestrian phase was recorded as Walk, Clearance, or Jaywalk. Crossing location was recorded as Inside the Crosswalk, Just Outside of the Markings (less than three ft), and Far Away from the Markings (greater than three ft). This information can help determine whether detection zones can adequately be drawn just within the marked crosswalks themselves, or if a high percentage of pedestrians begin or end their crossing outside of the designated area. Pedestrian pushbutton use was recorded to identify the number of call cancellations that the system could have theoretically initiated.

4. Results

4.1. Accuracy by site

Sensor accuracy (percent) and observation sample size (in parentheses) for all detection zones at the signalized intersection location are shown in Table 3. The thermal sensor detection zones had a mean accuracy rate of 89% with a standard deviation of 10%. The High-Res thermal sensor had a mean accuracy rate of 90% with a standard deviation of 9% and the Low-Res thermal sensor had a mean accuracy rate of 89% with a standard deviation of 10%. The optical sensor detection zones had a mean accuracy rate of 26% with a standard deviation of 18%.

Sensor accuracy (percent) and observation sample size (in parentheses) for all detection zones at the mid-block location is shown in Table 4. The thermal sensor detection zones had a mean accuracy rate of 82% with a standard deviation of 8%. The High-Res thermal sensor had a mean accuracy rate of 87% with a standard deviation of 6% and the Low-Res thermal sensor had a mean accuracy rate of 76% with a standard deviation of 6%. The optical sensor detection zones had a mean accuracy rate of 83% with a standard deviation of 18%.

4.2. Accuracy by Pedestrian, Weather, and lighting conditions

The Chi Squared Test for Independence with a 95% confidence level was used to determine if the pedestrian, weather, and lighting conditions affected detection accuracy by sensor type. Table 5, Table 6, and Table 7 compare accuracy by sensor type, location, and pedestrian type, weather condition, and lighting condition.

The chi-squared tests found evidence to suggest weather and lighting conditions affected thermal sensor accuracy, while only pedestrian type affected optical sensor accuracy. As compared to optical sensors, thermal sensors are frequently advertised for their strong performance under low light and adverse weather conditions. In all except one case, both thermal High-Res and Low-Res sensors performed better in cloudy and rainy conditions than clear conditions and better in twilight and darkness conditions than daylight conditions. The authors hypothesize that the observed stronger performance of the thermal sensors under low light and adverse weather conditions is due to greater thermal contrast between the pedestrians and surrounding environment when roadway infrastructure is expected to have a cooler thermal signature. The authors hypothesize that optical sensor accuracy varied according to pedestrian type due to pedestrian feature sensitivities in the image-based processing algorithms employed. Conversely, the thermal sensors demonstrated less sensitivity because the pedestrians' emitted heat signatures varied less according to unique pedestrian features.

For all observed conditions, the optical sensor was considerably less accurate at the signalized intersection than the mid-block crossing. Although the sensors were mounted at the same height and monitored

Table 3
Thermal and Optical Sensor Accuracy per Zone and Direction at Signalized Intersection with Sample Size.

	Thermal		Optical	
	Departing	Arriving^	Departing	Arriving^
North Curb	93% (*29*)	100% (*18*)	24% (29)	39% (18)
North/Left Crosswalk	88% (8)	N/A	13% (8)	N/A
North/Right Crosswalk	100% (21)	N/A	57% (21)	N/A
East Curb	79% (24)	95% (19)	4% (24)	10% (20)
East/Left Crosswalk	94% (16)	N/A	50% (16)	N/A
East/Right Crosswalk	88% (8)	71% (7)	25% (8)	N/A
South Curb	68% (25)	100% (27)	0% (25)	21% (29)
South/Left Crosswalk	92% (13)	100% (11)	36% (14)	N/A
South/Right Crosswalk	100% (11)	81% (16)	17% (12)	N/A
West Curb	77% (22)	97% (31)	10% (21)	18% (34)
West/Left Crosswalk	90% (10)	100% (20)	30% (10)	N/A
West/Right Crosswalk	83% (12)	82% (11)	62% (12)	N/A

*Thermal High-Res sensors were located at zones listed above the dashed line and Low-Res sensors were located at zones listed below the dashed line.
**Accuracy refers to the number of error-free pedestrian detection events of total events.
^Outlying data from the thermal arriving crosswalk zones and data for the arriving direction of the optical crosswalk zones was excluded due to the directional filter issue.

