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Testbed for evaluation of vehicular detection systems

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SUMMARY

Reliable and robust detection systems are the cornerstone in the efficient and proper functioning of vehicle infrastructure integration. This paper presents the design and implementation of a testbed for evaluating vehicular detection systems. The development of the testbed involved design of the hardware setup required for real-time monitoring of the sensors, programming the devices for data capture, and development of algorithms to automate the analysis of the recorded data. The methodology used to calibrate and validate the algorithms to automate the analysis of the data is presented as well. Although the testbed is presented in the context of evaluation of video detection systems at signalized intersections, it can be used for evaluating any vehicular detection systems. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: detection system; video detection; testbed; signalized intersection.

1. INTRODUCTION

The 2005 Urban Mobility Report [1] has reported that congestion has grown substantially in the U.S. cities over the past 20 years. In 2005, congestion resulted in 2.5 billion gallons of fuel wasted, 4.2 billion hours of extra time, and $78 billion of delay and fuel cost. The projected traffic growth in the next few decades in the U.S. would only exacerbate the situation further. With the limited resources to provide additional capacity, the only viable solution to these problems is to get more out of the existing capacity. Every year there are over 42 000 fatalities and 6 million crashes on the U.S. roads. In 2003, American Association of State Highway and Transportation Officials [2] set a goal to reduce the fatalities to 1 per 100 million vehicle miles traveled and save 9000 more lives a year.

Vehicle infrastructure integration (VII) hopes to achieve dual objectives of increased mobility and safety. Previous research has established that the VII could at least double the throughput on a highway lane from 2200 to 4400 vphpl [3]. Specifically, Cooperative Intersection Collision Avoidance System (CICAS) is part of VII and addresses safety at intersections in terms of permitted left-turns, left-turns from minor crossing streets to high speed roads, etc. A key building block of any VII system is sensors to detect the vehicles. The need for reliable and robust sensors for possible use in a VII system is imperative. This paper presents the design and implementation of a testbed for evaluation of vehicle detection technologies. The development of the testbed involved design of the hardware setup required for real-time monitoring of the sensors, programming the devices for data capture, and development of algorithms to automate the analysis of the recorded data. This paper presents how the testbed was

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successfully used to evaluate three video detection systems at a signalized intersection. Although presented in the context of VD systems, this test bed can be used for evaluating any detection system. Currently the testbed is being used to evaluate Sensys Networks' Wireless Vehicle Detection System.

2. DATA COLLECTION AND HARDWARE SETUP

The performance of video detection systems is affected by time of day, season, sunny or cloudy, wind, snow, fog, rain, etc. [4–11,13]. In addition, it was found that there can be significant variability in the performance of video detection systems even under similar conditions [12]. Consequently, to reach meaningful conclusions about the performance of video detection systems, it was required that large datasets be collected and analyzed. However, large datasets preclude the possibility of manual evaluation of the performance. Therefore, the setup had to be designed such that large datasets could be gathered for the wide array of conditions, and in addition the data should be amenable to an automated analysis to minimize manual verification. This section describes the different types of data that were required to accomplish the objectives of the study and the hardware setup used for this purpose. Two types of data were collected in this study: timestamps and video data.

2.1. Timestamp data

Timestamps refer to times at which each of the VD zones or inductive loops were activated or deactivated. The idea behind collecting timestamps was that their analyses could be automated using computer programs and could identify potential errors in the performance of the video detection systems. It should be noted that at this intersection inductive loops were used as a base to identify potential errors in the performance of the video detection systems.

In the detector rack, the presence of a vehicle is indicated by a voltage in the range of 0–8 V DC on the channels and the absence of vehicle is indicated by voltage in the range 16–24 V DC. Consequently, a device capable of sensing voltage (up to 24 V DC) on multiple channels was used to monitor the presence or absence of the vehicles (OPTO 22 SNAP I/O). SNAP I/O device is a programmable input/output device that can monitor signals on incoming channels and take appropriate control actions using output channels.

As shown in Figure 1, the study approach has two left-turn lanes and a shared right-thru lane. Apart from the Illinois Department of Transportation (IDOT) cabinet that houses the controller for the intersection, a separate cabinet was used to house the VD equipment and the data collection equipment for this study. The VD systems being evaluated do not affect the signal performance in any way. In addition to the VD systems, inductive loops (each 6 ft $\times$ 6 ft) were installed at the stop bar and advance locations on all the three lanes. The purpose of inductive loops is to serve as the pointer to potential detection errors, and visual inspection is used to verify the potential errors. The advance locations are about 250 ft upstream from the stop bar locations.

