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Low-Cost Portable Video-Based Queue Detection for Work-Zone Safety

Final Report

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16. Abstract (Limit: 250 words)

Highway work-zone safety is a major concern for government agencies, the legislature, and the traveling public. Several work zone intelligent transportation systems (WZITS) have been developed as a safety countermeasure to warn drivers of dangerous traffic conditions. Unfortunately, the effectiveness of a WZTIS is diminished if the actual traffic flow conditions do not correspond with the sensor information leading to false warnings; these confuse drivers and reduce the credibility of the system, which is often ignored. This can lead to situations where drivers crash into work-zone areas because they are unprepared to stop. The national cost of crashes due to this was estimated to be nearly $2.5 billion. Such “dangerous” traffic conditions are typically characterized by unpredictable queue formations that propagate rapidly into higher speed traffic immediately upstream from the active work zone. False positives or missed warnings could be reduced if the location of queue tails in addition to vehicle speeds in proximity to the active work zone can be accurately detected. In this study, a low-cost rapidly deployable and portable queue detection WZITS warning system is proposed. To demonstrate WZITS feasibility, a queue detection algorithm was designed and tested using widely available, field proven, machine vision hardware that can be integrated into the current portable system prototype, using video data collected in the field from the portable device. The warning trigger generated by the algorithm can then be transmitted to a remote upstream location for triggering roadside emergency warning devices (such as VMS, flashers, etc.).

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Executive Summary

The need to upgrade and repair the Nation's aging infrastructure has now been recognized as a national problem that will require significant construction projects into the foreseeable future. Many drivers will be forced to contend with congestion and hazardous conditions associated with the construction work zones. Historically, this has created significant impacts on road safety. The Fatality Analysis Reporting System (FARS) reported an average of 935 roadside work-zone related deaths between 2003 and 2008. The five-year period before this—when significant construction projects occurred as part of the ISTEA Act—averaged 1,170 deaths. In addition non-fatal injuries and property damage are significant and pose additional financial burden to society.

A well recognized reason for work-zone related crashes is that drivers encounter queue tails that form during congested traffic conditions and are unprepared to stop. There is evidence that one reason this occurs is that drivers disregard static traffic control treatments that are placed ahead of work zones. In response to this, various Work-zone Intelligent Transportation Systems (WZITS) have been tested and deployed to provide real-time active warnings to approaching drivers upstream of the work zone. Although some of the deployments appear promising, a significant number of accidents still occur. The effectiveness of a WZITS is reduced when the detected traffic flow characteristics do not correspond with dangerous conditions thereby confusing drivers, or leading other drivers to disregard the warnings similar to static warning treatments.

This study tested the feasibility of a previously developed low-cost portable video-based traffic data collection device to detect and follow the progression of the tail of the queue and trigger an alarm that can be transmitted to an upstream location for activating roadside warning devices (VMS, etc.). The objective of such a system is to prevent secondary crashes. The system could then be deployed at temporary work zones along the side of the road at major urban high-speed arterials and intersection work-zone sites. The video can be simultaneously recorded and provides a valuable research tool to further understand traffic flow behavior within work-zone areas.

An algorithm was designed and implemented using a widely available machine vision traffic sensor, to provide real-time detection of queue onset, queue length, and most important, an alarm trigger to activate warning devices placed upstream of the work-zone area being monitored by the portable device. Queue lengths can be measured up to approximately 122 to 137 meters for a single camera sensor deployed with the portable system (400 to 450 ft.). For these tests, a work-zone site and two high-volume arterial intersection test sites were used to evaluate the algorithm. The intersection sites were only selected because of the frequent queue formations; the limited budget available did not allow deployment at more work zones that require very long deployment times for incident recordings, queue formation and detection. One of the test sites provided insights into the limitations of this approach that can be used to guide appropriate deployment configurations to ensure good performance. Results of the experiments showed that the stopped vehicles resulting from a queue can be detected 86% of the time within five seconds of the observed occurrence. The warning alarm trigger output produced a false warning-deactivation rate of 7%. The false-positive alarm rate was estimated to be 0.143 false detections per hour.

Wireless transmission over common high-speed wireless service was evaluated in the field by integrating the equipment into the portable device, and then continuously transmitting video data back to a remote site and monitoring power usage and bandwidth. The initial tests were very successful; however, further evaluation utilizing this technology by conducting actual long-term deployments of the video detection hardware at work-zone sites is recommended.

The portability of the system and algorithm approach proved to be feasible. Further study is warranted to determine utility and performance in actual work zones especially during rapid queue onset events. Such deployments would require collecting data from work zones with different characteristics over the construction season to harvest sufficient queue events under different traffic dynamics. The collected data could also be used by researchers to further study traffic characteristics in work-zone settings to improve traffic sensor designs and work-zone safety measures. In this regard coordination with construction crews to allow the portable systems to be moved to different locations should be established. Multiple system deployments would be required for example to ensure coverage of the continuous and discontinuous lanes leading into the work-zone taper and buffer area, where the advent of dangerous conditions leading to rapid queue formations can occur.

1 Introduction

The need to upgrade and repair the Nation's aging infrastructure has now been recognized as a national problem that will require significant construction projects into the foreseeable future. Many drivers will be forced to contend with congestion and hazardous conditions associated with the construction work zones. Historically, this has created significant impacts on road safety. The Fatality Analysis Reporting System (FARS) reported an average of 935 roadside work zone related deaths between 2003 and 2008. The five year period before this—when significant construction projects as part of the ISTEA Act, averaged 1,170 deaths.

The costs to society for these fatalities and related injuries alone are significant. Mohan and Guatam [1] estimated over 26,000 lost day injuries resulted in a total cost of $2.46 billion alone, which according to the U.S. Treasury department, equates to over $3.3 billion in 2010 dollars, not including the enormous cost of potential injury liability. Highway work-zone fatalities per billion dollars spent cost at least four times more than in total U.S. construction. The study by Li & Bai [2] revealed that amongst various risk factors for fatal crashes in work zones, seniors (age ≥ 65 years) were significantly higher than other age strata at-fault drivers. This is somewhat troubling given that the US population is aging: the number of persons aged ≥65 years is now 40 million, and by 2025 expected to balloon to 64 million by 2025 [3], potentially pushing this cost significantly higher.

In addition to personal injury and fatalities, a large percentage of crashes produce significant property damage mostly due to high-speed rear-end collisions [4]. This type of crash accounted for 63% of all work-zone crashes on urban primary arterials. 83% of the rear-end collisions occurred in the open lane warning area upstream of the taper, and into the taper zone itself. The study from Garber and Zhao [4] examined roughly 2,000 work-zone crashes in the state of Virginia and determined a similar pattern, with 76% of this type of crash on primary urban arterials and 50% rate on rural, secondary arterials. Roughly one third involved serious injuries while the remaining was associated with property damage.

There are several factors that contribute to work-zone related crashes. Traffic conditions become congested due to lane closures or other capacity reduction measures required by the work zone. During periods of heavy congestion, this can lead to rapidly forming queues that travel upstream, and many drivers may not be prepared to stop [5, 6]. One well recognized cause is due to inattentive driving or disregarding the static traffic controls. According to the study by Li & Bai [2], "the odds of having fatalities in a severe crash contributed by disregarded traffic control tripled those for a severe crash not contributed by this driver error."

In response to improving static traffic control measures, many work-zone intelligent transportation systems (WZITS) have been designed and tested. Yet, the accident rates described above occurred in spite of recent advances in developing WZITS as a safety counter measure to mitigate such grievous situations [7, 8, 9, 5]. The effectiveness of a WZTIS is diminished if the measured traffic flow characteristics do not correspond with the crash risk: the incorrect warnings confuse drivers, while other drivers ignore or disregard them completely and instead rely on previous experience and subjective judgment [10]. This can lead to situations where drivers perform evasive maneuvers that intrude into work-zone areas or create rear-end crashes because they are unprepared to stop. Such ‘dangerous’ traffic conditions are typically characterized by unpredictable queue formations which propagate rapidly into higher speed traffic immediately upstream from the work zone [6, 7].

Adding queue and queue length detection to WZITS’s will improve detection of dangerous traffic conditions near the work-zone area thereby allowing the WZITS to provide more accurate warning information to drivers. It is recognized that video detection is adaptable to changing conditions at intersections and the roadway where temporary lane closures due to work-zone activities take place [11]. Furthermore, implementing the queue detection on a low-cost rapidly deployable video data collection device will make utilization of WZITS more attractive especially for temporary work zones where utilizing more invasive and costly trailer-based systems may not be practical or justified. The video can also be used to further research in work-zone traffic flow behavior or to improve operational characteristics of existing WZITS systems.