Table 4
Thermal and Optical Sensor Accuracy per Zone and Direction at Mid-Block Crossing.

	Thermal		Optical	
	Departing	Arriving	Departing	Arriving
North Curb	84% (204)	94% (196)	80% (206)	95% (196)
North Crosswalk	91% (206)	90% (198)	94% (205)	92% (198)
Middle Curb	80% (206)	81% (198)	74% (206)	74% (198)
South Crosswalk	75% (206)	75% (202)	93% (195)	97% (207)
South Curb	68% (189)	85% (198)	34% (196)	94% (203)

*Thermal (High-Res) sensors were located at zones listed above the dashed line and Low-Res sensors were located at zones listed below the dashed line
**Accuracy refers to the number of error-free pedestrian detection events of total events

Table 5
Pedestrian Condition Accuracy Comparison Across All Sensors and Locations with Sample Size.

Sensor	Location	Typical Pedestrian	Cyclist	Atypical Pedestrian	P-Value
Thermal (High-Res)	Intersection	92% (147)	N/A (0)	67% (3)	N/A
	Mid-Block	87% (837)	85% (326)	91% (45)	0.328
Thermal (Low-Res)	Intersection	90% (195)	67% (6)	88% (8)	N/A
	Mid-Block	77% (548)	72% (206)	73% (30)	0.335
Optical	Intersection	24% (289)	0% (6)	33% (9)	N/A
	Mid-Block	88% (1397)	70% (538)	79% (75)	< **0.001***

*Accuracy refers to the number of error-free pedestrian detection events of total events

Table 6
Weather Condition Accuracy Comparison Across All Sensors and Locations with Sample Size.

Sensor	Location	Clear Conditions	Cloudy Conditions	Rain Conditions	P-Value
Thermal (High-Res)	Intersection	86% (78)	97% (37)	97% (35)	**0.048***
	Mid-Block	85% (963)	94% (101)	95% (144)	< **0.001***
Thermal (Low-Res)	Intersection	84% (124)	96% (44)	97% (41)	**0.016***
	Mid-Block	72% (622)	96% (67)	90% (95)	< **0.001***
Optical	Intersection	25% (170)	18% (66)	27% (68)	0.472
	Mid-Block	82% (1601)	84% (171)	88% (238)	0.092

*Accuracy refers to the number of error-free pedestrian detection events of total events

Table 7
Lighting Condition Accuracy Comparison Across All Sensors and Locations with Sample Size.

Sensor	Location	Daylight Conditions	Twilight Conditions	Darkness Conditions	P-Value
Thermal (High-Res)	Intersection	87% (99)	100% (22)	100% (29)	**0.026***
	Mid-Block	86% (1058)	94% (72)	96% (78)	**0.004***
Thermal (Low-Res)	Intersection	90% (114)	83% (53)	95% (42)	0.163
	Mid-Block	73% (684)	92% (48)	98% (52)	< **0.001***
Optical	Intersection	24% (181)	25% (63)	22% (60)	0.887
	Mid-Block	83% (1769)	88% (121)	81% (130)	0.312

*Accuracy refers to the number of error-free pedestrian detection events of total events

crossings within the rated tracking radius, the authors hypothesize that the observed accuracy difference relates to the distance from which sensors viewed pedestrians. At the signalized intersection, the optical sensor monitored pedestrians at up to an approximate 120-foot distance. The monitoring distance was considerably and consistently shorter for observations at the mid-block crossing. Viewed from a smaller distance, the pedestrian would appear larger and more detailed in the camera's field of view and thus might be easier for the optical sensor to process. Unfortunately, this is only conjecture, as the optical sensor's algorithms were proprietary.