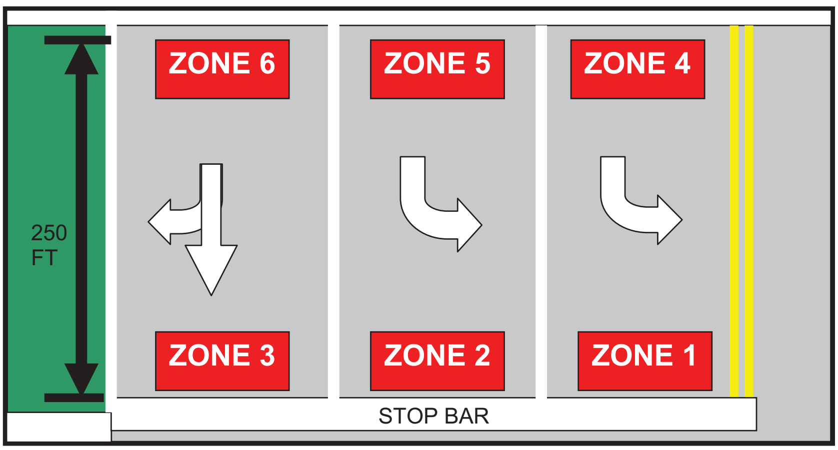

Figure 1. Schematic diagram of the study approach.

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In this study, the I/O device was instrumented to monitor the four detection states (one from the inductive loop and three from the VD systems) at each of the six detection locations (three at the stop bar and three at the advance locations), resulting in 24 channels for monitoring. The I/O device verifies the state of these 24 detectors once every 50 milliseconds resulting in 20 checks per second. The I/O device has been programmed to record the timestamps for each of the six detection locations separately. At each detection location, whenever the detection state of any of the four detectors (three VD and one loop) changes, the time and the state of all the four detectors is recorded. Every hour the timestamp data is uploaded to the computer located within the data collection cabinet. Figure 2 depicts the process to record the timestamps.

Figure 3 shows a sample timestamp dataset recorded by the I/O device. The first column is the row number or observation number, followed by the detection zone number and the time at which the timestamp was generated. The next four columns are the detection states of loop, and the three video detection systems (Peek, Iteris, and Autoscope), in that order. A value of ''1'' indicates the presence of a vehicle and ''0'' indicates absence of any vehicle. The I/O device records a timestamp whenever there is a change in the state of any of the VD/loop systems. The times shown in the table are shown to the nearest second. Therefore if the state of the system changes multiple times in less than a second, multiple entries are recorded corresponding to the state changes.

2.2. *Video data*

Although timestamps are used to identify the times of potential errors in the performance of VD systems, further verification is required. Therefore, video images were recorded in addition to the timestamp data. The recorded video images are used to calibrate and validate the algorithms that analyze the timestamps, and for verification of the preliminary results given by the computer algorithms. The video data is also required for ascertaining the lighting/weather/traffic condition at the study location and identify the possible causes and solutions for errors in the VD performance.

Video data was recorded on the computer in the data collection cabinet. Figure 4 depicts the process to record the video images. The processed images from the three VD cards were fed as inputs to a quad processor. When given four images as input, the quad processor has the capability to produce a single image with all the four images in it (such an image is called a quad image). Figure 4 also shows a sample of the recorded image. The images of Autoscope, Peek, and Iteris are labeled A, P, and I, respectively. It can be seen that when the VD zones are activated, they change color of the arrows/boxes or highlight the corners. However, there is no visual indication of the status of the loop detectors. Therefore, a real-time graphical depiction of the detector states was generated, using the I/O device to indicate the status of the loops and the three VD systems at the six detection locations. The graph shows the status of the detections in the last 2 minutes and it is updated every 125 milliseconds for the advance

