Title: Evaluation of Stop Bar Video Detection Accuracy at Signalized Intersections

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ABSTRACT

Many agencies nationwide have adopted video vehicle detection technology as an alternative to inductive loops. While many product evaluations have been performed, the majority of these evaluations have concentrated on freeway applications where speed and volume were the primary evaluation criteria. At an actuated intersection, the metrics of speed and volume do not necessarily represent how well a device will operate as a presence detector.

Video detection at signalized intersections was evaluated at a test intersection in Indiana. Cameras on all approaches were located at the optimal camera position recommended by the vendors, approximately 60 feet from the strain pole. Two additional cameras were located on each mast arm at slightly less optimal positions at 36 and 48 feet from the strain pole.

Traditional inductive loops were also available at the intersection and were used as baseline data to screen for discrepancies. Each time the detectors were not in agreement, a discrepancy was noted. A digital video recording was later viewed by a human observer to determine whether the video detector or the loop detector was in error. An analysis of the data showed video detection was found to produce statistically significantly more false detections and missed detections than the loop detectors on most phases.

A small incremental increase in performance was observed when the camera was mounted at 60’ rather than 36’ on two of the approaches, but this marginal improvement likely does not justify the additional expense of mast arm, pole, and pole foundation associated with this camera location.

INTRODUCTION

Literature Review

Many agencies nationwide have adopted video vehicle detection technology as an alternative to inductive loops. Some advantages of video detection are that it does not require lane closures, saw cutting pavement, or workers in or adjacent to traffic. Additionally, loop failures may occur due to pavement distress or by utility or other construction.

The majority of recent research on video detection has focused on product evaluations (*1, 2, 3, 4, 5, 6, 7*). Many of these evaluations have occurred exclusively in freeway settings (*2, 3, 4, 5*). As the collective experience with the technology has expanded, many agencies are using video detection at actuated signalized intersections, where the demands on the detector are significantly different than in a freeway application. The state of Texas has even developed a manual for deploying video detection at signalized intersections (*8*).

Typically, freeway detectors have been evaluated by comparing the detector output with speed and volume, from manual measurements or from a device known to provide a high degree of accuracy (*2, 3, 4, 5, 6, 7*). Research on freeway evaluations of video detection have provided many general observations applicable to both freeway and intersection applications. The majority of these observations pertain to environmental factors during the test, including weather, lighting and traffic conditions. Generally, weather has a minimal impact on performance (*1, 6*). However, headlight glare from wet pavement and false calls were documented in several research papers (*1, 5, 6*). Additionally, any environmental condition that reduces visibility will have a negative impact on the video detector's performance (*5, 6, 7*).

Lighting is the most cited condition for causing video detection errors (*1, 2, 3, 5, 6, 7*), especially during transitional periods at sunrise and sunset (*5, 6*). Usually night periods are characterized as having more detection problems than daytime periods because headlights are often all that are visible. However, daytime sun position can also have an impact on operations. The sun may cause reduced visibility due to glare or create moving vehicle shadows and stationary shadows that can sometimes confuse the detector. Newer video detector systems include shadow processing to mitigate these effects.

Cameras mounted at lower mounting heights have been reported to have more detection errors because of vehicle occlusions and more direct headlight reflections on the pavement (*2, 5, 6, 7*). However, a high camera mount may experience sway and vibration which may compromise detection performance (*6, 7*). Several video manufacturers and researchers have noted that the optimal lateral placement for the camera is a head-on view to minimize perspective distortions and eliminate cross lane occlusion events (*2, 5, 6, 7*).

At an actuated intersection, the metrics of volume and speed do not necessarily represent how well a device will operate as a presence detector. Occasional errors may not present problems in a freeway application but even a single error may cause a safety concern at a signalized intersection. For example, a driver who is not served by a signal, because the detector has missed a call, may grow impatient and violate a red indication.

Several researchers have recognized that the demands on a vehicle detection device are significantly different at an intersection than on a freeway. In 2000, Indiana developed a presence based procedure for evaluating video detection (*1*). That report introduced a method of tabulating the periods of discrepancy between inductive loops and video detectors to identify which time periods required a human to develop ground truth data from a recorded video.

MacCarley and Palen (*9*) proposed a common method and metrics for evaluating detectors at actuated signalized intersections. Common definitions were introduced to describe the types of detector errors possible in the intersection environment. One part of the methodology penalizes a detector if it makes a mistake. Another part penalizes the detector if the controller makes incorrect decisions because of a detector mistake, such as terminating a phase early or failing to call or extend a phase. Abbas and Bonneson (*8*) described the performance of video detection in terms of discrepant call frequency, the number of discrepant calls per signal cycle, and an error rate of discrepant calls to true calls. Baculinao (*10*) documented that if the video detector is used for advanced detection the effective vehicle length will increase because the top of the vehicle is being detected and the signal timing will have to be adjusted accordingly.

State of Indiana Experience

In 2001, the State of Indiana suspended the deployment of video detection at signalized intersections after several problems with video detection systems were identified by Grenard et. al. (*1*). That report documented several scenarios, particularly at night in unlit intersections. During night periods, vehicle headlights often caused the cameras to place a call early, thereby extending the effective detection zone and reducing the efficiency of the signal. Also, at night the video detection would sometimes miss or drop a call of a vehicle stopped at the stop bar. The test was repeated with street lighting and showed an incremental improvement in the video detection performance.

In contrast to most freeway evaluations of video detection, Grenard used detector presence to compare two different detectors. It provided an effective evaluation of signalized intersection stop-bar detection where speed and volume would be less appropriate Measures of Effectiveness (MOE). The same detector presence procedure for comparison is used in this paper for the evaluation of newer video detection technology.

Subsequent to the publication of the Grenard report, a consensus of video detection vendors recommended lighting the intersection, raising the camera height from 30 feet to 40 feet, and locating the cameras, at an optimal position along the projection of the lane line separating the left-turn and the through lanes. An example of this placement is illustrated in Figure 1, labeled C1N. The dashed line “P1” is the projection of the striping separating lane NL and lane NA.

This paper reports on the performance observed with the vendor recommended camera locations (Figure 1, C1N, C1S, C1W, C1E) as well as slightly less desirable, but less expensive camera locations (Figure 1, C2N, C2S, C2W, C2E, C3N, C3S, C3W, C3E). The additional material and transportation costs of 60’ mast arms associated with a larger mast arm, larger pole and pole foundation can be very significant to locate cameras at the optimal location.

TEST METHODOLOGY

Discrepancies between Video Detectors and Loop Detectors

To identify video detection errors, it is necessary to either provide a human observer or compare the video detector with another detector with a high degree of precision and accuracy. It was decided that a 24-hour evaluation would capture the performance of the video detection on each phase over a wide variety of traffic and lighting conditions. Due to the intense labor requirements of providing a human observer over such a long period of time, the video detector output was compared with the output from an inductive loop. A human observer was then required to observe the video only where there were identified discrepancies between the two detectors.

Each detection event was classified into any one of four different states. The first two states occur when the two detectors are in agreement either not placing a call, or both placing a call. For simplicity, these states are referred to as L0V0 and L1V1, where L represents Loop and V represents Video, and the numbers indicate whether the detector is off [0] or on [1].

The other two states occur when the two detectors are not in agreement. These are referred to as L0V1 and L1V0 discrepancies. For example, the discrepancy L1V0 can be interpreted as the loop placing a call but the video not placing a call. A graphical explanation of the detection states is shown in Figure 3a.

There are two possible causes of L1V0 and L0V1 discrepancies; either the loop has made an error or the video has made an error. For example, a L1V0 discrepancy might be caused by the loop correctly detecting a vehicle and the camera missing the call; therefore the 'L1V0 discrepancy' can be described as a 'L1V0 video error.' Conversely, the video may have correctly not placed a call and the loop has placed a false call, so the discrepancy can be categorized as a 'L1V0 loop error.'