The primary objective of this study was to test the capability of a previously developed low-cost portable video-based traffic data collection device to address this need [12]. Specifically, the goal of the system is to detect and track the progression of the tail of the queue and trigger an alarm that can be transmitted to upstream location for activating roadside warning devices (VMS, etc.). The objective of such a system is to prevent secondary crashes. The system could then be deployed at temporary work zones along the side of the road at major urban high-speed arterials and intersection work-zone sites.

The original objective of the proposed project was to test the feasibility of a previously developed low-cost portable video-based traffic data collection device by:

1) Using previously collected video to develop and test a real-time machine vision queue detection algorithm (cost-saving tool).
2) Modifying an existing low-cost traffic data and video collection apparatus in order to integrate the queue detection algorithm and hardware, and to wirelessly transmit the detection data to remote locations.
3) Crudely demonstrating the capability at a field site.

Rather than using only previously collected video, a decision was made by the research team to collect additional data in order to better examine algorithm feasibility using the portable apparatus previously developed. More intersection data sets were collected at high-volume intersections because they provided frequent queue formations. Data sets were also collected within arterial work-zone settings. The additional time exceeded the limited time and budget for completing the last two objectives and therefore only one construction site was tested. However, the design of the lab experiments and testing was such that the operation and performance of the algorithm in the lab would have been identical to field deployments. Furthermore, the amount of data to be transmitted wirelessly by the machine vision sensor to such a remote warning device located upstream is very small and does not demand significant bandwidth (~10 bytes/second) which can be achieved with many wireless technologies on the market today. The collected data were sufficient to ascertain the feasibility of the approach.

The report is organized as follows. First a summary of queue warning systems that are applicable to work-zone queue warning detection will be provided. An overview of the queue detection algorithm developed and tested in this study will then be presented. Then, the field experiments conducted to collect and ground truth the necessary data followed by the method to test the algorithm are summarized in detail. The results of the experiments using the algorithm with the collected data are presented. This is followed by a chapter that describes the algorithm logic and development in further detail. A description of the modifications that would be required for wireless deployment is discussed in the chapter preceding the last chapter. The last chapter presents conclusions and recommendations for future improvements and research.

2 Background

The likelihood of an increase rate of crashes at work zones has been well recognized over the years. A recent study from Bai & Li [13] reported that driver errors caused 92% of the fatal work-zone crashes in the past thirteen years. The most common driver errors include inattention, disregarded traffic controls, speeding, and alcohol impairment. According to their analysis, most Kansas fatal work-zone crashes (67%) during 1992 and 2004 occurred on non-intersections of the highways, and 19% were intersection related. Field studies by Fontaine [14] determined that WZITS are most effective in areas where queue lengths as well as speeds are variable throughout the day. Further, Wang et. al [15] noted that crashes, many of which are rear-end collisions, are attributed from preceding vehicles rapidly reducing their speeds (e.g., shock waves). Essentially, there is a 'grey zone' containing a transition point between rapidly forming queues and vehicles traveling the posted speed limit upstream of the work zone. In short, the speed of such queue tail movements precludes manual intervention by a human traffic controller, and static warning signs are also not sufficient under such circumstances [7]. Efforts undertaken by others to address this need as well as their limitations are summarized next.

Static signs in a work zone typically inform drivers of the location and nature of a work zone, but not the real-time information of downstream congestion and queues that drivers may need to know for safety reasons. For this reason, others have developed and proposed systems for real-time monitoring of queues and will be reviewed. Many WZITS implementations today comprise the use of Doppler Radar units, RTMS (Remote Traffic Microwave Sensors), or in some instances infrared 'trip-wires' [16], or machine vision to detect vehicle speeds and presence. All such systems measure vehicle speed at different locations upstream of the work zone. The speed measurements are then categorized into meaningful warning levels that are conveyed to drivers (Variable Message Sign (VMS), triggered light flashers, HARN, etc.). For example, Mn/DOT deployed several skid-trailer 'nodes' with machine vision systems or radar units along several upstream locations of work-zone sites [9]. Wireless communication was used to relay warning messages (e.g., 'slow speeds ahead', etc.), to a portable VMS. Results of the field evaluations for this system indicated a significant reduction in speeds through the work-zone area when the WZITS was in use. The cost of each node was $78K. Tudor et al. [17] also deployed a similar system in Arkansas. The cost of their system (subtracting the 60K for the HARN system), was $263K, and consisted of Doppler Radar speed stations integrated with a VMS, plus an additional VMS sign. The stations were deployed approximately 3.5 miles from the work-zone taper while the individual VMS was stationed between seven to twelve miles upstream of the work zone. The warning level triggered to 'incident mode' when the measured speeds dropped below 20 MPH. Note that vehicle related crash fatalities decreased from 3.4/3.2 per 100 million miles traveled to 2.2 per 100 million miles traveled over the course of the deployment (1 year). McCoy and Pesti [18] evaluated a work-zone adaptive speed advisory and warning system based on Doppler radar and determined a smoothed reduction of speed coming into the work zone.

Other Mn/DOT recent projects employed RTMS radars to measure vehicle speeds and control merging up to the work-zone taper area. For example, Mn/DOT's Dynamic Late Merge System (DLMS) used an RTMS radar sensor to detect vehicle speeds. When speeds were high, the system advised drivers to merge early. When vehicles began to queue, lower speeds were detected and drivers were advised to wait to merge until a preset merge point. The findings from field tests with this system were that the detector did not report accurate speed data when traffic volumes were low [19]. Note RTMS sensors differ from Doppler radars; they are a true RADAR sensor (Radio Detection And Ranging): they provide presence detection of stationary or moving vehicles in multiple zones.

AutoScope machine vision sensors were evaluated on a congested freeway section in Texas in 2006 and 2007 [5]. Autoscope Cameras configured with lane specific speed detectors were mounted on sign gantries which extended over the freeway lanes of interest. Predefined speed thresholds (< 20 mph) trigger flashers located above static message signs one and two miles upstream of the camera sensors. The system reduced speed variation of drivers although queues that formed downstream of the sensor would go undetected and therefore the alarm never triggered, indicating more sensors needed to be deployed downstream of the initial sensor.

The systems above are designed on the premise that the speed differential between the stopped or slow moving traffic due to high traffic densities in the work zone and traffic moving at the posted speeds create dangerous situations that can result in crashes. Wiles et. al [7] and Sullivan et. al [8] contend that the speed differential becomes a hazard due to the driver's uncertainty "about the *location* of the differential, the *magnitude* of the speed differential, and the *span* of roadway over which the differential is observed". Researchers in [8] proposed a rapidly deployable WZITS that consist of 'smart-barrels'. Without going into great detail, the essence of the system would be to 'track' the tail of queues by detecting a 'rapid' reduction of vehicle speed along several regularly spaced points—in this case every 50 feet, up to about ¼ mile upstream of the work zone. By knowing the position of the queue with respect to the position of the road side warning signal location, a deceleration rate to stop a moving vehicle at the warning signal can be calculated, and rated for severity ('dangerous' deceleration rates). A single prototype barrel was instrumented using several low-cost sensor technologies to test vehicle speed detection feasibility. Significant hardware development remained in order to implement wireless data communication between multiple barrels, crashworthiness of the modified barrels, and the proposed queue location and driver warning trigger algorithm, and therefore the *system* was never actually deployed. However driving simulation experiments were conducted to 'test' the system under several controlled scenarios and remote, upstream roadside warning configurations. The results of the driver simulation study indicated significant speed reduction amongst subjects.

Very recently, a system called the iCone embeds a Doppler radar sensor, wireless communication, and battery into a standard channelizing drum similar to what was proposed by Sullivan et. al [8,20]. The system aggregates speed data and reports the information to a nation-wide centralized server system which then disseminates the data to various agencies and traveler information portals. The Minnesota Department of Transportation has recently begun a field test study to evaluate accuracy and performance of the system in work zones which will conclude at the end of the 2010 construction season.

In conclusion, queue length propagation into upstream traffic without sufficient warning to drivers is recognized to increase accident risk near work-zone areas. Secondly, the need to accurately detect queues with easily deployable, cost effective WZITS has been recognized by others. Video-based machine vision offers the possibility of detecting the location of propagating queues combined with surveillance capability that can be used by researchers and engineers to study work-zone safety, or to improve state-of-the-art for WZITS. The approach tested in this study is to construct multiple ‘trip-wires’ within the video scene of the roadway in order to detect stopped vehicles in rapidly forming queues by deploying the portable system developed previously in [12] along roadside infrastructure. Timely and accurate detection and advanced warning of stopped vehicles that result from a shockwave rapidly propagating upstream can then be used to mitigate secondary and potentially dangerous crashes. A brief overview of the algorithm to accomplish that could then be deployed with the portable system will be described next.