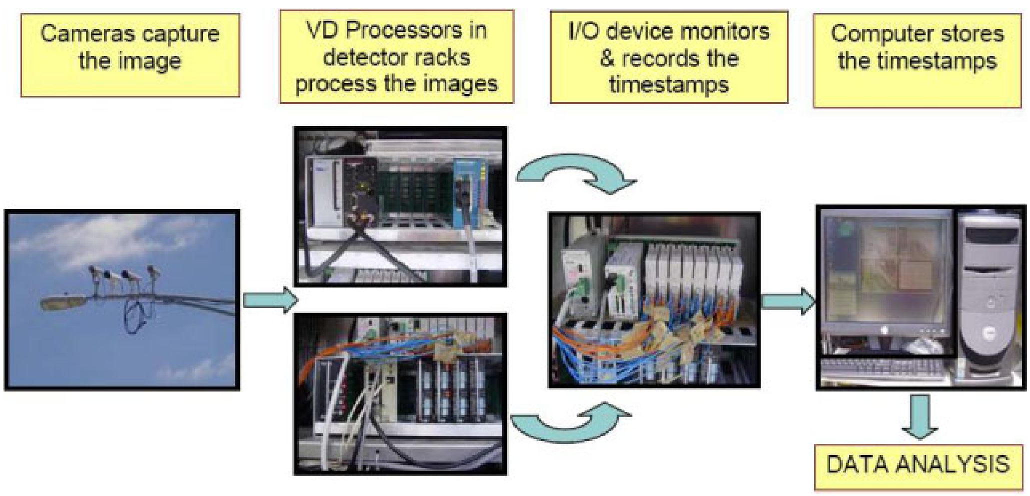

Figure 2. Setup for recording the timestamps.

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Row	Zone	Time	Loop	Peek	Iteris	Autoscope
[12]:	1	14:35:26	0	1	0	1
[13]:	1	14:35:26	0	0	0	1
[14]:	1	14:35:27	0	0	0	0
[15]:	1	14:37:12	0	0	1	0
[16]:	1	14:37:12	0	1	0	0
[17]:	1	14:37:13	0	0	0	0
[18]:	1	14:37:13	0	0	1	0
[19]:	1	14:37:14	0	0	1	1
[20]:	1	14:37:14	0	1	1	1
[21]:	1	14:37:14	1	1	1	1
[22]:	1	14:37:15	0	1	1	1
[23]:	1	14:37:15	0	1	0	1
[24]:	1	14:37:15	0	0	0	1
[25]:	1	14:37:15	0	0	0	0
[26]:	1	14:37:34	0	0	0	1
[27]:	1	14:37:34	0	0	1	1
[28]:	1	14:37:35	0	1	1	1
[29]:	1	14:37:36	1	1	1	1
[30]:	1	14:37:41	0	1	1	1
[31]:	1	14:37:42	0	1	0	1
[32]:	1	14:37:42	0	0	0	1
[33]:	1	14:37:43	0	0	0	0

Figure 3. Sample timestamp data recorded by the I/O device.

locations and every 250 milliseconds for the stop bar locations. This image was fed as the fourth input to the quad processor. The video recording was scheduled to cover the sunrise, sunset, day, and night conditions.

It should be noted that in the graph depicting the detector states, there are six sub-graphs corresponding to the six detection locations (three at stop bar and three at the advance locations). Each sub-graph has four lines: black, blue, red, and green corresponding to the status of loop, Autoscope, Iteris, and Peek, in that order. When the line corresponding to a system is ''low'' it indicates that the system did not detect any vehicle presence and when it is ''high'' the system detected the presence of a

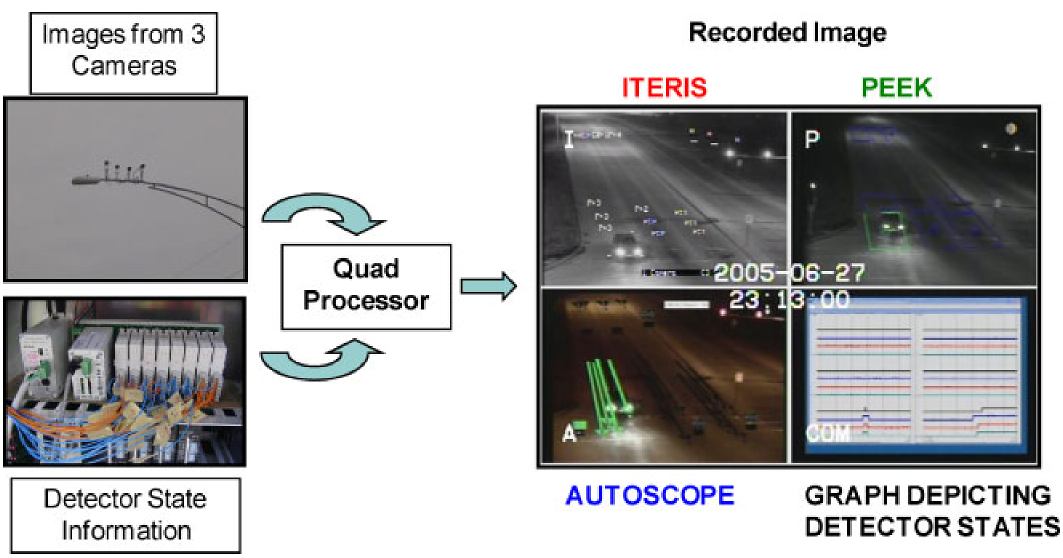

Figure 4. Recording of image.

vehicle. Figure 4 shows a vehicle waiting at the stop bar in the right-thru lane (Zone 3) and also shows that all the three VD systems and the loop detected the vehicle at the stop bar location. Also all the VD systems and the loop detected the vehicle at the advance location (Zone 6) on the right-thru lane as well. There was no vehicle present in the previous 2 minutes at any of the other locations, thus the lines of all the three VD systems and the loop at these locations are "low."