4.3. Error types

Identifying and quantifying error type frequency is an important step towards improving sensor detection capabilities. The following error type information is intended to help manufacturers identify specific areas for sensor improvement and encourage further investigation into error source. Where a potential error source in the environment was observed, it is noted. However, because the software algorithms performing the detection for both the optical and thermal platforms was proprietary, the authors cannot speak to algorithm-specific recommendations.

4.3.1. Signalized intersection

The primary error type for the High-Res thermal sensor at the signalized intersection location was Held. This error type occurred only at departing zones. The average duration of the six Held errors was three seconds, with a maximum duration of five seconds. The primary error types for the Low-Res sensors at the signalized intersection location were Held and Late, which most often occurred at the departing curb zone. For the nine Low-Res sensor Held detection errors, the zone was held for an average duration of approximately 20 s, with a lowest duration of two seconds and highest of 55 s. For the eight Low-Res sensor Late detection errors, the zone was late by an average duration of approximately four seconds; the lowest duration was two seconds and the highest duration was nine seconds.

The optical sensor at the signalized intersection location had a wider range of detection errors. The most prevalent error was Spotty. Every zone experienced this error, with no consistency. The elapsed duration of a Spotty dropped call before re-instating ranged from less than one second to more than 30 s. Most Spotty detections dropped the call for under five seconds and the zone activated on and off between one and ten times. The optical sensors also made many Late calls, especially at the departing curb. The average duration before zone activation was approximately five seconds late; the lowest duration was two seconds and the highest was 13 s. Miss errors were also present, although they occurred only at the curb zones.

4.3.2. Mid-block crossing

The High-Res thermal sensor at the mid-block location had distinctive Late, Held, and Miss errors at the middle curb proportionately distributed across pedestrian types. Most Late errors occurred when pedestrians walked towards the sensor (from south to north) and lasted approximately two seconds in duration. The majority of Held errors occurred when pedestrians walked away from the sensor (from north to south) and lasted approximately three seconds in duration. The other two major error types were Late errors at the departing curb and Held errors at departing zones. The Late errors were typically two seconds late and the Held errors were typically three seconds in duration.

The most prevalent error for the Low-Res thermal sensor at the mid-block location was Held, particularly at the departing curb. In approximately two thirds of cases, the detection would be held for over 20 s on average. In approximately one third of cases, the zone would be held for approximately two s. There were also a high number of Miss errors in the crosswalk zone.

The optical sensor had three especially prevalent errors at the mid-block location: Miss, Spotty, and Late. Of all Miss errors at the middle curb, 95.6% were cyclists. Of all cyclists who passed through the middle curb, the sensor missed 61.7%. Spotty and Late errors were most prevalent in the departing curb zones, distributed across both north and south curb zones. The Spotty errors typically lasted less than < four s and the Late errors were usually delayed no longer than two s.

4.4. False detections

4.4.1. Signalized intersection

The High-Res thermal sensor at the signalized intersection location experienced two types of false detections related to installation configuration and nearby infrastructure. First, the east/right crosswalk detection zone sometimes activated in absence of vehicles or pedestrians. The call duration ranged between one s and 15 s, with a typical duration of less than five s. This did not occur at a consistent frequency: for some video data it happened a few times per hour; in others it never happened. The hypothesized trigger is a set of utility lines running through the top right portion of the sensors' frame of view.

The High-Res thermal sensor-monitored east curb zone also occasionally activated with no consistent duration or frequency. The activations lasted between two and 30 s. The hypothesized trigger is a street sign extending into the curb zone which shook under what appeared to be wind loading. The High-Res thermal sensor also made a false detection when a small mammal entered the curb zone. The animal was detected for less than two seconds.

The Low-Res thermal sensor experienced false detections typically when vehicles and bicycles crossed through zones. Approximately once per hour, a right-turning vehicle would trigger the left crosswalk at either the west or south intersection corners with a duration ranging from less than one second to 30 s. Usually, the vehicle would creep into the crosswalk zone while seeking a gap in traffic to make a permitted right turn. Approximately once every two hours, a right-turning vehicle drove too close to the curb and triggered detection in the curb zone for approximately one second.