To accurately categorize each discrepancy, it is necessary for a human observer to interpret and judge each discrepancy and determine which detector is in error. By using this L1V0/L0V1 screening mechanism, it is a much easier process because the observer must only watch the video where discrepancies have been identified.

It is theoretically possible that both detectors are in error at the same time and therefore no discrepancy is recorded. However, if both detectors are functioning as intended, the likelihood of such an event is quite small. These cases were not evaluated.

Impacts of Detection Errors

The impacts of detector errors are twofold, efficiency and safety. The operational efficiency of the intersection is reduced when false calls extend or call a phase unnecessarily.

Missed detections represent a possible safety problem at the intersection. If the detector does not place a call at the appropriate time, a phase may be skipped and a vehicle demand may not be served. If it is obvious to the driver that the controller is skipping their phase or if the driver becomes impatient, they may choose to violate the red signal rather than continue to wait.

Obviously, missed detections that may pose possible safety problems are of much higher concern to agencies than the operational inefficiencies introduced by false detections. Therefore minimizing missed detections should be a priority over the minimization of false detections. However, the operational efficiency should not be neglected and a detector that minimized both of these types of errors would represent a technology that is best suited for intersection detection.

The impacts of the various combinations of states are tabulated in the “Impact” column of Figure 3b.

TEST SITE

Site Geometry

The test intersection is located at State Route (SR)-32/38 & SR-37. SR-37 is a major north-south route that serves as a main arterial between Noblesville and Indianapolis. The posted speed limit on SR-37 is 55 MPH. SR-32/38 is also an arterial that runs to the west through downtown Noblesville with a posted speed limit of 35 MPH. To the east SR-32/38 travels through sparse commercial and residential development with a posted speed limit of 45 MPH. The intersection is shown in plan view in Figure 1.

The northbound and southbound legs (SR-37) each feature two through lanes (Figure 1, NA, NB, SA, SB), an exclusive right-turn lane (Figure 1, NC, SC), and an exclusive left-turn lane (Figure 1, NL, SL). The left turns on these approaches are signalized as protected only.

The westbound and eastbound legs carry significantly less traffic than the north-south approaches. On the eastbound approach there is one through lane (Figure 1, EA), one exclusive right-turn lane (Figure 1, EB), and one exclusive left-turn lane (Figure 1, EL). On the westbound approach there is one through lane (Figure 1, WA), one through-right lane (Figure 1, WB) and one exclusive left-turn lane (Figure 1, WL). The left turns on the east and west legs are protected-permitted. The intersection configuration and phasing sequence is shown in Figure 1.

Detection

The entire intersection was reconstructed during the summer of 2003 with instrumentation to compare intersection detection technologies. Each approach was instrumented with multiple stop bar and advance loop detectors in each lane. The inductive loop locations are displayed in Figure 1 and an aerial photograph of the intersection with loop detector locations is shown in Figure 2a.

The video detection cameras were mounted according to vendors preferred installation practice, 40 feet above the pavement. Three (3) cameras were installed on each mast arm for a total of twelve (12) cameras. The first camera was located at the vendor preferred location at the end of the mast arm (approximately inline with the lane-line between the left-most through lane and the left-turn lane) at 60 feet. The next two cameras were located at 48 feet and 36 feet out on the mast arm, respectively. Herein, the camera at 60 feet on the mast arm is referred to as Camera 1, the camera at 48 feet is referred to as Camera 2, and the last camera at 36 feet is referred to as Camera 3. The dimensions for the cameras mounted on the southwest corner of the intersection are shown in Figure 1 and are typical of each quadrant. A photograph of the camera installation on one of the poles is shown in Figure 2b.

The camera location on the mast arm affects the viewing angle of the lanes it is detecting. As the camera is mounted further out on the pole, cross lane occlusion events are minimized because the view will be of a head-on perspective rather than a side view. The view from each camera on the Northbound and Westbound approaches and the viewing angle of the inside left-turn lane line are shown in Figure 4. As the camera is mounted further from the pole, the viewing angle approaches 90 degrees (Figure 4c,f). As shown in Figure 1, the distance from the cameras to the Southbound stop bar is 165 feet. The distances between the cameras and the stop bars on the Northbound, Eastbound, and Westbound approaches are 160 feet, 165 feet, and 165 feet respectively.

The video detector layout was configured using a software program provided by the vendor. In the software, zones of detection were drawn in each lane. The cameras and detection zones were set-up by a vendor representative in the field in December 2003 over a three day period. After conducting some initial tests the vendor made a subsequent visit in March 2004 for fine tuning and firmware update over a three day period. The results presented in this paper are based on data collected after the camera configuration and firmware upgrade installed during the March 2004 visit.

Software

Each of the twelve video detection systems is capable of logging the status of up to 8 inputs to a text file. The video detection system can also display dynamic detector states and phase indications on a video overlay. The complete video overlay for this test is shown in Figure 5 and includes the following information:

- Eight (8) Inputs to Camera 1
    - Through-Right Lane Group
        1. Through-Right Lane Group Phase Color Status (Figure 5, Item 21)
        2. Status of Loop Detector (Figure 5, Item 22)
        3. Status of Video Detector in Camera 2 (Figure 5, Item 24)
        4. Status of Video Detector in Camera 3 (Figure 5, Item 25)
    - Left-Turn Lane Group
        5. Left Lane Group Phase Color Status (Figure 5, Item 26)
        6. Status of Left Turn Lane Loop Detector (Figure 5, Item 27)
        7. Status of Video Detector in Camera 2 (Figure 5, Item 29)
        8. Status of Video Detector in Camera 3 (Figure 5, Item 30)
- Information Internal to Camera 1
    - Status of Through-Right Lane Group Detector Camera 1 (Figure 5, Item 23)
    - Status of Left Turn Lane Group Detector Camera 1 (Figure 5, Item 28)
    - Detector Box (for each lane) (Figure 5, Item 31)
    - Date and Time (Figure 5, Item 32)
    - Visible heartbeat showing operational status (Figure 5, Item 33)

It was only necessary to log data for each approach using one camera because the states of the other two cameras in the test were mapped as inputs to this camera. All of the information on the video overlay was also logged in a time-stamped data file each time a detector state or phase state changes.

Further processing with spreadsheet and database tools was used to tabulate discrepancies between the loop detectors and video detectors. Once the discrepancies were identified, a human observer consults the recorded video, with the overlay, to judge the cause of the discrepancy.

RESULTS

Data was collected in late March 2004 for the four approaches over four separate 24-hour periods. Phase 5 (NB Left-turn) and Phase 8 (WB Through) were chosen for demonstration in this paper of some of the observations made from the test.

Several common errors are described with video captures in Figure 6 and Figure 7. Figure 6 corresponds to the Northbound Left-Turn Lane L1V0 graph shown in Figure 8c. Figure 7 corresponds to the Westbound Through Lane L0V1 graph shown in Figure 9d. Although, Figure 6 and Figure 7 refer to different types of errors (L1V0 versus L0V1), different lanes (left-turn versus through), and different cameras (Camera 1 versus Camera 3), each of the errors presented is a typical error that has been observed across several cameras and lanes at this test site.

Example Analysis – L1V0

In Figure 6, the L1V0 errors on camera 1 corresponding to the screen captures are identified on the 24-hour L1V0 graph (Figure 6a, P5E1, P5E2, P5E3). The error P5E1 shows a missed call on the left-turn, even though there are two vehicles present (Figure 6b). This type of error, where a vehicle would not be detected, was observed frequently especially on the left turn lanes. Cameras 2 and 3 are detecting the vehicles correctly in this example.