3. ALGORITHMS FOR DATA ANALYSIS

This section describes the performance measures (PMs) and the algorithms for the automated analysis, their calibration, and validation. Four PMs (shown in Table I) were defined for quantifying the performance of the detection systems:

- *False call*: System detects a vehicle, when there is no vehicle.
- *Missed call*: System does not detect a vehicle that is present.
- *Stuck-on call*: System continues to detect a vehicle, even after the departure of the vehicle.
- *Dropped call*: System correctly detects the vehicle's presence, but later on does not detect it while the vehicle is still present.

The data analysis is accomplished in three stages: the first stage comprised of analysis of the timestamps by the algorithms to identify the potential errors; the second stage further enhanced analysis of the timestamps and is performed to address some special cases which are artifacts of video detection; and in the third stage a visual (manual) verification of the potential errors is performed.

3.1. Algorithms for identification of potential errors

3.1.1. Missed call logic

For every valid loop call, if there is no corresponding VD call, it is considered a potential missed call. As shown in Figure 5a, the algorithm checks if there is a VD call in a window that starts "*X*" seconds before the start of loop call and ends "*Y*" seconds after the end of the loop call. If no VD call is in this window, it is counted as a potential missed call.

It is necessary to use the time windows of "*X*" and "*Y*" seconds because the VD zones and loops are not exactly located at the same place or are of the same size. In addition, the primary interest is to determine if the VD systems detect the vehicle presence or not. Note that the *X* or *Y* values for false, missed, stuck-on, and dropped calls are not necessarily the same.

It should be noted that this stage is only for preliminary identification of possible errors in VD performance. That is why these errors are considered potential errors at this stage. In the later stage, further enhanced analyses and visual inspections (described in the following sections) are performed to verify if the initial determination is accurate.

3.1.2. False call logic

For every call by a VD system, if there is no corresponding call from the loop detector, it is considered a potential false call. The algorithm (illustrated in Figure 5b) verifies if there is a loop call placed in a time window that starts "*X*" seconds before the beginning of the VD call and ends "*Y*" seconds after the VD call is dropped. If there is no loop call in this time window, it is considered that the VD system had a potential false call.

Table I. Definitions of the performance measures.

Error	Ground truth (verified loop calls)	VD indicates	Explanation
False call	No vehicle	Vehicle is present	Places a call for no vehicles
Missed call	Vehicle is present	No vehicle	Vehicle is present but no call is placed
Stuck-on call	Vehicle was present	Vehicle is present	Vehicle left, but call is maintained
Dropped call	Vehicle is present	Vehicle was present	Vehicle is still present, but call is dropped