3 Queue Detection Algorithm

The purpose of the algorithm is to detect queue tails as they propagate upstream into oncoming traffic, and output a warning alarm trigger that can be used by roadside warning devices placed upstream of the sensor to warn drivers of the impending queue. In order to achieve this, an algorithm that utilizes ‘trip-wire’ presence detection was developed (figure 1**)**. Others have adapted off-the-shelf machine vision systems for measuring queue lengths [21]. However, the objective of such algorithms was to estimate queue lengths at signalized intersections to improve signal timing rather than to detect stopped vehicles that result from shockwaves originating from rapid queue formations within work zones, downstream of the detection area. In order to detect queues, the red-phase from the traffic controller was utilized. However, construction sites do not have signals. Second, the machine vision cameras are mounted permanently on the signal mast above the approach lanes, since this is an optimal placement for lane specific vehicle detection [11]. Such a camera position cannot be attained under most work-zone situations and any approach should not be required to rely on traffic signal phasing information to detect stopped vehicles during queue formation in work zones.

The algorithm developed and tested herein used video from the previously developed portable video traffic monitoring device deployed along the side of the road, at intersections, clear of oncoming traffic.

Figure 1. Presence detector ‘ladder’ configuration of algorithm used to detect the onset of queues, queue length, and queue warning alarm trigger.

The algorithm produces three outputs. The first output is a detection event of a ‘stopped’ vehicle, or the start of a queue. The second output is an alarm trigger that can be transmitted to an upstream roadside warning device. The third output is a real-time estimate of queue length which can be used to estimate the queue tail location within the detection area. The additional information can be used by the upstream warning devices to more accurately associate and convey a warning severity level to drivers. For example in [20], the severity level was represented in driving simulation experiments by changing the blink frequency of roadside warning flashers. The frequency is assigned by calculating required deceleration rates over the stop distance from the location where the driver receives the warning to the tail of the queue [20]. A brief description of the algorithm logic and approach is provided next. Further details of the algorithm design are provided at the end of the report, in Chapter 6.

The algorithm requires the configuration of a virtual 'stop bar' region to detect stopped vehicles as the shockwave of stopped vehicles progresses into the detection area of the camera sensor. This is constructed by drawing a detector covering all lanes to be monitored as well as lane specific detectors as shown in figure 1. In order to determine if a vehicle 'stopped', a time occupancy threshold for each of the detectors in the ladder must be determined. This was accomplished using a stepwise calibration procedure that consisted of running several experiments varying the threshold time-on-detector value. For each threshold, the observed and detected queue lengths at 15 m (50 ft) increments from 0 (start of the queue) to 140 m (450 ft) were compared with the manually observed length in the video, up to the beginning of queue dispersion. A calibrated time on detector threshold of 2.0 seconds yielded an accuracy of about 97%. Details of the ladder logic design and experiment procedure are provided later in the report in Chapter 6.

The control of the queue/stopped vehicle warning alarm trigger requires two events: turn-on, and turn-off. Turning on the trigger occurs after the detection of the queue has been established. In this application, the intent was to turn off the alarm trigger when the traffic conditions within the detection area are restored to uncongested flow conditions. In this regard one approach that was considered to sense this condition was to employ a speed detector and determine a threshold speed value to deactivate the warning trigger. However, an earlier study with the portable system deployed on the roadside to detect speed was too far from the design specifications of the sensor to achieve accurate vehicle speeds, particularly for lanes that are beyond a lateral offset of two lane widths from the camera [12]. Work-zone deployments can create similar situations when monitoring the through lane of the taper from a roadside shoulder location. Therefore another approach was implemented for this study.

The method for deactivating the warning trigger is achieved by monitoring for a queue 'break point' as described in [22]. Break points are "time instants that traffic condition changes within a cycle" (they are referring to a traffic signal cycle between effective red and green times). Such instances in time are monitored by presence loop detectors located upstream **from the origin of the queue**. The traffic condition change refers to transitions between queued and non-queued vehicles which they determined can be delineated by an abrupt change in headway gap times between vehicles. Such a state change indicates when the tail of the queue passed over the detector. The headway gap times are measured by their data acquisition system that sampled the in-pavement loop detector state. From their data, the breakpoint immediately upstream of the stop bar was delineated empirically with a gap time of approximately 2.5 seconds (slightly longer for large sized vehicles). This was implemented in our algorithm by monitoring per-lane gap headway times between vehicles with the virtual stop bar presence detectors. A detailed discussion of the detector logic formulated to implement gap time threshold monitoring is provided in chapter 6.

4 Data Collection and Experimental Method

As explained earlier, due to the limited time and resources available, queue formation and detection was initially performed at two signal controlled intersection sites and implemented at one highway construction site. A two hour period was utilized to develop the algorithm, while ten hours were used to evaluate algorithm performance. The rational for utilizing traffic data at the intersections is that the frequency of queue onsets provided many more samples to test the algorithm than would be expected during the same deployment periods at a work-zone site [10, 17]. Furthermore, they allowed us to investigate the limits of this approach in order to define deployment constraints that would ensure good performance. In this regard, we needed to ascertain the number of lanes that could be monitored relative to the camera sensor placement as well as practical limits of detection area that can be used in the video image. The forthcoming analysis of the results demonstrates these limitations and their affect on detection performance.

The intent of recording data at a work-zone site was to capture the onset of queues and test algorithm performance within an actual temporary work-zone area, since it was expected that queue formations resulting from the lane closures and other activities occurring within the work zone would be different than at a signal controlled intersection, albeit the frequency of their occurrence being considerably less than at the intersections. Second, and of equal importance, it provided the opportunity to test false alarm occurrence under ensuing traffic conditions through the temporary lane closure.

The remaining organization of this chapter is as follows. First, each of the test sites utilized for algorithm testing will be described in detail. Second, the ground-truth process will be described. This is followed by a description of the in-lab methodology for evaluating and testing the algorithm. Note that vehicle speeds for the test sites where measured from the video by manually recording vehicle travel times between two identified reference points spaced 30.5 meters (100 ft.) apart. The travel times are calculated by summing the difference between video frame stamps and utilizing the video sampling rate.

4.1 Description of Data Collection Site Characteristics

Two intersection sites were used to collect queue data. Both intersection sites are located along a high-speed, high-volume suburban arterial that carries traffic into (Eastbound) and out of (Westbound), the core city of Minneapolis.

4.1.1 Site 1 Description

The first intersection site is located west of Minnesota State Highway 100, at the crossing of Glenwood Ave. and Minnesota State Highway 55 and carries an estimated daily traffic volume of 32,000 vehicles per day (VPD). The peak hour traffic volume for the east bound lanes tested in this study is 1700 vehicles per hour (VPH). [23]. The posted speed limit along this area of Highway 55 is 55 miles per hour (MPH), with the observed speed of 45.0 ±7.42 MPH (N=200 vehicles). A diagram of the site with the location of the camera is shown in figure 2, with a photo of the portable video traffic measurement system deployment show in figure 3. The approach lane widths are 12 ft. (3.66m). The lane stripe end points were used to reference queue length.

The end points were measured relative to the intersection stop bar. All measurements were calculated by walking a measuring wheel twice and recording the indicated displacements.

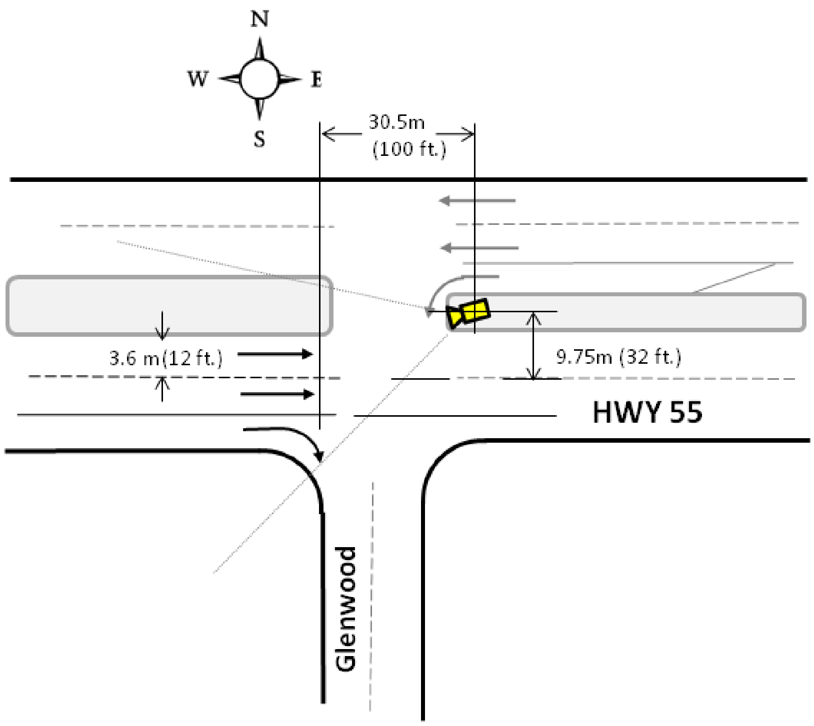


Figure 2. Camera location with respect to chosen stop bar at HWY 55 & Glenwood Ave. intersection.