The error P5E2 is occurring on all three cameras (Figure 6c). This error occurred after sunset and is likely because the headlights are not bright enough or large enough to be detected.

The final L1V0 error presented is an unusual error that was witnessed in multiple video clips (Figure 6a, P5E3). At first, a vehicle pulls up to the stop-bar and is detected correctly by all three video detectors (Figure 6d). A large vehicle, usually a class-9 truck, passes on the perpendicular roadway, briefly occluding the camera’s view of the vehicle at the stopbar (Figure 6e). As the large vehicle passes, one or more of the video detectors drop the call and the vehicle is not re-detected (Figure 6f).

Example Analysis – L0V1

In Figure 7, the L0V1 errors corresponding to the screen captures are identified on the 24-hour L0V1 graph (Figure 7a, P8E1, P8E2, P8E3). The error P8E1 demonstrates that it is not always the camera that is the source of the error. Such is the case where a vehicle has pulled beyond the loop’s detection zone, although it is still waiting for the signal to change (Figure 7b). The only loop errors that were observed consistently were the type where the vehicle pulled ahead of the stop-bar and out of the loop detection zone but not out of the camera detection zone.

Two common L0V1 errors that are caused by cameras are shown in Figure 7c and Figure 7d. The error labeled P8E2 in Figure 7c is an example of the camera placing a false call in the through lanes, perhaps due to headlight splash. In this case, Camera 2 and Camera 3 are displaying false calls where Camera 1 does not perhaps due to camera position.

The second error (P8E3) is caused by the shadows from the vehicles in the left-turn lane. In this case, all three cameras have placed a false call.

Comparison of Results for Two Sample Phases

By placing cameras at different positions on the mast arm and testing each camera during the exact same time period, lateral camera placement can be evaluated. It was hypothesized that as the camera was mounted further from the pole that better performance would be observed from this “head-on” view.

The video detectors were tested over 24-hour periods so that the performance of each camera was evaluated over a wide range of weather, traffic and lighting conditions.

The data was processed to find discrepancies between the video detectors and the loop detectors. Only those discrepancy events whose duration is longer than 0.5 seconds are plotted on the graphs shown in Figure 8 and Figure 9. This eliminates many small discrepancies that naturally occur because the states of both detectors do not change at precisely the same moment.

The L0V1 and L1V0 discrepancies are displayed graphically for the 24-hour test periods. Details are shown for Phase 5 – Northbound Left-Turn Movement (Figure 8) and for Phase 8 – Westbound Through-Right Movement (Figure 9). The y-axis represents the duration of the discrepancy in seconds; in some cases the duration was longer than 60 seconds; however the scale was chosen to provide consistency between graphs. The actual duration of some errors that exceed the 60-second scale are denoted on the graphs. The x-axis represents the 24 hour testing period.

The longer errors on the L0V1 graphs were frequently caused by a false video call held during red until serviced. Most of the time, the camera would drop the call after the queue had cleared, but during the red phase would place a call back onto the approach even in the absence of vehicles. This behavior was not consistent between cameras, or at certain time periods. For example, in Figure 9e, the large errors at the end of the test were caused by Camera 2 operating in a failsafe recall mode during the evening hours.

By visual inspecting the graphs in Figure 8 and Figure 9, there are no apparent gross changes in performance between the camera at the optimal position (60') and the cameras at the two less optimal positions (48' and 36').

Tabulation of Errors

To ground truth the data each discrepancy longer than 10 seconds was observed on the digital video to categorize it as either a loop error or a video error. The value of 10 seconds was chosen to minimize the labor required for a human observer to categorize every discrepancy on the graph and therefore concentrate only on the most egregious errors. Ideally, the discrepancy between detectors should be less than 1 second, but the performance can still be characterized by looking at only these larger errors.

When developing the ground truth data by categorizing each discrepancy as a loop or video detector error, careful attention was given to the position of each vehicle on the detector to avoid penalizing a detector for having a slightly different detection zone compared to the other detector. For example, westbound right turning vehicles often drive on the shoulder and are not detected by the loops but are detected by the video because of its larger detection zone. Similarly, a driver on occasion would stop a car length or more prior to the stop bar so that only the front bumper of the vehicle was in the camera's field of view and not detected by the video detector but close enough that the loop indicated a presence. The purpose of the categorization was to identify missed calls of vehicles that were in a detection zone and false calls where there were no vehicles in the detection zone; therefore, errors caused by detection zone positional discrepancies were not counted.

Evaluation of the error count for statistical significance was calculated considering the number of phases served as the number of trials, assuming only one large error would occur per cycle.The tabulation of errors greater than 10 seconds is presented in Figure 10. Based on this data, a two-tailed test of hypothesis was performed between the proportion of loop errors and the proportion of errors of each camera. A normal distribution was assumed since the number of trials in the test was sufficiently large. The null hypothesis that the number of errors by loops and cameras are the same is expressed as:

$$H_A : p_2 = p_1$$

where p_1 = error percentage for video detection and
p_2 = error percentage for loop detection.

The alternative hypothesis represents the case where the number of video detection errors is significantly different than the number of loop detection errors. The alternative hypothesis can be expressed as:

$$H_A : p_2 \neq p_1$$

Once the L1V0 and L0V1 discrepancies were categorized as either a camera error or a loop error, the total number of camera errors on a phase were compared to the total number of loop errors on a phase for statistical significance. Figure 10a summarizes missed detection and Figure 10b summarizes false detections. If the proportion of errors are statistically significant compared to the proportion of errors on the loop detector, an ‘S’ is used to indicate this significance on the bar graphs in Figure 10.

In comparison to loop detectors, video detectors produced a statistically significant number of missed calls on phases 2, 3, 4, 5 and 7. The odd numbered phases are left turn phases and experienced the majority of missed calls.

In all cases, the cameras displayed a significantly higher proportion of false detections than the loops, except for cameras 2 and 3 on phase 6. This exception was due to a faulty loop splice which caused the loop to produce false calls during wet weather. Although the loop splice was subsequently repaired, the errors in Figure 10b, Phase 6 were not discarded because the problem was present during the test. Similarly, the performance of camera 2 on phases 3 and 8 was affected when the video detector went into a failsafe mode and placed a constant call after a loss of contrast was detected in the video image. These errors were also not discarded.

Conclusion

These experiments indicated that in most cases video detection performs statistically significantly worse than loops. The missed calls are particularly troublesome because of the safety implications involved. However, the false calls are also undesirable as increasing traffic congestion is requiring increasingly efficient signal systems.

The only case where the loops performed worse than the video detection can be attributed to a faulty loop splice that created false calls during wet weather. Additionally, the high number of false calls for Camera 2 on the Westbound approach can be explained by contrast loss; the majority of the other video detector errors are not easily explainable by observing the digital video. For example, the errors identified as P5E1 and P8E2, shown in Figure 6 and Figure 7 respectively, cannot be explained by any observable phenomena such as occlusion, shadows or poor visibility. Therefore, without intimate knowledge of the video detection algorithm it is not always possible, from a traffic engineer’s point of view, to conclusively understand why video performance varies from one installation to the next.

The lateral placement of the camera does not appear to have a strong impact on a video detector's overall performance. Referring to Figure 10, if the errors created by the contrast loss on camera 2 (phases 3 and 8), are not considered, the errors on each approach are relatively similar for the three camera positions. Very minor improvements were observed on the Northbound (Phases 2 and 5) and Eastbound approaches (Phases 4 and 7) for the camera that was placed at the far position on the mast arm (60') when compared to the camera located at the less optimal position of 36'.

Finally, several of the recurring errors identified in this text (Figure 6 and Figure 7) have resulted in vendor upgrades to detection logic that will be included in subsequent releases of the firmware. Future tests are planned to evaluate the performance of these upgrades.