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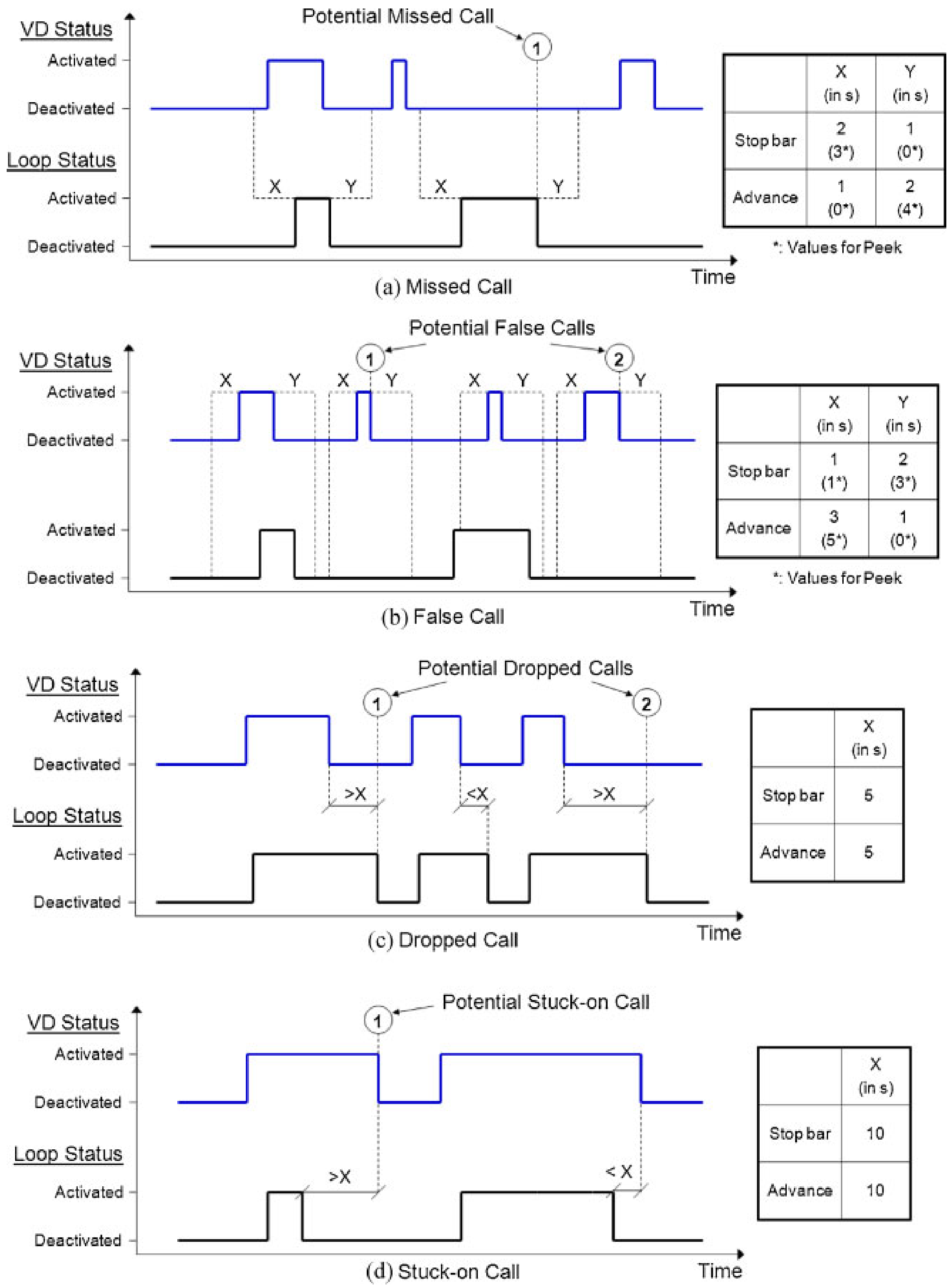

Figure 5. Algorithms for preliminary identification of potential errors: (a) missed call, (b) false call, (c) dropped call, and (d) stuck-on call.

3.1.3. Dropped call logic

Under some conditions, it was observed that the VD systems prematurely dropped the call, even though the vehicle was still present in the detection area. These are most likely to occur at night when the headlights of the vehicles were no longer falling on the VD zones. If the detection in the traffic controller is in non-locking mode, dropped calls may cause drivers to be undetected and that may lead

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to driver frustration. As illustrated in Figure 5c, if the VD call is terminated more than ''*X*'' seconds before the end of loop call, it is considered as a potential dropped call.

3.1.4. Stuck-on call logic

For an efficient operation of the intersection, the calls placed to the controller should be dropped once the vehicle departs. However, it was observed that sometimes the VD systems do not drop the calls after the departure of the vehicles. ''Stuck-on calls'' are used to quantify this aspect of the performance. As shown in Figure 5d, if the VD call continues to be active more than ''*X*'' seconds after the end of the loop call, it is counted as a potential stuck-on call.

A computer program was written in SAS to automatically analyze the timestamp datasets and identify the potential errors.

3.2. Calibration of the algorithm parameters

The parameters (*X* and *Y*) used in the algorithms described in the previous section need to be calibrated for the system at hand. Ideally, if the detection zones of the system being tested activated and deactivated at the same time as the inductive loops the values for *X* and *Y* would be zero. However, this may not be true either because the locations of the two sensors are not identical or their operating principles are different. In this study, the location and size of VD zones was different from that of the loops and in addition the operating principles are different. It should be noted that this would be the case even if other technologies such as radar or microwave were to be used. Therefore, this section describes the procedure used to calibrate the algorithms to identify the potential errors.