Figure 3. Apparatus deployment at HWY 55 & Glenwood Ave. site.

For the experiments traffic data from the two through lanes immediately upstream of the intersection were utilized. The camera was tilted down 20 degrees from horizontal, with a height of 28 feet above the roadway to provide a view of traffic well over 500 feet from the intersection. Note that the detection area study for this work was limited to be within 450 feet from the camera sensor. This is because the resolution of the camera image provided too few pixels for reliable detection accuracy beyond this distance.

The system was configured to record video during peak hour traffic 6-9AM, 3:30-6:30PM, and midday traffic between 11-1PM, with MPEG4 digitized video stored to a flash drive at 15 frames per second using a constant bit rate of 1800 kbps. A keyframe value of 1 frame for every 15 frames of video was used for all experiments. In video compression algorithms, keyframes (also refered as I-frames or intra-frames) represent background images that serve as a reference image used by the video compression algorithm to discriminate the moving foreground information (e.g., vehicle traffic). The small keyframe interval (a more typical interval is every 10 seconds) accurately captured the subtle changes in the background image due to variations in the lighting and slight camera sway on the mast during windy conditions.

Approximately 30 hours of video were collected to ensure a suitable amount of data was available for the analysis. Two videos were used from this location. A two hour peak morning video was used initially to tune a time-on-detector (occupancy) threshold needed by the detector algorithm logic. The algorithm and threshold determination is described in chapter 6. A second, three hour afternoon peak travel time on a different day was used for testing. Many large queue formations – some extending well beyond the queue detection area, were observed. The weather condition for the first video used for calibration was sunny. The weather conditions for the second test video ranged from partly cloudy to a one hour period of rain. Further details regarding the deployment procedures and configuration of the portable video traffic measurement system and data collection procedures are in [12].

4.1.2 Site 2 Description

The second intersection, Rhode Island Ave. and Minnesota State Highway 55, allowed for testing significant cross-lane view angles from an off-shoulder location covering three lanes of traffic. The exclusive left turn lane, which was furthest from the deployed camera location, provided situations where vehicles are stopped in one lane, while traffic flow continued in the middle, and near-camera (right) lanes. The deployment situation provided guidance in deployment constraints that must be followed to ensure good performance; this will be discussed further in the results. A brief description of the site characteristics is provided next.

The site carries an estimated daily traffic volume of 23,650 vehicles per day (VPD). The peak hour traffic volume for the east bound lanes tested in this study is 1600 vehicles per hour (VPH). [23]. The posted speed is 55 MPH. The uncongested speeds extracted from the data used in the study were 55.9 ±7.0 MPH (N=66) during the midday peak hour and 49.0 ±8.0 MPH (N=100) during the peak PM rush hour period. A diagram of this site with the location of the camera is shown in figure 4, with a photo of the portable system deployment shown in figure 5. Lane marking distances as well as the measurements indicated in the diagram was obtained by a distance measuring wheel.

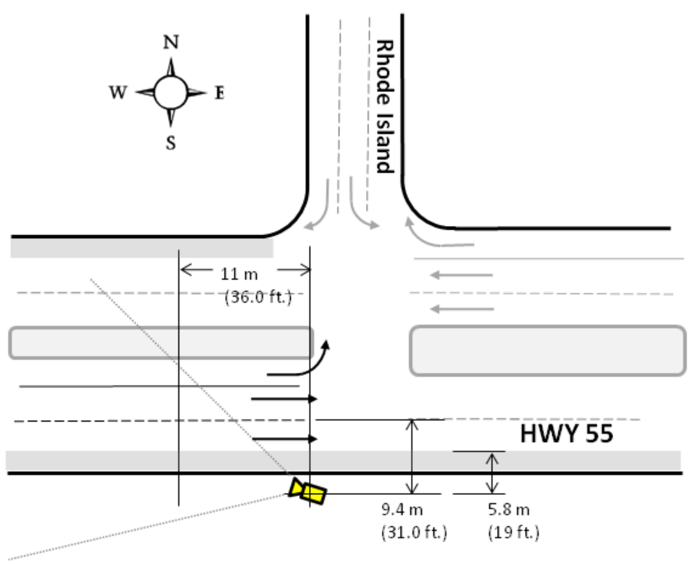


Figure 4. Camera location with respect to chosen stop bar line at HWY 55 & Rhode Island Ave. intersection.

Figure 5. Camera location with respect to chosen stop bar line at HWY 55 & Rhode Island Ave. intersection.

The experiments utilized traffic data from the two through lanes and the far, isolated left turn lane upstream of the intersection. The camera was tilted down 30 degrees from horizontal, with a height of 28 feet above the roadway to provide a view of traffic just over 500 feet from the intersection. Unlike the HWY 55 & Glenwood Ave. site, the traffic signal stop bar of the intersection was downstream of the camera view. The larger downward tilt angle also reduced the sky horizon in the image, thereby increasing the number of pixels that can used for oncoming vehicle detection.

The system was configured to record video during peak hour traffic 6-9AM, 3:30-6:30PM, and midday traffic between 11-1PM.. A mid-day and afternoon peak three hour portion was selected that contained several instances of stopped vehicles in any of the three lanes. The environmental conditions consisted of partial clouds to complete sunshine.

4.1.3 Site 3 Description

The third site, located north of the Broadway Ave. Intersection along Minnesota State Highway 280 was at a work-zone site with temporary traffic control measures in place compliant with MMUTCD protocol [24**]**. The taper zone was approximately 1000 feet .(304 m). The activity area covered about 2,000 feet (608 m), consisting of an overpass bridge construction, shoulder replacement, and an above grade exit ramp off the highway. The location to collect data was within the work area over 400 feet (122 m) downstream from the end of the taper zone. The location is shown in the site diagram in figure 6. The system was attached to a luminary pole resulting in a lateral offset of 60 ft. (18 m) from the edge of the open single lane through the work zone (Figure 7). The height of the camera was elevated approximately another 15 feet from the roadway, resulting in a camera height of 43 feet. The system was deployed for 10 days at this location, with scheduled recordings between 6-9 AM and 3:30-6:30 PM on mid-week days during the month of September. The location of the construction activities varied considerably within the work area from day to day. The environmental conditions consisted of partial clouds to cloudless sunny lighting. The speed of traffic observed from the video during the period of the experiment was 54.8 ±7.3 MPH (N=184).

Figure 6. HWY 280 work-zone site with camera location (white dot) and activity area (orange) indicated.

Figure 7. HWY 280 work-zone site deployment of portable traffic video data collection apparatus.

Observing the data collected over this deployment revealed two queue formations due to a construction vehicle backing into the open lane. However in both circumstances the queues were too far upstream of the detection area being monitored. Nevertheless, a midday afternoon peak period was utilized to test the occurrence of 'false positive' queue detections. Note that the portable system could not be moved to other upstream locations since the research team was not given access to these areas during the construction.

4.2 Ground Truth Process

The video datasets (3 intersection videos and one work-zone set) were then manually observed to find stopped vehicles and log the video frame number where this event occurred. A reference line extending across the approach lanes to be monitored was demarcated in the near field of the video image. The reference line delineates the beginning, or origin, of a queue. Vehicles that stop downstream of the reference line are not considered. Therefore this location defines the beginning boundary of the queue detection area to be analyzed (i.e., the location of the queue detection algorithm virtual stop bar).

Three other upstream locations within the image were used in order to quantify the queue length and as well as the queue origin. The queue origin reference line and queue marker locations are indicated in figure 8 and figure 9. The point in time when the tail of queue traveled beyond each of the ground truth queue locations was logged until the beginning of queue dissipation. This point in time was defined when the first vehicle began moving and passed through the stop bar detectors and was also tabulated in the ground truth data. This was useful as a reference point during the analysis to delineate queue or stopped vehicle events; in actuality the tail of the queue can continue to grow upstream when vehicles first begin to dissipation, particularly during heavy flow conditions.