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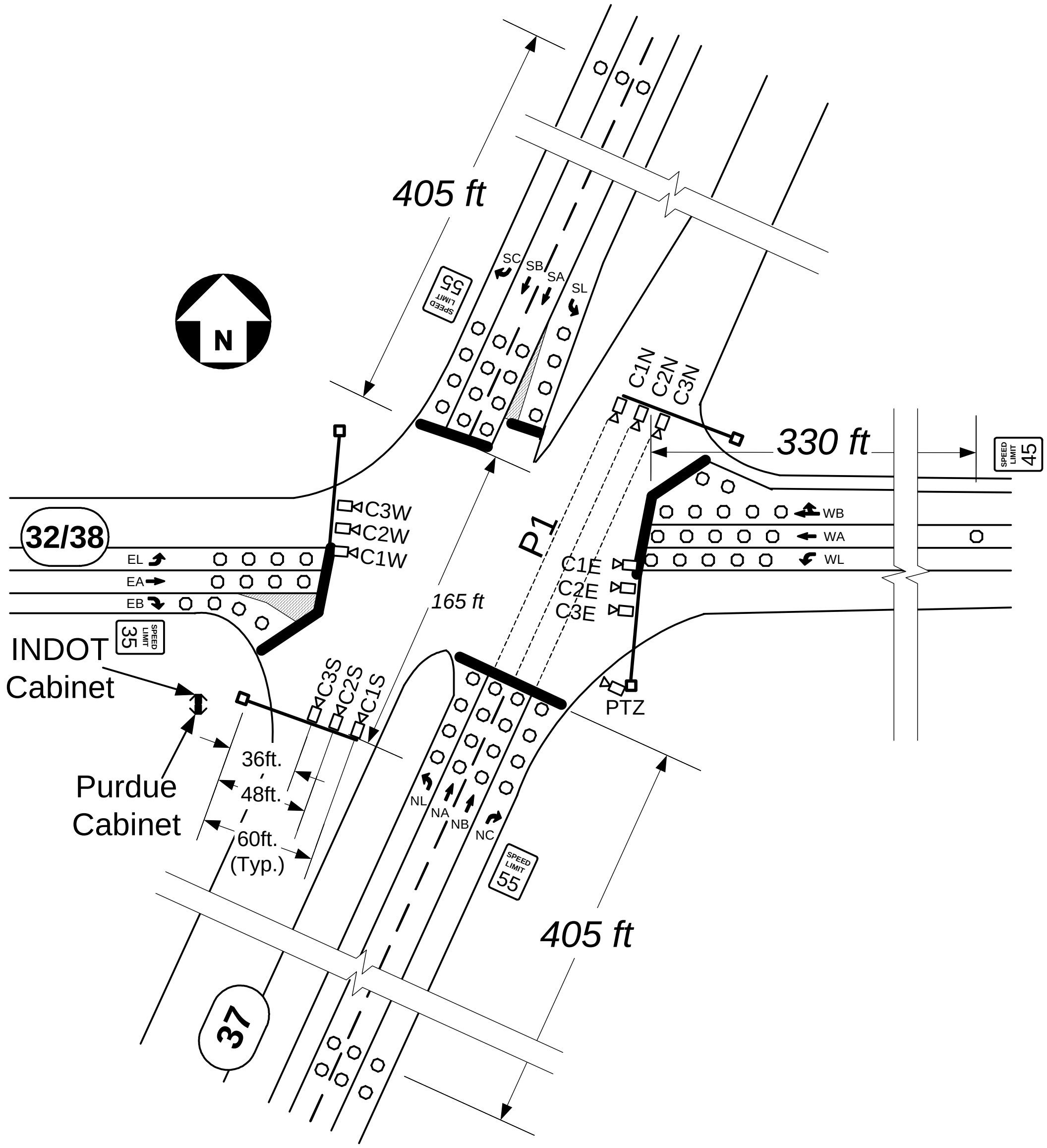
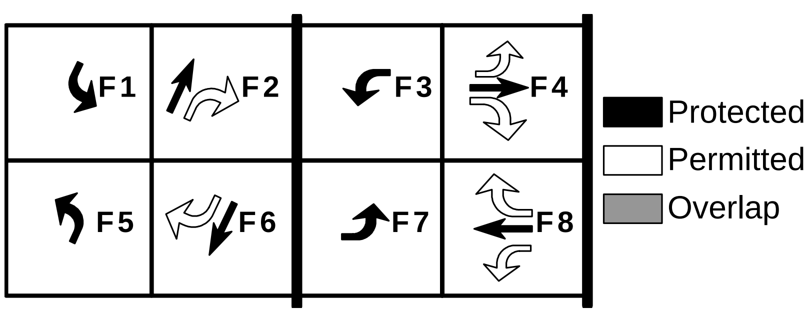
LIST OF FIGURES