The optical sensors also experienced false detections at the signalized intersection location. Two errors were similar to those observed for the thermal sensors: the sensor occasionally detected bicycles traveling through the bike lane and right-turning vehicles or bicycles when they crossed into the curb. Two false detection types were unique to the optical sensor: (1) the sensor activated for less than one second for a bicycle mounted to the back of a vehicle driving perpendicularly through the crosswalk zone; and (2) the sensor flickered on and off for approximately two minutes for the shadow cast by signal heads and span wire in the curb zone, usually holding for one to two seconds at a time. These occurrences are shown in Fig. 5.

4.4.2. Mid-Block crossing

The thermal sensors made no false detections and the optical system recorded only one false detection at the mid-block location: the optical sensor detected a vehicle with a bicycle mounted to a rear bike carrier driving perpendicularly through a crosswalk zone.

4.5. Auxiliary data

Waiting habits, occlusions, jaywalking, crossing location, and pushbutton use was analyzed to explore the potential operational and safety benefits of DPPD technology and the importance of sensor selection considerations, like detection zone coverage. The percentage of observations for which these behaviors were observed is shown in Table 8.

4.5.1. Waiting habits

Most pedestrians were relatively stationary while waiting for the pedestrian phase in the departing curb detection zone. At the signalized intersection and mid-block locations, 89% and 97% of pedestrians (91 pedestrians), respectively, waited with minimal movement. However, sensors must be capable of detecting pedestrians who pace throughout the curb zone, or leave the curb zone to wait for the walk phase after pushing the pushbutton. It may be prudent to incorporate a drop delay of approximately 30 s to account for pedestrians who move in and out of the zone before dropping the pedestrian call. If the pedestrian were to re-enter the zone within 30 s, the signal controller would not drop the call.

4.5.2. Occlusions

Three separate occlusions were observed in the data, all related to the optical sensor at the signalized intersection location. In two cases, a large semi-truck drove across the video screen and occluded a pedestrian at a curb for approximately two seconds. While heavy vehicles only occluded pedestrian observations twice, many other heavy vehicles were observed occluding detection zones when pedestrians were not present. The third occlusion occurred when a signal head attached to the span wire moved, possibly by a gust of wind, blocking a pedestrian for approximately one second at a time. Sensors should be positioned to mitigate occlusions.

4.5.3. Pushbutton use and jaywalking

At the signalized intersection location, 91% of pedestrians (93 pedestrians) started crossing during the Walk interval, 1% (one pedestrian) started crossing during the Change interval, and 8% (eight pedestrians) jaywalked. This percentage of jaywalking pedestrians is abnormal for a large arterial and could be attributed to traffic reduction due to the COVID-19 pandemic. Of the eight pedestrians that jaywalked, 75% (six pedestrians) pressed a pushbutton before jaywalking. The other 25% (two pedestrians) jaywalked without pressing a pushbutton. Of signalized intersection pedestrian calls, 6% (six pedestrians)

Fig. 5. False Detection Triggered by Signal Head Shadows (A) and a Bicycle Mounted on a Rear Bike Carrier (B) on the Optical Sensors.

Table 8
Auxiliary Data Percentages with Sample Size.

	Signalized Intersection	Mid-Block
Waiting Habits		
Stationary	89% (91)	97% (397)
Zone Movement	8% (8)	2% (10)
Leaves Zone	3% (3)	1% (3)
Crossing Timing		
Walk	91% (93)	51% (203)
Change	1% (1)	5% (20)
Jaywalk	8% (8)	44% (178)
Pushbutton Use of Jaywalkers		
Pressed Pushbutton	75% (6)	33% (59)
Did Not Use Pushbutton	25% (2)	67% (119)
Total Possible Cancelled Calls	6% (6)	15% (59)
Crossing Location		
Within Markings (Start)	96% (98)	98% (397)
Just Beyond [<3ft] (Start)	3% (3)	1% (5)
Outside [>3ft] (Start)	1% (1)	1% (5)
Within Markings (End)	88% (90)	98% (391)
Just Beyond [<3ft] (End)	9% (9)	1% (3)
Outside [>3ft] (End)	3% (3)	1% (3)

could have utilized pedestrian call cancellation to improve operational efficiency.