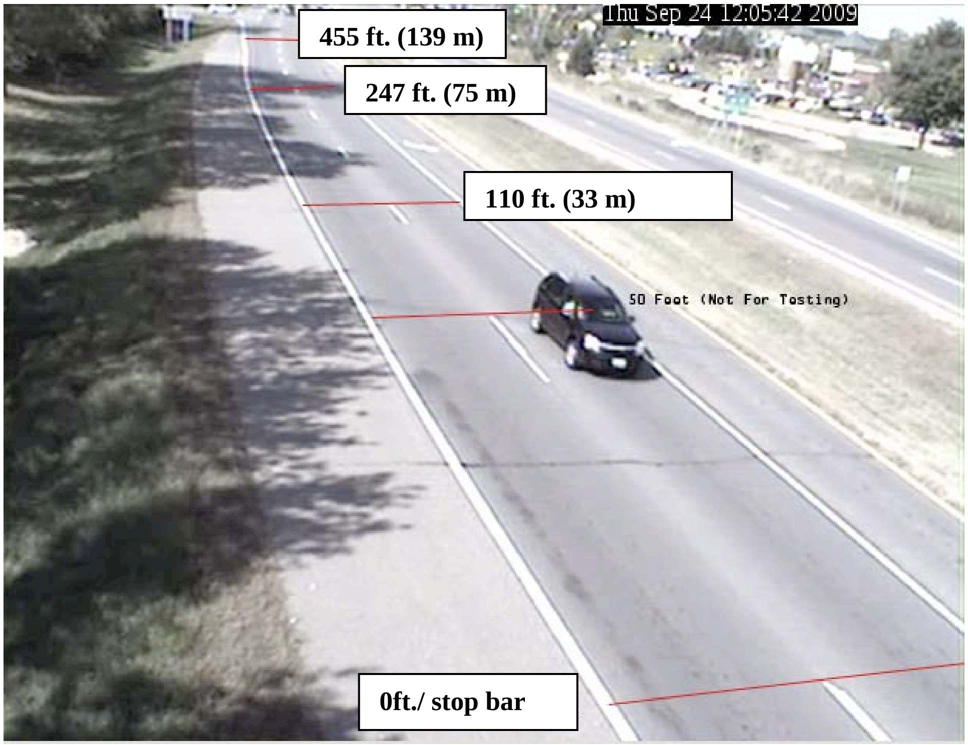


Figure 8. Front of queue and length measures at HWY 55 & Rhode Island Ave. intersection used for ground truth observations.

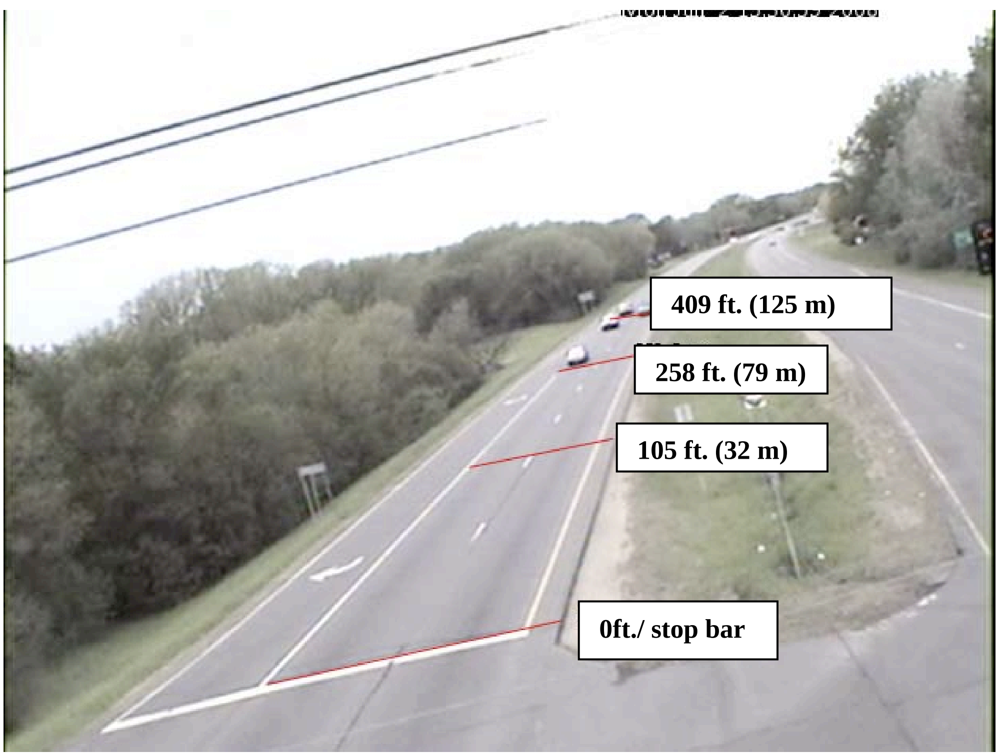


Figure 9. Beginning of queue and length references at HWY 55 & Glenwood Ave. intersection used for ground truth observations.

The ground truth observation process required the determination of the point in time when a vehicle joined the queue. Our observations were based on a similar criterion as in [22]. In their work, upstream vehicles approaching the queue tail are considered ‘stopped’ if they are traveling 5 mph or less. This is acceptable for traffic control operations in order to estimate delay. The authors of that study pointed out that a limitation of manual observation from the video to satisfy this criterion cannot be done precisely. For example, it is possible to observe oncoming vehicles that may be moving faster than this threshold speed particularly when attempting to observe the oncoming vehicles in the far field of the video image. Second, it was observed that vehicles stopped well behind the actual tail of the queue, and then ‘creep’ forward; the time selected was the point just before the initial stop, not the additional time to wait until the vehicle pulled up to the apparent tail of the queue. To conclude, some engineering judgment must be made during the ground truth process; the observations were reliable insofar as quantifying onset of queue events and queue length at the prescribed distance intervals.

Second, our definition of the queue was not lane specific since the algorithm was designed and calibrated to operate over all lanes and does not identify the lane. Therefore, the observed length considers the longest length out of all lanes being detected, and all lanes must therefore have no queue present for the ‘no queue’ or stopped vehicles condition. This was due to the CCD resolution limitations of camera and machine vision hardware (details of this are further described in chapter 6). Such a resulting ‘no queue’ condition is actually a safety benefit because multiple lanes are impacted when rapid queue build-ups occur in all the lanes upstream of the work zone [7].

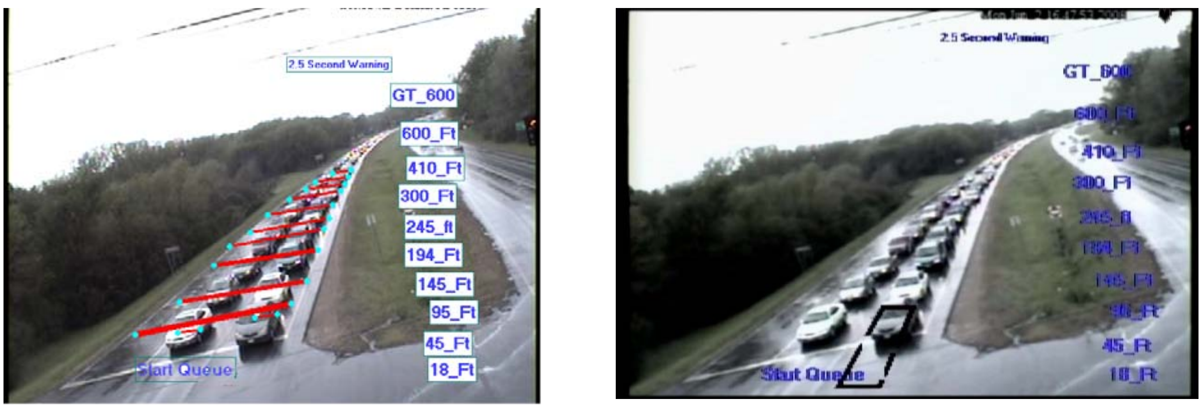
All video time frame timestamps representing the aforementioned events were entered in a spreadsheet for later analysis, with five columns representing the start location (essentially a queue length of “0”), the three intermediate lengths, and the point in time when the queue begins to discharge. A subsample (20 random samples across all videos) of the ground truth data was verified by a second observer as a quality assurance measure.