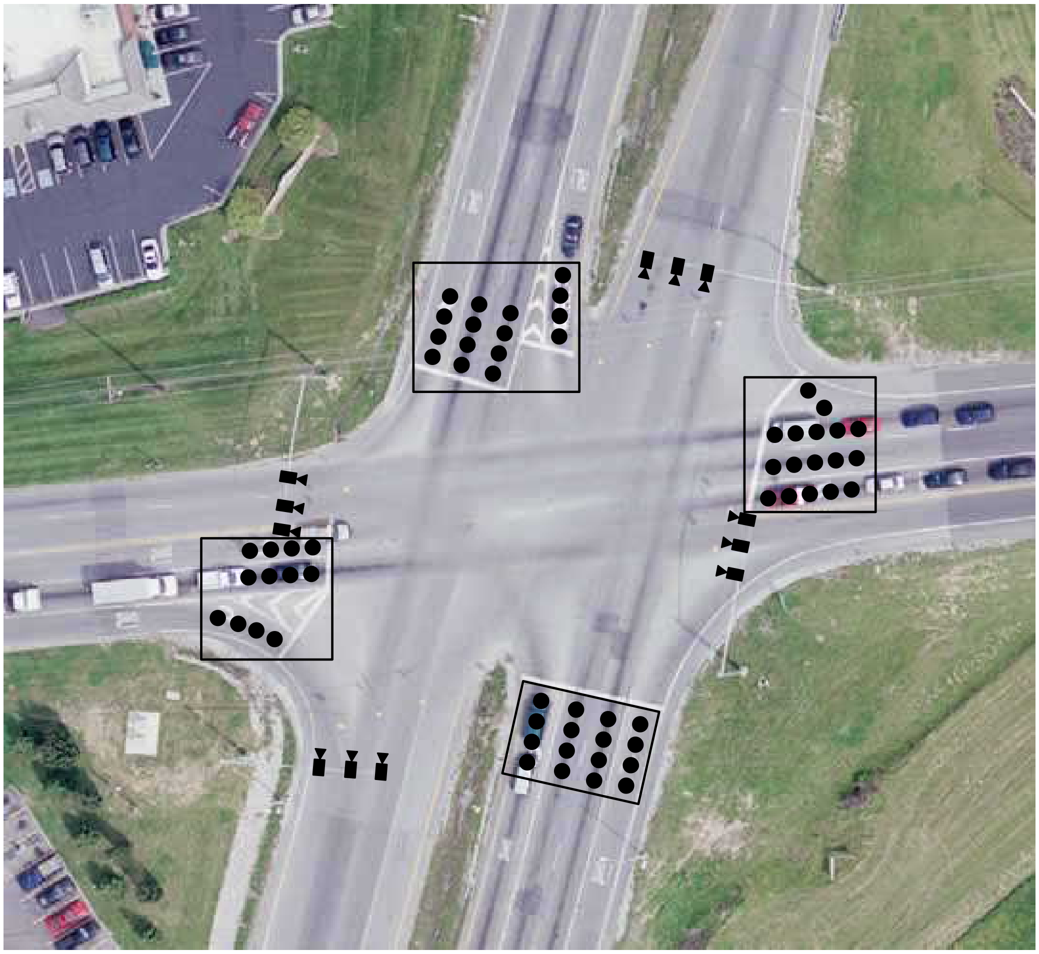


a) Loop Detector and Camera Layout

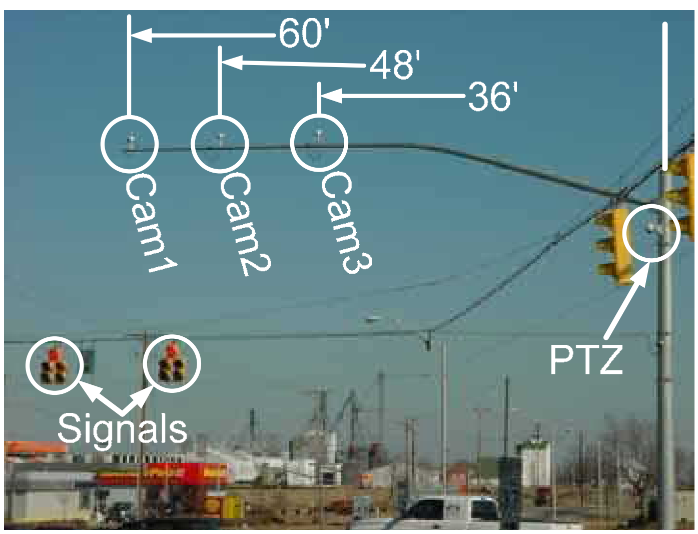


b) Phase Sequence

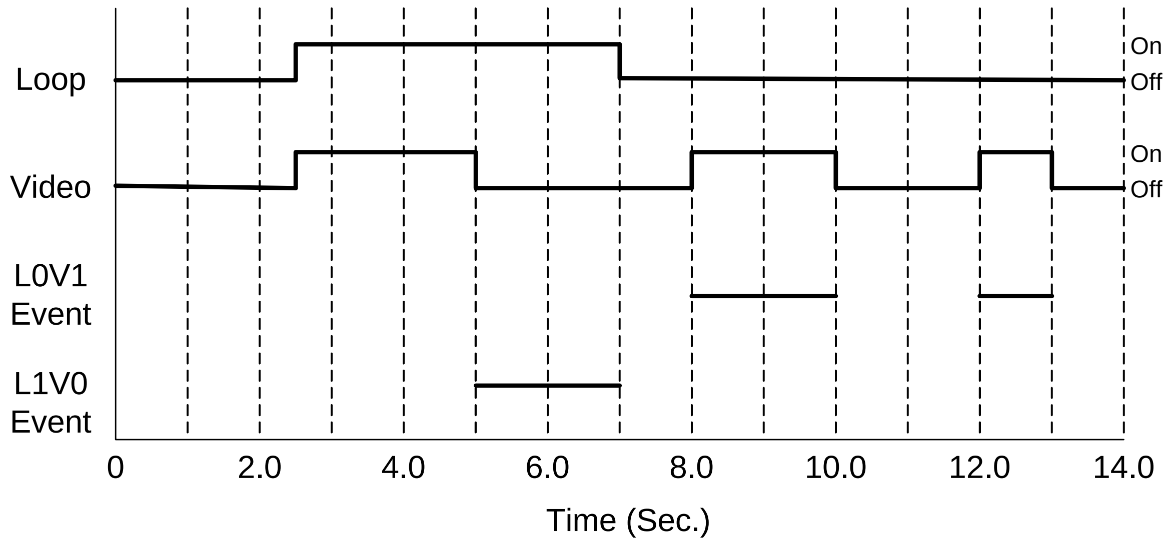
FIGURE 1 Intersection Layout and Phase Diagram (Noblesville, Indiana).



a) Aerial Photograph with Inductive Loop Detector Zones and Camera Positions



b) Annotated Camera Installation Photograph
FIGURE 2 Intersection Photographs (Noblesville, Indiana).

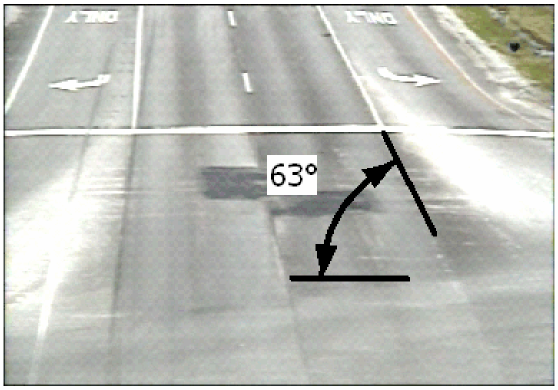


a) Graphical Example of Discrepancies

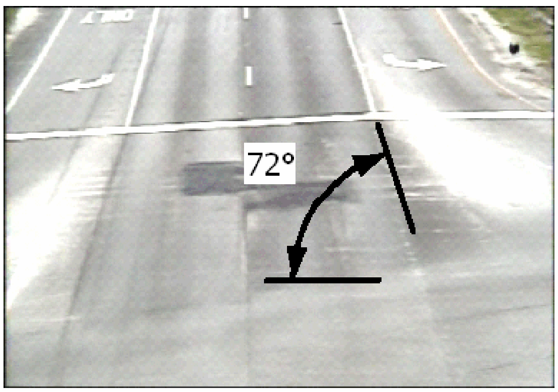
States	Loop Detector Status	Video Detector Status	Discre-pancy	Possible Detection Errors	Impact
L0V0	Off	Off	None	Missed Detection by Both Systems	Safety
L1V1	On	On	None	False Detection by Both Systems	Efficiency
L0V1	Off	On	✓	Missed Detection By Loop Detector	Safety
				False Detection by Video Detector	Efficiency
L1V0	On	Off	✓	False Detection By Loop Detector	Efficiency
				Missed Detection by Video Detector	Safety

b) Enumeration and Interpretation of State Combinations

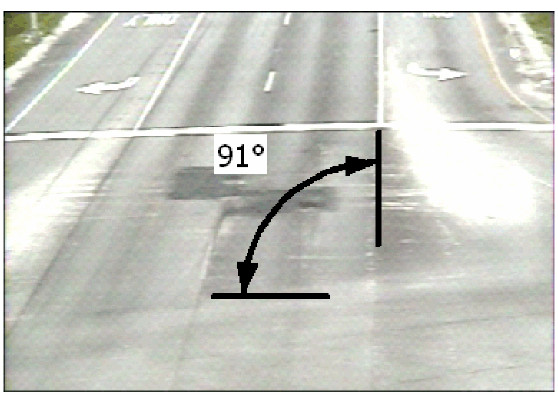
FIGURE 3 L0V1 and L1V0 Discrepancy Concept.