As shown in Figure 6, the detection zones of each of the VD systems have different shapes and sizes. Also, the VD zones are different in shape and size than the loop detectors. Consequently, the algorithms for computing the four PMs utilize different time windows for different VD systems, as these windows

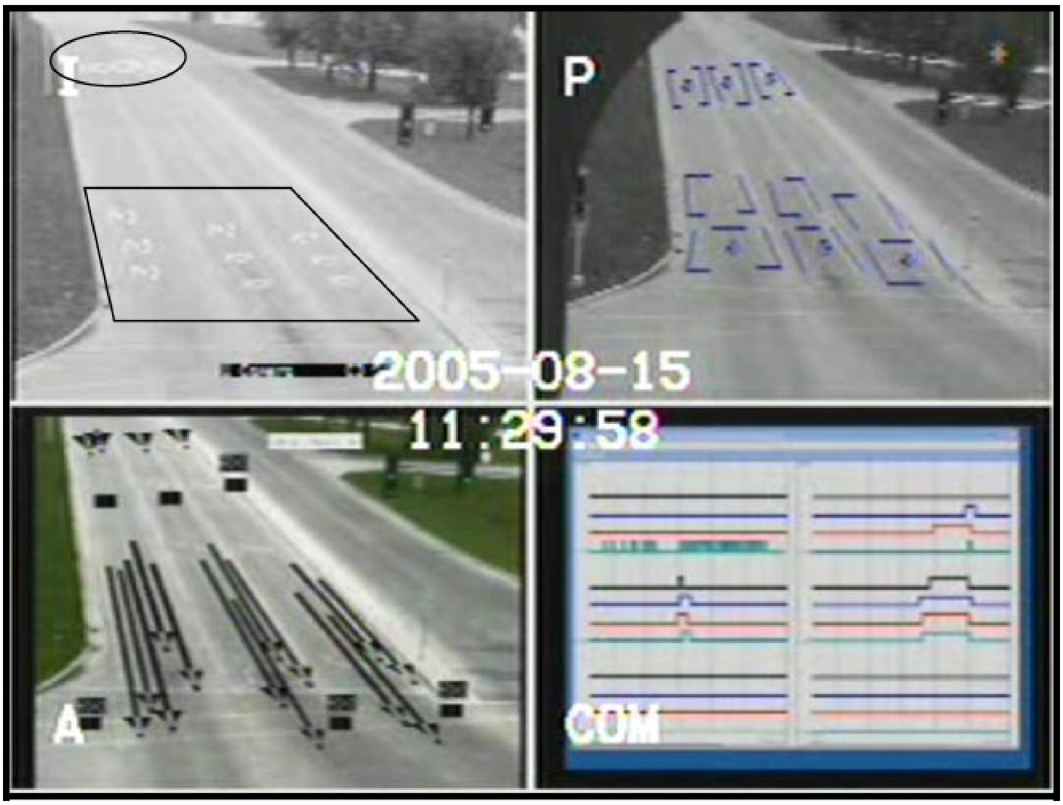

Figure 6. Configuration of VD zones.

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Table II. Pre-calibration values for the algorithm parameters.

Performance measures	Variable *X*	Variable *Y*
Dropped call	4 seconds	n/a
Missed call	2 seconds	1 second (3 seconds*)
False call	3 seconds (5 seconds*)	3 seconds
Stuck-on call	10 seconds	n/a

*Values for Peek's advance zones.

will depend on the location and size of the detection zones. Based on the experience gained by watching the videos, a set of values were used as the preliminary values for *X* and *Y*, as shown in Table II. From Figure 6 it can be observed that the advance zones of Peek are significantly bigger than the advance zones of Autoscope and Iteris. Thus, a different set of values had to be used for determining potential false and missed calls in Peek's advance zones.

The expected values for the four PMs were obtained by watching the videos for three datasets. Each of the datasets was 1 hour long. Two of the three datasets were from noon time and one was from night time. None of the datasets had any rain, wind, fog, or any such inclement weather condition.

The above-mentioned algorithms (with the pre-calibration values for the parameters) for computing the PMs were coded in a SAS program. The timestamps corresponding to the three datasets were used as input to the SAS program and the PMs were computed. The computed PMs were compared to the expected PMs, and the values for the parameters were modified such that the PMs computed by the SAS program match the expected PMs. Expected PMs were calculated by manually watching the video recordings from the intersection and tallying the errors. The post-calibration values for the algorithm parameters are shown in Table III.

3.3. *Validation of algorithm parameters*

In the previous section, the calibration procedure, the values of the algorithm parameters after calibration were introduced. It was shown that the algorithms with post-calibration parameters correctly predicted the potential errors for all the PMs. In this section, the validation of the final parameters is discussed. The objective of validation was to ensure that the algorithms would correctly identify the potential errors when applied to other datasets as well. Validation was performed using two different datasets than the one used for calibration: one from night time and one from noon time. Datasets were 1 hour long each. The expected values for the four PMs were obtained by watching the videos and these were compared with the computed values. For all the zones, it was found that the expected PMs and the computed PMs (using the post-calibration parameters) by the SAS program were identical for both the noon dataset and the night dataset. Figure 7 illustrates this for false, missed, and stuck-on calls in Zones 1 and 4 for the noon dataset. There were no dropped calls. Thus for this VD zone configuration, the post-calibration values of the algorithm parameters yield the expected numbers for all the PMs and therefore can be used in all further analyses. It should be noted that if the VD zone configuration were to be modified the algorithm parameters may need to be calibrated and validated again.