4.3 Lab Experiment Procedure

The experiments simulated the field deployment by routing the recorded video through the machine vision system, setting up the ladder detectors and recording the algorithm results. Capturing the output video is done using the following method. The collected video is played back on a PC in full screen mode onto a second VGA monitor output. The VGA signal was converted to an NTSC video signal with a scan converter. The scan converted video signal then provided the camera input to an AutoScope Terra NC (No Camera) device. The output of the queue detection algorithm – start of queue, queue length, and the warning alarm trigger state, was presented and overlaid on the Terra video output channel and recorded to disk using an off-the-shelf DVR device (Monsoon Media). Figures 10 through 12 illustrate the input and corresponding processed output video from the Terra, and the detector configuration for each site. The algorithm detector configuration and data collection file were saved out as separate files respectively.

a) Input video overlaid with detector file. b) output video from AutoScope Terra

Figure 10. HWY 55 & Rhode Island Ave. test video detection and the queue detection output.



a) Input video overlaid with detector file. b) output video from AutoScope Terra

Figure 11. HWY 55 & Glenwood Ave. test video detection and the queue detection output.

a) Input video overlaid with detector file. b) output video from AutoScope Terra

Figure 12. HWY 280 video detection and the queue detection output.

The final logic of the algorithm and parameters are stored in a detector program file which is uploaded into the Terra NC device. The process of laying out each of the detectors consisted of locating and scaling the length of AutoScope detector lines to match the ground truth separate queue length and stop bar configuration. The AutoScope required a 'warm-up' period before the data collection proceeded. This period is used by the sensor to determine appropriate thresholds to discriminate background from foreground vehicle movement. In our case, a warm-up period of about 10 to 15 minutes proved to be adequate. After the warm-up period, the input video was reset to the beginning and the algorithm output video collection was started, with a 5 minute calibration window to average slight differences in the sun angle and clouds from the end of the warm-up period.

The same data tabulation process as the ground truth procedure was then repeated to record detector event times that displayed on the AutoScope output video. Frame accurate recording of the event time stamps required converting AutoScope Terra output video recorded from the DVR to XVID MPEG4. In addition to the queue detection times, the time stamp of when the queue warning alarm trigger deactivated (turned-off) was recorded.

False-positive or missed queue detections, and incorrect warning alarm trigger deactivation were also tabulated. The criterion used for determining if the warning turned off incorrectly was based on visual confirmation of jammed vehicles within the detection area. This represents an obvious error in the warning alarm trigger output state generated by the algorithm. More detailed measurements to quantify the warning alarm trigger output performance entailed comparing vehicle speeds immediately after the warning trigger turned off with the vehicle speeds during uncongested flow. These and the other performance indicators will be discussed in the ensuing chapter.

Once all the AutoScope data points were properly tabulated, the original site video used for tabulating the ground truth measures, and the AutoScope output video were synchronized to align a beginning time stamp where the experiment data collection actually begins. This was achieved by observing identical video images of the traffic before the first observed queue event occurred and recording each timestamp. A MATLAB script was written to properly time-order and re-align the manually entered timestamps with the ground truth data.

5 Results

Before discussing results, the criteria for evaluating algorithm performance must first be provided. Then, the results of queue/stopped vehicle detection and the warning trigger output will then be presented. This will be followed by results of queue length detection. Several limitations will be discussed that became apparent as the lab experiments progressed, and provide a basis for future implementation of such an approach.

5.1 Performance Evaluation Criteria

As previously noted, the algorithm produces three outputs: (1) queue detection, (2) queue/stopped vehicle alarm, and (3) queue length. The criteria for evaluating each of these outputs were guided by consulting literature in incident detection [25,26,27]. In essence, the queue 'event' is analogous to an incident event. The evaluation criteria used in these results are summarized as follows.

- Queue detection Performance:
  - Accuracy rate refers to the number of true-positive detections with respect to the total number of observed queues (an indication of sensitivity of the algorithm).
  - Queue detection false alarm rate refers to the number of false-positive detections with respect to the total time period of when the algorithm was in operation.
  - Algorithm response performance is defined using the mean time to detect the onset of a queue relative to the "actual" occurrence of each queue as observed from the ground truth data.

- Warning alarm trigger:
  - There are two events; the instant the alarm trigger is enabled, and the time instant the trigger turns off. The algorithm essentially ties the trigger-on event with the advent of a detected queue. The 'false alarm' rate of the trigger is therefore equivalent to the false alarm rate definition of the queue detection output.
  - A false warning deactivation rate is defined by the number of times the trigger turned off when stopped or very slow moving vehicles were observed to be within the detection area for a detected queue.
  - The performance of the warning alarm trigger-off speed is defined by the observed speed of vehicles at the instant the alarm trigger turns off compared to the speed of vehicles during uncongested flow.

- Queue length detection:
  - Queue length is detected up to the detected start of dissipation. The evaluation of queue length accuracy is based on comparing the number of matches between the maximum length detected and ground truth queue lengths.

5.1.1 Queue Detection Performance

To investigate the limits of the queue detection accuracy, a sensitivity analysis was conducted to tabulate the true positive detection rate while increasing the cut-off time difference between the onset queue time detected by the algorithm and the onset queue time estimated observed manually from the recorded video. The detection accuracy decreased significantly at approximately 2.0 seconds (40% and 55% for Rhode Island Ave., PM and mid-day, and 87% for Glenwood Ave.). As mentioned in chapter 3, the vehicle occupancy threshold for the presence detectors was set at 2.0 seconds and therefore it was expected to see a significant drop-off in queue detection accuracy at or below this value. Between 2.0 and approximately 5.0 seconds, the queue detection accuracy increased rapidly (at 3.0 seconds, 60% and 62% for Rhode Island Ave. intersection, PM and mid-day, and 93% for Glenwood Ave.; at 4.0 seconds, 73% and 83% for Rhode Island Ave., PM and mid-day, and 97% for Glenwood Ave.). At the cut-off difference of 5.0 seconds, the rate of increase in detection accuracy began to level off significantly, with no change occurring beyond 15 seconds, for all three intersection test conditions; the remaining discussion will focus on queues detected for the two aforementioned cut-off values.

The results of queue detection for the intersection sites are summarized in Table 1, for all queue onset detections that were within ±5 seconds from the observed ground truth time. The overall results indicated a true-positive queue detection rate of 84%, with the highest rate occurring at the Glenwood Ave. site (96.7%) and lowest rate occurring at during midday test for the Rhode Island Ave. site (74%). The overall mean queue onset detection time difference was 1.32 seconds ±1.59 seconds (±1 std. dev). Table 2 indicates that onsets of a detected queue event tended to occur slightly later than the ground truth observations. Despite the noted latency, the queue detection onset time is sufficient to raise an alarm trigger to provide timely information for drivers well upstream of the queue [8].

The false-positive alarm rate was very low, averaging 0.143 false detections per hour. As previously noted, the false positive queue warning alarm trigger-on rate is equivalent to the true-positive queue detection rate.

No false positive queue detections were observed at the work-zone site. Note that before the lab experiment was run for this site, the algorithm needed to be tested to ensure it was responding properly. This was achieved by pausing the video for prescribed amounts of time greater and less than the assigned trigger delay, t_d with vehicles covering the stop bar region detector, and observing the detector state output.

Table 1. Algorithm Results for Queue Detections within ±5.0 Seconds of Ground Truth Observations

	Glenwood, PM	RhodeIsland, MD	RhodeIsland, PM	Aggregated results
N, Ground truth queues	60	50	101	211
Number of identified queues detected	58	37	86	181
True positives rate	96.7%	74.0%	85.1%	85.8%
Number false alarms	0	0	1	1
false Warning turn-offs	7	3	2	12
false Warning turn-off rate	12.1%	8.1%	2.3%	6.8%
Mean time –to queue detection (sec.)	1.26	1.57	1.24	1.32
Std. dev of time to queue detection (sec.)	±0.56	±1.92	±1.89	±1.59
Maximum Queue length matches	50	26	39	115
% maximum queue length matches	86.2%	78.8%	45.3%	65.0%

Table 2. Detected Mean Queue Onset Time Results

	*Glenwood, PM	*RhodeIsland,MD	*RhodeIsland,PM
mean	1.26 sec.	1.57 sec.	1.24 sec.
stdev	±0.56 sec.	±1.92 sec.	±1.89 sec.
Paired- T, $p < 0.05$	**T=16.27	**T=4.81	**T=5.88
**$p < 10^{-4}$			

Note that the remaining 18 'missed' queue detections occurred within fifteen seconds and primarily for the Mid-day (MD) data set at the HWY 55 & Rhode Island Ave. site (Table 3). Further observations of the video revealed that there were many instances when the first observed stopped vehicle in the far exclusive left turn lane were not completely landing on the stop bar detectors, which correlated with late queue onset detection. The number of false warning alarm trigger turn-off conditions remained the same, indicating that the performance of the warning alarm trigger output was independent and robust to differences in mean time to detect the queue