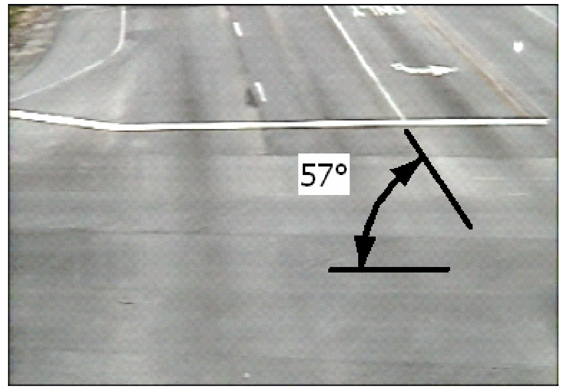
a) Northbound Camera (C3N) at 36’ Offset



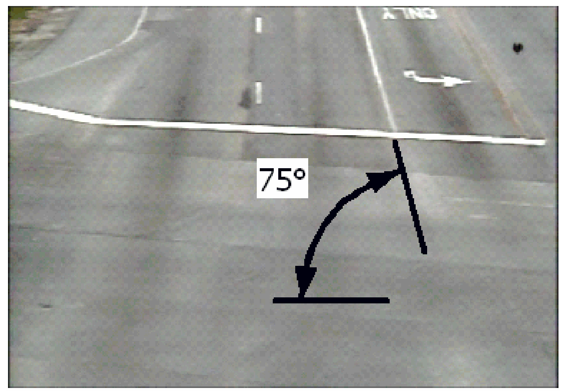
b) Northbound Camera (C2N) at 48’ Offset



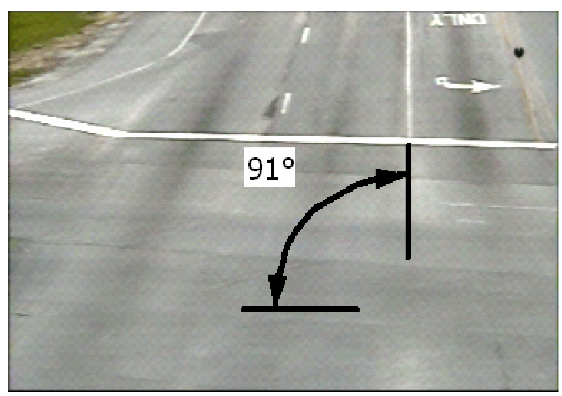
c) Northbound Camera (C1N) at 60’ Offset



d) Westbound Camera (C3W) at 36’ Offset



e) Westbound Camera (C2W) at 48’ Offset



f) Westbound Camera (C1W) at 60’ Offset

FIGURE 4 Camera views for Cam3 (36’), Cam2 (48’) and Cam1 (60’) on the Northbound and Westbound Approaches.

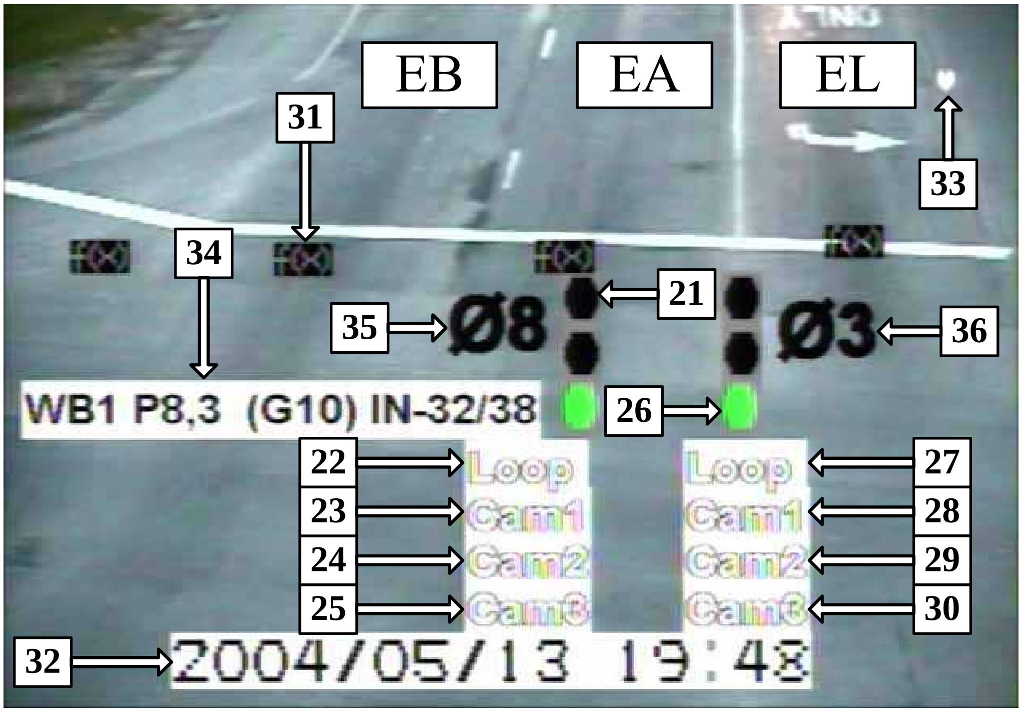
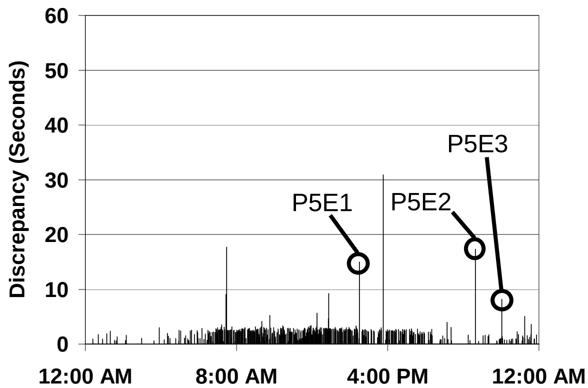


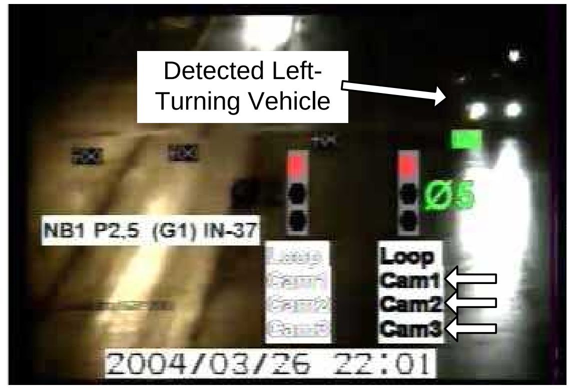
FIGURE 5 Screen Overlay



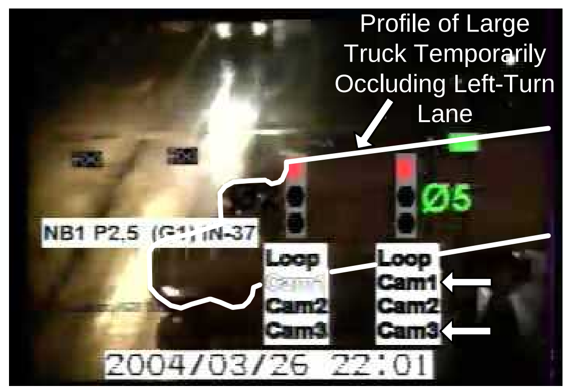
a) L1V0 Graph for Camera 1 NB Left-Turn Lane

b) Undetected Vehicle on Camera 1

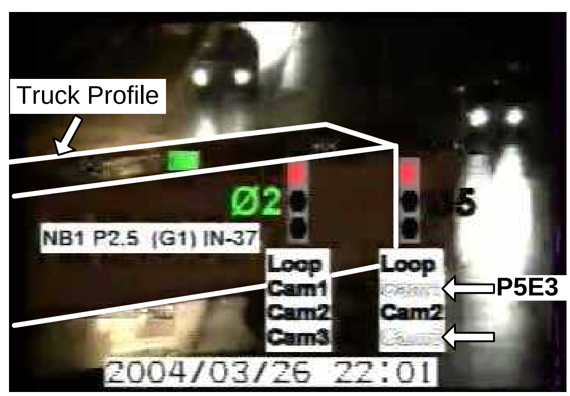
c) Undetected Vehicle at Night on Cameras 1, 2, and 3



d) All Three Cameras Detect Vehicle (t=22:01:38)