Table III. Post-calibration values of algorithm parameters.

Performance measures	Stop bar zones		Advance zones	
	Variable *X*	Variable *Y*	Variable *X*	Variable *Y*
Dropped call	5 seconds	n/a	5 seconds	n/a
Missed call	2 seconds (3 seconds*)	1 second (0 second*)	1 second (0 second*)	2 seconds (4 seconds*)
False call	1 second (0 second*)	2 seconds (3 seconds*)	2 seconds (4 seconds*)	1 second (0 second*)
Stuck-on call	10 seconds	n/a	10 seconds	n/a

*Values for Peek's zones.

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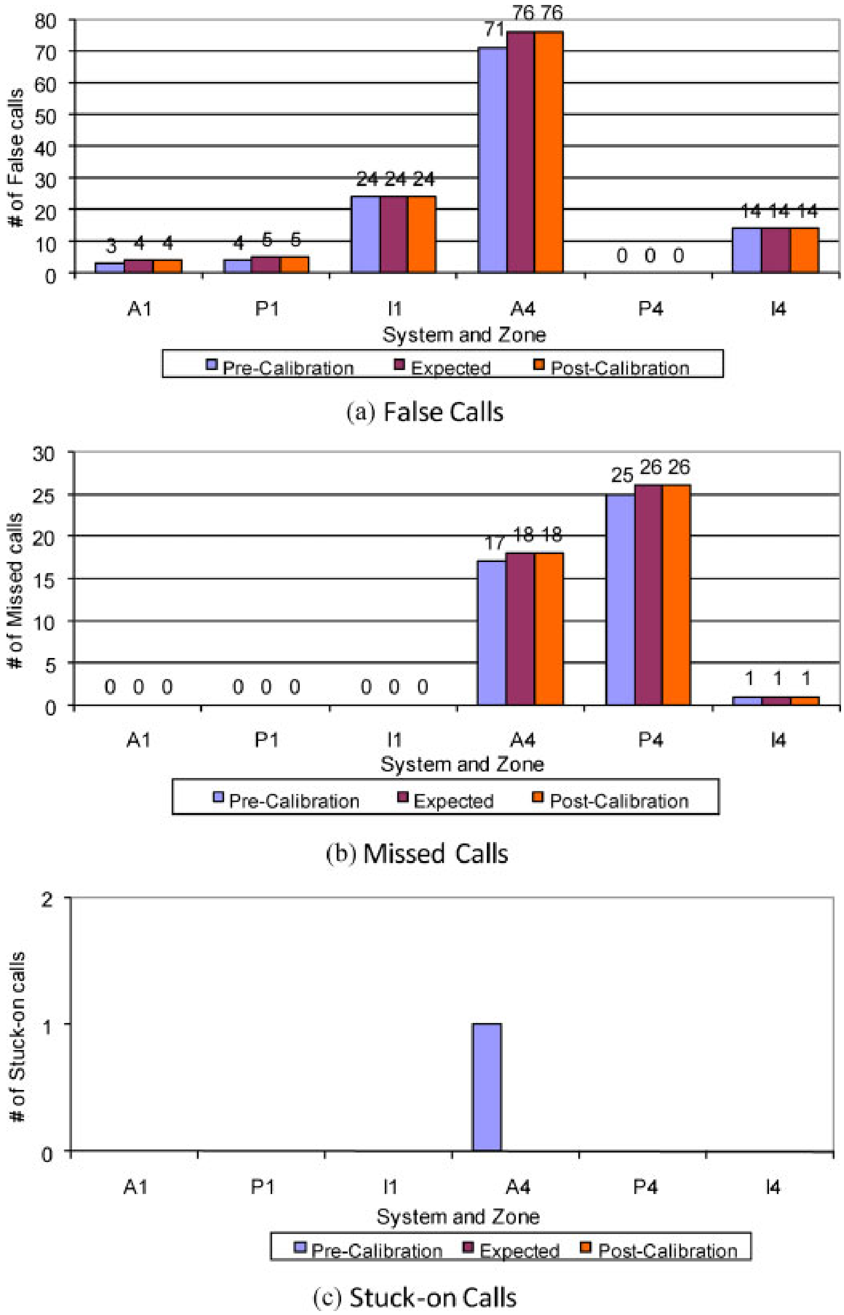

Figure 7. Expected and computed PMs from noon data in Zones 1 and 4.