Table 3. Algorithm Results for All Queue Detections (within ±15.0 Seconds of Ground Truth Observations)

	Glenwood, PM	RhodeIsland, MD	RhodeIsland, PM	Aggregated results
N, Ground truth (GT) queues	60	50	101	211
Number of GT detected	59	47	93	199
True positive rate	98.3%	94.0%	92.1%	94.3%
*Number false alarms	0	0	1	1
false Warning turn-off	7	3	2	12
false Warning turn-off rate	11.9%	6.4%	2.2%	6.0%
Mean time to queue detection (sec.)	1.15	3.13	1.66	1.83
Std. dev of time to queue detection (sec.)	± 0.99	± 3.78	± 2.83	± 2.81
Maximum Queue length matches	52	30	43	125
% maximum queue length matches	88.1%	63.8%	46.2%	62.8%

5.1.2 Warning Alarm Trigger Performance

The queue warning alarm trigger turned off when traffic flow returned to an uncongested state. This was confirmed by watching the video as well as comparing the speeds of vehicles immediately after the warning trigger turned off with an estimate of vehicle speeds during non-queue conditions. The false warning deactivation rate as indicated in table 1 was approximately 6.8%. The Glenwood Ave. site contributed to the majority of these errors. The Glenwood Ave. and HWY 55 site experienced more periods of heavy congestion than Rhode Island Ave. and generated longer queues. Figure 13 compares uncongested speeds, observed well after the queue dissipated, and the vehicle speed immediately after the warning trigger turned off on Glenwood Ave. The trends in speed differences between indicate that vehicle speeds were approximately 5 MPH less than uncongested speeds at the point where the warning trigger turned off ($V_{trigger\text{-}off}$ = 41.1 ±6.7 MPH, T=4.0, $p < 1 \times 10^{-4}$).

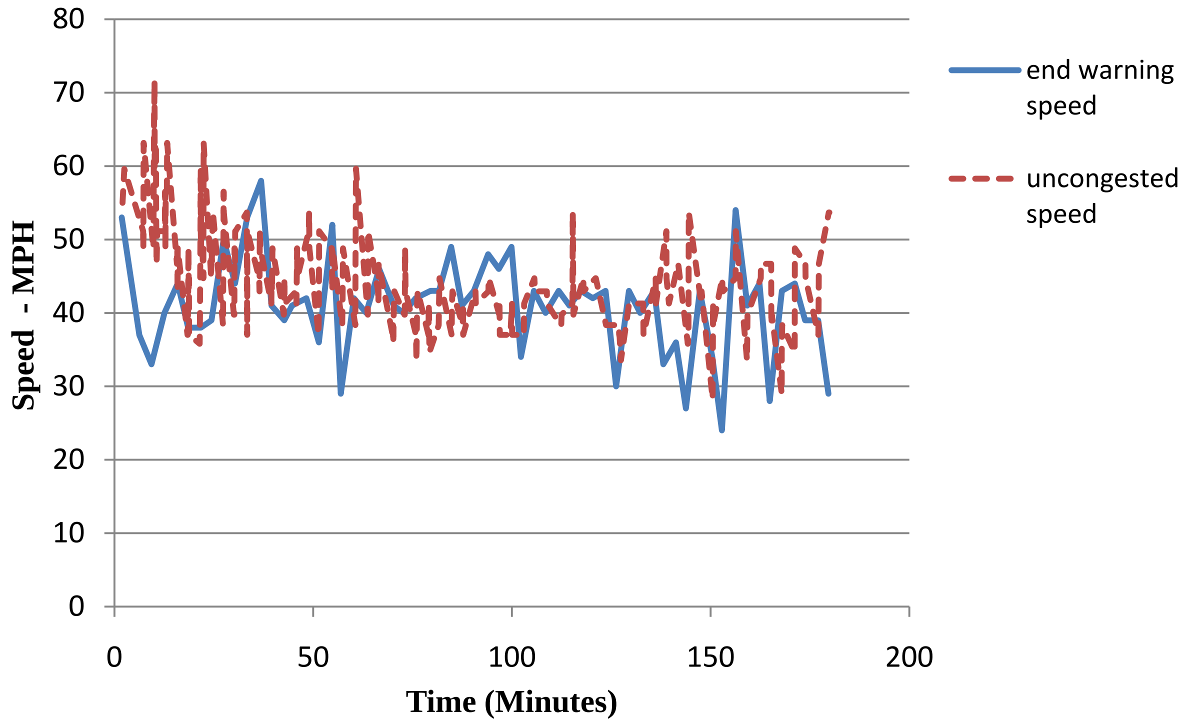


Figure 13. Observed uncongested speeds vs. observed vehicle speeds immediately after warning trigger turn-off at HWY 55 & Glenwood Ave. site.

5.1.3 Queue Length Performance

Queue length measures were reasonably accurate for the Glenwood Ave. test site but less accurate for the Rhode Island Ave. site. Part of the error was due to a tendency for the AS detections to overestimate queue length for the Mid-day (MD) Rhode Island Ave. and Glenwood Ave. PM experiments (Table 4). The overestimate of queue length indicates the detectors may be too 'sensitive' to the queue detection length for some of the samples. This was confirmed by visual observation of the video. The left lane Rhode Island Ave. site also contributed to the errors. In some cases the queue detectors failed to trip in this lane. The camera angle particularly for the far left lane produced vehicle movements with a large component of lateral movement over a portion of the detectors, instead of traveling perpendicularly over them, which may have contributed to some of the observed misfires.

Table 4. Comparison of Average Detected vs. GT Queue Length

	Glenwood, PM		RhodeIsland,MD		RhodeIsland,PM	
	*AS	GT	*AS	GT	AS	GT
Mean (ft.)	394.1	378.4	120.6	67.3	95.8	84.5
std	±62.5	±85.0	±166.5	±88.1	±128.0	±106.2
Paired- T, $p < 0.05$	2.19, $p < 0.033$		2.96, $p < 0.0054$		0.71, $p < 0.4777$	

5.2 Results Summary and Discussion

The results indicated an overall queue detection onset accuracy above 85%. Out of all hours tested, one false positive occurred. Visual observation found nothing obvious that would cause such a case to occur. The work-zone site, although no queues were detected during the deployment, also produced no false positives, regardless of bottle neck conditions upstream or downstream of the detection area. False positives are an important operations indicator of algorithm performance because they erode credibility that the information provided to drivers is meaningful.

Algorithm queue detection performance for the Rhode Island Ave. intersection site indicated a reduction in detection accuracy of about 10% accompanied by larger queue detection onset delays compared to the HWY 55 & Glenwood Ave. site. Two reasons for this were determined when examining the videos. First, the oblique azimuth angle crossing the lanes produced a camera view that exposed between-vehicle gaps at jam density. The stop-bar region consisted of additional detectors on each lane and image corner to mitigate this problem (figure 10). Vehicles which only partially occluded the detector tended to increase stopped vehicle detection latency. Detection of stopped vehicles that partially remained in the image (lower right edge) produced a similar effect.

Monitoring headway times between vehicles to turn off the warning alarm trigger provides a viable alternative to using the machine vision speed detection which proved to be error prone under typical road side deployment configurations where more optimal above lane camera views cannot be readily achieved [12]. A detailed analysis of the first intersection site, which contained several instances of very large queues that grew beyond the detection area, indicated the warning trigger turned off at vehicle speeds moderately or slightly below the uncongested vehicle speeds that were measured between the observed queue conditions. Very rarely were false warning trigger deactivations observed. This suggests that the algorithm produced warning trigger output is robust over varying traffic conditions even when the queues grew beyond the detection area of the sensor.

Queue length detection accuracy was significantly affected by deployment configuration outlined in the second site. Some reasons for the larger discrepancies at this site can be hypothesized. For cases of 'over-shooting' the queue length, the global time delay may be too short for the detectors in the far field of the camera. In a theoretical analysis from [28], the effective occupancy time increases due to camera perspective affect of approaching vehicles passing over a detector in the far field of the camera. However, their analysis does not consider vehicle behaviors during rapid queue formations, or other affects such as variability in detecting foreground motion from moving vehicles, or vehicle motion which is not perpendicular over the detector. As discussed previously in chapter 4, vehicles were observed to stop well behind the tail of the queue before gradually creeping forward. The headway gaps between vehicles during these circumstances also contributed to queue length detection error. Further research is warranted to understand if increasing time-on-detector thresholds as a function of distance can improve the current queue length detection algorithm. Another issue is that the presence detector area size as a function of distance from the camera might be considered when setting up the detectors.