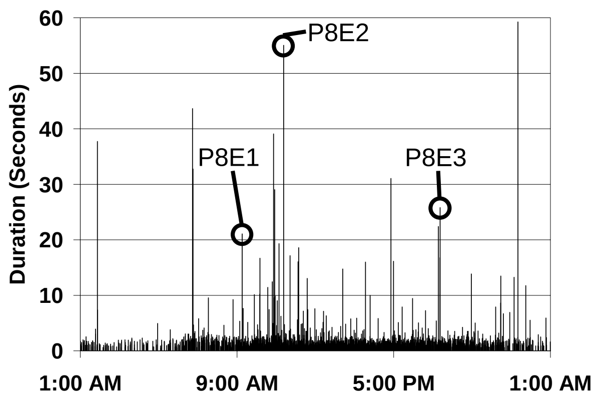


e) Truck Passes on Perpendicular Street and Calls on Phase 5 are dropped (t=22:01:44)

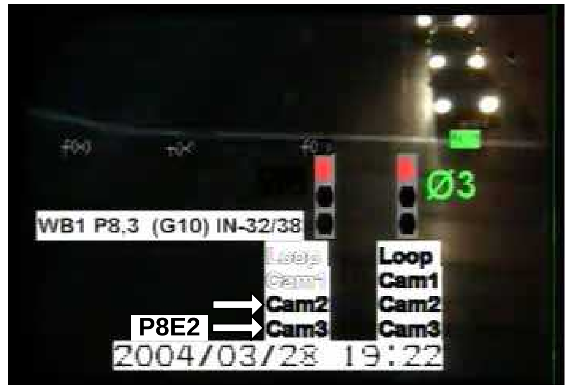


f) Calls on Camera 1 and 3 remain off after truck passes (t=22:01:48)

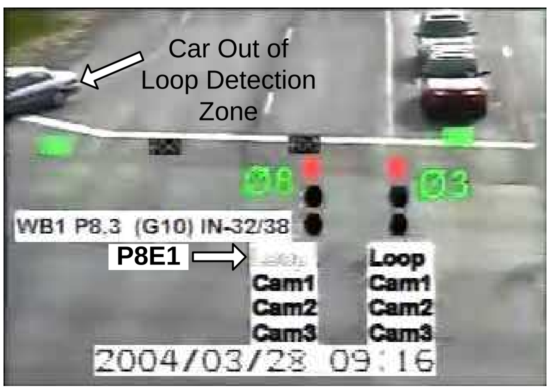
FIGURE 6 Example L1V0 Errors.



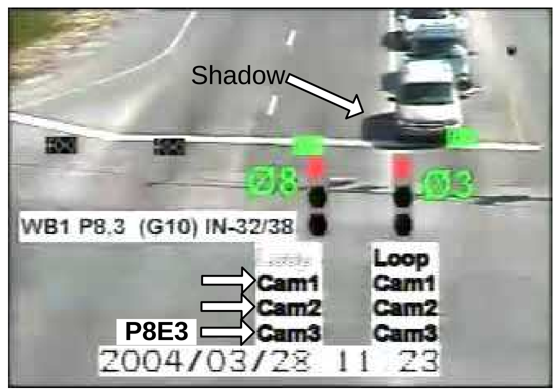
a) L0V1 Graph for Camera 3 WB Through Lanes



c) False Calls on Phase 8, Cameras 2 and 3



b) Car Outside of Loop Detection Zone



d) False Call on Phase 8, Camera 1, 2 and 3, Triggered by Shadow of Left-Turning Vehicles

FIGURE 7 Example L0V1 Errors.

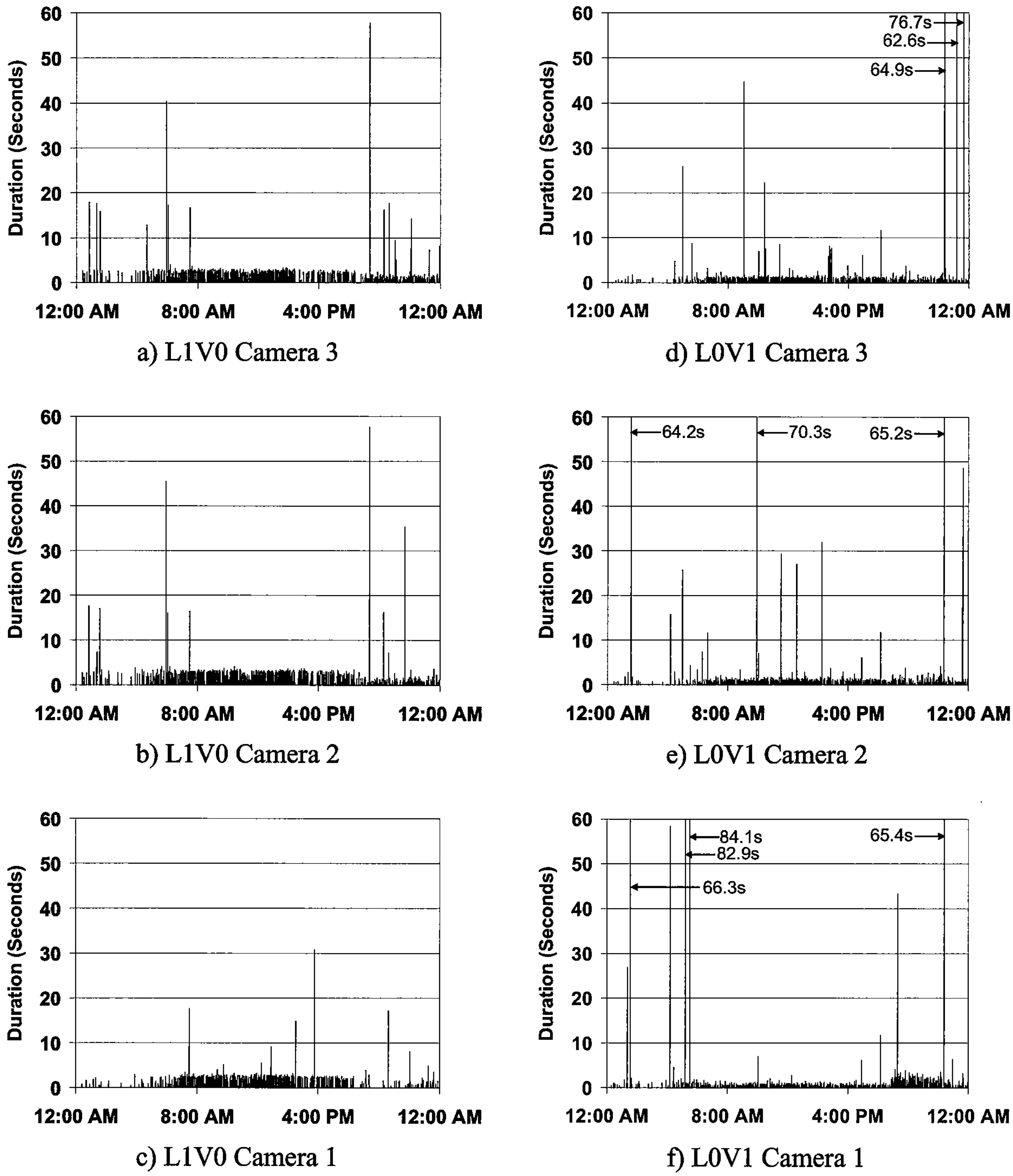


FIGURE 8 Northbound Left Turn Movement (Phase 5), 12:00 AM March 26th – 12:00 AM March 27th L1V0 and L0V1 Graphs for Cameras 1 through 3.