At the mid-block location, 51% of pedestrians (203 pedestrians) started crossing during the Walk interval, 5% (20 pedestrians) started crossing during the Change interval, and 44% (178 pedestrians) jaywalked. Nine pedestrians were excluded from this analysis because their crossing time was obscured by sunlight glare on the pedestrian signal head. Of the 178 pedestrians that jaywalked, 33% of them (59 pedestrians) pressed a pushbutton before they jaywalked. The other 67% (119 pedestrians) jaywalked without pressing a pushbutton. Of mid-block pedestrian calls, 15% (59 pedestrians) could have utilized pedestrian call cancellation to improve operational efficiency.

4.5.4. Crossing location

Where a pedestrian begins and ends their crossing relative to crosswalk markings is important for determining the required width of a crossing detection zone and the effectiveness with which the walk time could be extended. At both signalized intersection and mid-block locations, the majority of persons started and ended their crossing within the crosswalk markings. More than 95% of pedestrians began crossing within the crosswalk markings at both locations, while 88% of pedestrians at the signalized intersection location and 98% of pedestrians at the mid-block location ended their crossing within the crosswalk markings.

5. Discussion

One objective of this study was to establish a framework for evaluating sensor capabilities which enables comparison between sensor types. Similar to prior sensor studies (Beckwith and Hunter-Zaworski, 1998; Turner et al., 2007), this study classified detector outcomes into Valid, Spotty, Dropped, Held, Late, Miss, and False categories and calculated accuracy as the proportion of Valid detections to all detections. The observed accuracy of the thermal sensors at the signalized intersection and mid-block location was 89% and 82%, respectively; the observed accuracy of the optical sensor was 26% and 83%, respectively. As expected, the observed accuracies for the thermal sensors represent an improvement from the 20 to 30 percent error rates reported by Turner et al. (2007). However, the most frequently observed error reported by Turner et al. and observed in this study align: false detections triggered by vehicles in the crosswalk (Turner et al., 2007).

A second objective of this study was to identify considerations for deploying sensors such that the highest level of accuracy is achieved. The researchers worked closely with sensor manufacturers to ensure proper setup—and a key takeaway from this experience was the importance of building these collaborations. Careful planning, which may include a site-visit and/or coordination with the sensor technical support, is important to get the camera make/model, mounting location, view orientation, and mounting height correct to facilitate accurate detection. Site characteristics like overhead utility lines, trees or other vegetation, span wire versus mast arm signal head mounting, and signage can all affect the line-of-sight for potential detection zones. The required detection distance and angle of a sensor system must be considered in tandem with site characteristics because conflicts with existing infrastructure can induce false detections or occlusions.

The calibration and placement of sensor detection zones within the field-of-view must also be site specific. Bicycles traveling one direction may need to be detected, while bicycles traveling from another direction may not. For example, the optical sensor at the signalized intersection location made false detections when bicycles traveling in the bike lane crossed a crosswalk zone perpendicularly. Detection zones also need to be large enough to detect all crossing pedestrians, while compact enough to only detect pedestrians waiting to cross the street. Additionally, distance and location can become relative and distorted when trying to create horizontal detection zones from isometric views.

The desired functionality of DPPD should also be considered when selecting sensor systems and developing error mitigation schemes. If pedestrian call extension functionality is desired, the detection system will need to accurately track a pedestrian for the entire crossing movement and one or more detection zones must monitor the entire length of a crosswalk; intersection size will inform sensor selection. Spotty calls may be mitigated by instituting a stretch time, in which the controller holds calls for a short amount of time. A maximum extension could prevent Held calls from holding the extension indefinitely. If pedestrian call cancellation functionality is desired, the detection zone boundaries must monitor all areas in which a pedestrian can wait for service at a curb. In this study, some curb zones were too small to monitor all areas in which pedestrians waited to cross. For detectors prone to Late or Miss calls, the signal could hold service calls after the pushbutton is pressed until a pedestrian is detected. The signal could also integrate audible or visual warnings to notify the pedestrian that a service call has been or will be cancelled, unless the pedestrian reactivates the push button. Upon instating a second service call, the signal would not be able to cancel a pedestrian call until the next signal cycle.