3.4. Further enhanced analyses

As explained above, the automated data reduction is accomplished in two stages, and the logics used in the first stage identified the potential errors. As a complement to the first stage, additional algorithms were implemented to handle some special cases that the previous logic could not handle. Some of the special situations discussed in the following sections are artifacts of video detection and may not be applicable to other detection technologies.

3.4.1. Shadows/turning vehicles causing false calls

Shadows of vehicles could potentially activate the VD zones on adjacent lanes. As mentioned above, in this location there are two left-turn lanes and one shared right-thru lane (Figure 1) shows the schematic diagram of the study approach. It should be noted that this is the eastbound approach of the intersection, thus the shadows of vehicles in the right-thru lane fall on the left-turn lanes and the shadows of vehicles in the middle lane fall on the median left-turn lane.

At an approach like this, the VD Zones 1 and 2 would together place calls for the left-turn phase as it would Zones 4 and 5. Therefore when Zone 2 places a valid call due to a vehicle, if Zone 1 places a call due to the shadow of vehicle in Zone 2 it does not affect the operational performance of the intersection. However, if the shadows of vehicles on Zone 3 activate Zone 1 or 2, it would deteriorate the performance because the left-turn phase would be serviced unnecessarily. Similar reasoning holds for the advance locations. Not only shadows but also turning vehicles could cause similar situation.

In the preliminary quantification of potential errors, the activations of Zone 1 (or Zone 4) due to shadows of vehicles on Zone 2 (or Zone 5) are counted as potential false calls. In order to remove the false calls due to the shadows/occlusion, an additional logic was applied to Zones 1 and 4. For every potential false call in Zones 1 and 4, it was checked if the loop detector reported a vehicle present on the adjacent lane (Zones 2 and 5, respectively). If so, the potential false call could be no longer considered, since the phase requested by this call is the same as the phase requested by the zone the vehicle is traveling on.

3.4.2. Vehicles changing lanes

At the location of advanced loops, it was observed that a significant fraction of vehicles changed lanes. Due to the lane changing, the VD systems (or any other detection system) may not detect the vehicle on the same lane as the loop detectors. Consider this scenario: a vehicle in the middle lane changes to the median left-turn lane at the advance location. The loop in the middle lane is activated while the VD systems detect the vehicle in the left-turn lane. The preliminary algorithms would consider this as a potential missed call in the middle lane and a potential false call in the median lane, but these are not actually errors. To eliminate such discrepancy, when all the three VD systems missed a vehicle but placed calls on the adjacent lane, they were no longer considered as potential missed calls since that would be a clear sign of a vehicle changing lanes.

4. MANUAL VERIFICATION

The algorithms used in the initial and the enhanced analyses relied on automated data reduction to identify potential errors. However, there might still be some situations that may not be handled by the algorithm accurately. For example, consider the following scenario: a vehicle in the middle lane goes to the median lane at the advance locations; this vehicle is detected by two of the VD systems and the loop as a vehicle in the middle lane, but the third VD system detected it as a vehicle in the median lane. The algorithms used in the initial and the enhanced analyses would consider this as a potential missed call by the third VD system, while in reality it is not. To correctly identify the error and resolve situations like this, manual error verification was performed on all of the potential errors. Video files were observed by a member of the research team to verify if a potential error was actually an error.

It should be noted that this manual verification does not require the whole video file to be viewed. Only the times at which the algorithms reported potential errors, the videos were viewed, and all the four PMs were verified. This manual verification ensures that the potential errors identified at the automated data reduction stage are actually errors. It should be noted that the percentage of potential errors that were not errors (after manual verification) were in the order of 2%.

5. CONCLUSIONS

This paper presents the design and implementation of a testbed for evaluation of vehicle detection systems. Four PMs have been identified: false calls, missed calls, dropped calls, and stuck-on calls. The hardware was set up to collect timestamp data and also to record video data. Broad definitions for the four PMs were coded as general algorithms and used to do an initial data reduction. Some situations under which the general algorithms may not compute the PMs correctly were identified. To address those situations, enhanced algorithms were developed and implemented to obtain more refined data

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reduction results. The computer algorithms were calibrated and validated to ensure identification of potential errors and reduce the time required in the manual verification stage. Manual verification on every potential error was performed to ensure that the PMs computed by the algorithms are factual. Although presented in the context of video detection systems evaluation at signalized intersections, this testbed can be used to evaluate any detection system at signalized intersections as well as highways.

6. ABBREVIATIONS

VII Vehicle Infrastructure Integration.
VD Video Detection.
PM Performance Measure

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