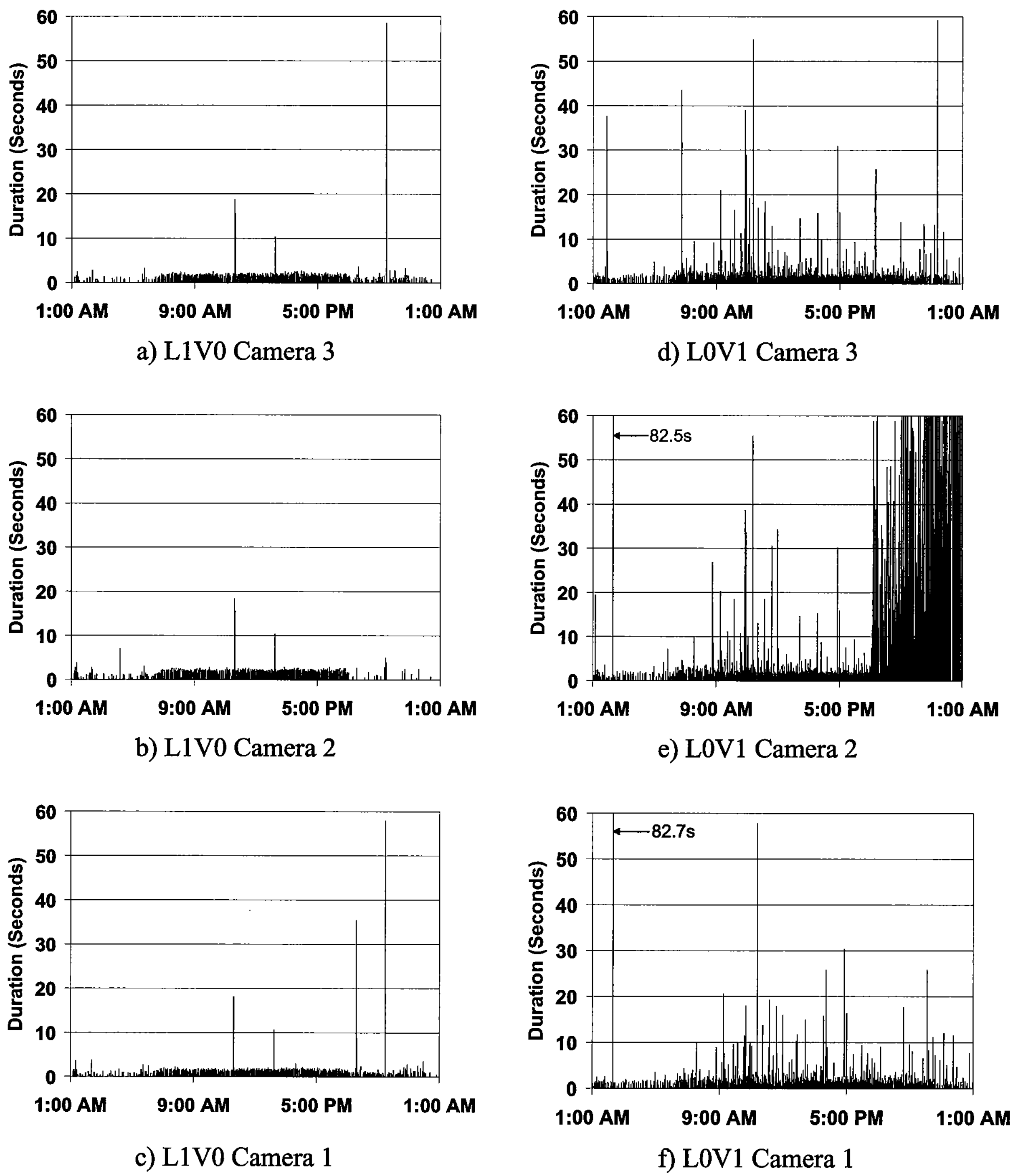
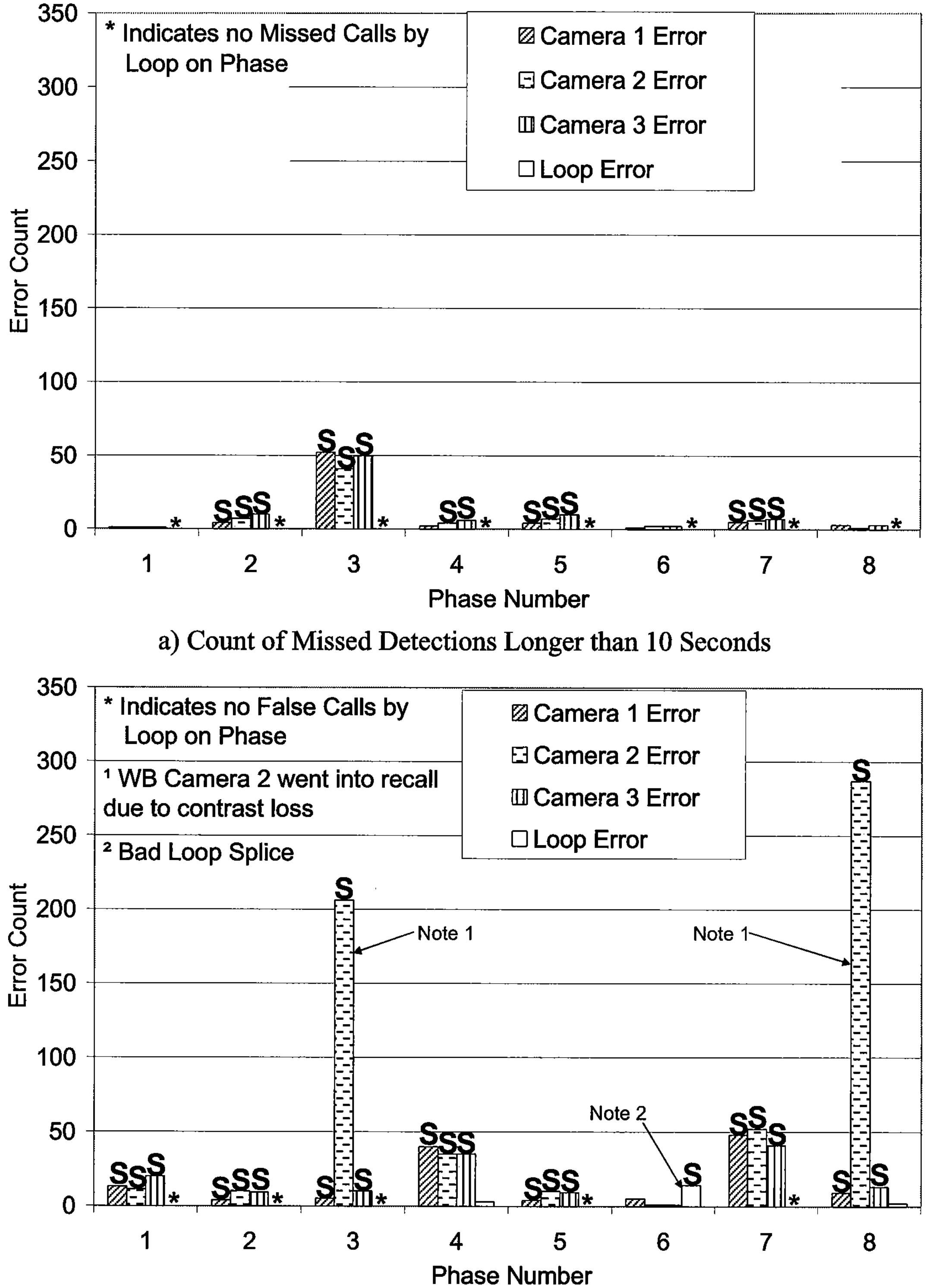


FIGURE 9 Westbound Through-Right Movement (Phase 8), 1:00 AM March 28th – 1:00 AM March 29th L1V0 and L0V1 Graphs for Cameras 1 through 3.



a) Count of Missed Detections Longer than 10 Seconds

b) Count of False Detections Longer than 10 Seconds

FIGURE 10 Tabulation of Errors Longer than 10 Seconds for All Approaches.