In sum, different sensor types provide different advantages based on specification ratings (e.g. detection range), sensitivities to various conditions (e.g. weather), desired use case functionality (e.g. pedestrian call cancellation), and agency goals. Thermal sensors, for example, performed better under low light and adverse weather conditions than sunny and clear conditions and had a higher overall accuracy rate than the optical sensor. However, optical sensors may be more advantageous for scenarios in which an agency desires, for example to simultaneously use its video to monitor the intersection.

6. Conclusions

The results of this study indicate optical and thermal sensors have accuracy differences. In general, thermal sensors achieved higher accuracy rates than the optical sensors. At the signalized intersection location, the thermal sensor detection zones detected with a mean accuracy rate of 89% and a standard deviation of 10%: the High-Res thermal sensor had a mean accuracy rate of 90% with a standard deviation of 9% and the Low-Res thermal sensor had a mean accuracy rate of 89% with a standard deviation of 10%. The optical sensor at the signalized intersection location detected with a mean accuracy rate of 26% and a standard deviation of 18%. At the mid-block location, the thermal sensor detection zones had a mean accuracy rate of 82% and a standard deviation of 8%: the High-Res thermal sensor had a mean accuracy rate of 87% with a standard deviation of 6% and the Low-Res thermal sensor had a mean accuracy rate of 76% with a standard deviation of 6%. The optical sensor at the mid-block location had a mean accuracy rate of 83% and a standard deviation of 18%.

Results from the sensors were compared by pedestrian, weather, and lighting conditions. There is evidence to suggest weather and lighting conditions affected thermal sensor accuracy, while only pedestrian type—whether the pedestrian was Typical, a Cyclist, or Atypical—affected optical sensor accuracy. The success of the detectors in detecting Atypical pedestrians varied by what made the pedestrian Atypical. For example, the thermal sensor was more successful at detecting a pedestrian with a stroller, while the optical sensor was more successful at detecting a pedestrian with an umbrella. The primary detection error types for the thermal sensors were Late and Held, while the primary detection error types for the optical sensor were Spotty and Miss. Each sensor type initiated false detections to a varying degree, but the most common attribute was short false detections of vehicles in the pedestrian zones lasting less than a few seconds.

6.1. Limitations

One study limitation was sample size: observation frequency per unit time was lower than anticipated due to observed changes in travel patterns prompted by the COVID-19 pandemic. Additionally, certain weather conditions (e.g. fog and snow) were not evaluated because they did not occur during the data reduction window. Finally, significant installation and calibration efforts were performed by the sensor manufacturers at the specific sites for this research study. Such efforts may not represent typical installation for this technology. As calibration and zone determination must be performed for every installation, results can be site specific.

6.2. Future work

There is a need for a systematic research laboratory to field measure, validate, and certify existing and future sensor systems for DPPD applications, including multimodal count recording. Sensor systems should be examined under a variety of installation placements and for a variety of pedestrian types and pedestrian volumes, including crowding scenarios; different angles, distances, and configurations may produce varying results even within the rated tracking distance. There is also a need for future research on how best to communicate information related to pedestrian call cancellation and extension functions—what message and interface should the signal system use to communicate warning to a pedestrian who has left a detection zone, or whose detection was dropped in error, that their pushbutton call was cancelled?

CRediT authorship contribution statement

Travis Larson: Conceptualization, Methodology, Validation, Investigation, Formal analysis, Investigation, Writing - original draft. **Amy Wyman:** Visualization, Writing - original draft, Writing - review & editing. **David S. Hurwitz:** Conceptualization, Methodology, Validation, Investigation, Formal analysis, Project administration, Funding acquisition, Writing - original draft, Writing - review & editing. **Matt Dorado:** Conceptualization, Investigation, Resources, Writing - review & editing. **Shaun Quayle:** Conceptualization, Methodology, Resources, Writing - review & editing. **Stacy Shetler:** Conceptualization, Methodology, Resources, Writing - review & editing.

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