From these results, the following deployment recommendations should be followed in order to ensure good performance: (1) Aligning the camera azumith angle with the roadway as much as possible must be considered with respect to the location of the stop bar region even if this necessitates a reduction in queue length detection area, since it is paramount to first accurately detect the onset of a queue, (2) A stop bar must be completely visible and projected horizontally across all lanes to be monitored, (3) if such a portable system is deployed at a lateral distance greater than one lane from the lane edge, monitoring more than two lanes may be problematic due to cross-lane occlusion.

Lastly, determining queue detection true positives requires a criterion to select an acceptable maximum limit of queue detection onset time. The onset time dictates the response latency of the warning system. The determination of this criterion depends on appropriate engineering judgment that considers site characteristics (geometry, stop distance sight lines, traffic volumes, lane closure configuration), and desired safety objectives.

6 Algorithm Design

As introduced and discussed previously in chapter 2, the algorithm produces three outputs. The first output is a detection event of a 'stopped' vehicle, or start of a queue. The second output is an alarm trigger that can be transmitted to an upstream warning device to warn drivers of an impending queue. The third output is an estimate of queue length. The formulation of the detector logic to implement the queue detection, followed the detector logic used to control the trigger alarm output is described next.

6.1 Queue Detection Logic

The premise of the algorithm is that vehicles traveling slowly over a given presence detector will occupy the image region of the detector for a length of time proportional to speed and their distance from the camera [28]. The algorithm consists of a real-time regression ladder approach, which utilized Boolean logic (logic operations) and occupancy for estimating queue length and stopped vehicle events. The queue detection was done as a per-approach detector set rather than a per-lane set in order to minimize occlusion and pixel resolution errors. Distance perspective constrains vehicles further from the camera to appear much smaller in the image plane than when the same vehicle is closer to the camera. Since the camera has a finite resolution, foreground far objects such as vehicles must be discriminated with fewer pixels.

Here, the effective queue length signifies the queue length from a queue origin location defined by the user in a visible portion of the observed camera image. If the origin of the shockwave begins upstream of this user defined stop bar detector region, the stopped vehicles cannot be detected because the stopped vehicles will land upstream of the stop bar detectors.

Figure 14 illustrates the locations of the 'ladder' of trip wires used to detect queue length for the calibration experiments. The horizontal bars are presence detectors, which are triggered by vehicle occupancy. The threshold time, t_d, required for these presence detectors to be triggered as active by defining when a vehicle is 'stopped' over the detector must then be determined. Details describing the use of Boolean functions are described next.

Figure 14. Queue detection and length configuration for experimental determination of threshold time on detector value.

In order to implement the queue detection algorithm, Boolean functions were used to build state-machines (figure 15). The state-machines can be implemented by setting the time-on-detector delay, or an extension time of the Boolean function. As an example, suppose a presence detector is attached as an input to a Boolean function with a delay time of 1 second. Until the detector remains occupied for at least one second, the output from the Boolean logic function is zero. If instead, an extension time of 1 second is specified, the output of the Boolean function will remain 1 until the detector is off for at least 1 second. Referring back to the algorithm, to couple the ladder detection with the stop bar detectors, each presence detector m_j in the ladder is attached to a state-machine, which is used to implement the delay time t_d. The "1" output of the state machine function is attached to the input of an AND-Boolean logic function, for the queue length detector m_j. The sequential ladder is implemented by attaching the output of the AND-Boolean logic function of the previous detector, m_{j-1}, as a second input to the AND Boolean logic for m_j. The output of each AND function, d_j, for queue length presence detector m_j drawn on the image, was wired to a label detector to display a length value on the output video from the AutoScope Terra system. Under actual deployment situations, the output state d_j of each queue length detector m_j is routed to a TTL I/O bit on the TS-1 front panel connector that can be interfaced to a separate communications device. The length information can then be transmitted to upstream warning devices.

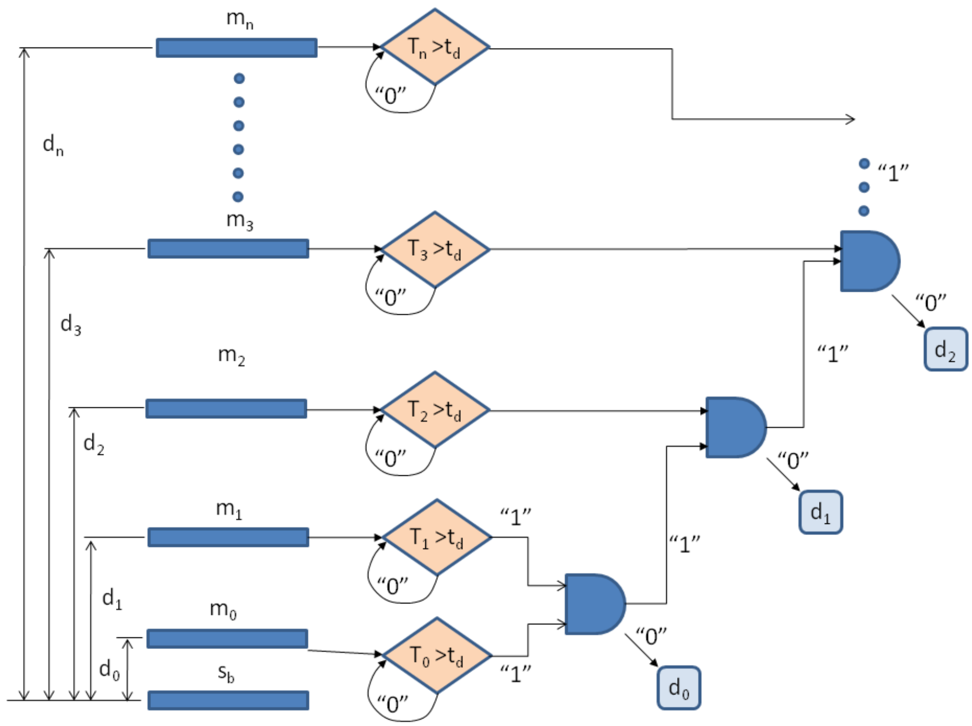


Figure 15. Queue detection ladder logic using 'triggered' presence detection.

A suitable threshold value of t_d was determined as follows. Ground truth measurements of queue length were obtained at the point when the first vehicle crosses the user defined stop bar. This signifies the beginning of queue dissipation. This event was obtained by placing a presence detector just upstream of the signalized intersection stop bar shown in figure 14. Then, many experiments varying t_d by 0.1 seconds were run to compare the relative accuracy with respect to the ground truth observations. Each threshold experiment was repeated 3 times in order to compute each result. As mentioned previously, a two hour portion from a morning rush hour at the HWY 55 & Glenwood Ave. intersection site was used for this process.

A minimum at $t_d = 2.0$ seconds corresponded with the ground truth values 97% of the time for queue lengths up to approximately 450 feet, for N=61 queue samples (table 4, not all experiments are shown in the table). In this case, the ground truth comparison was done at the beginning of queue dissipation. This time-on-detector occupancy value was used for the remainder of experiments.

Table 5. Queue Length Detection Results

Threshold t_d (seconds)	% correct queue length
0.5	77.1
1.0	77.1
1.5	85.2
1.8	88.5
1.9	86.9
2.0	96.7
2.1	90.2
2.3	88.5
3.0	83.6
3.5	72.1
4	70.4

6.2 Queue Warning Alarm Trigger Logic

The start-of-queue detection is used to control the onset of an alarm trigger that can be transmitted to an upstream warning device; if there is no start-of-queue detected, the alarm will not be triggered. Additional logic needed to be formulated to reset the alarm trigger when prevailing traffic conditions restores to the previous conditions before the queue was detected. This was achieved by monitoring headway times between vehicles. The implementation is described next.

The headway gap breakpoint as discussed previously in chapter 2 is implemented in the algorithm by adding an extend time of 2.5 seconds to the presence detectors in each lane, near the stop bar region, and attaching a Boolean function which triggers TRUE when the time between occupancy detections exceeds this value (figure 16). Each presence detector was attached to "OR" logic functions that were assigned a delay value, t_d , of 5 seconds (to ensure that one or more vehicles did not stop momentarily), with the extension, t_e , (delay to turn off) of 2.5 seconds to represent the gap headway time threshold. As elucidated in the previous example, when a vehicle leaves the detector, the state remains "1" until the time *off* the detector exceeds the threshold, t_e . The output from each of the lane state machines is then routed to an input of a Boolean "OR" function. The output of the "OR" function represents the algorithm trigger warning output. The warning trigger output can be configured to route through an Open Closure TTL signal through the AutoScope front panel TS1 I/O port. The stop bar region detection output, S_b, is also routed to the input to the "OR" function. This was done as an extra fail-safe to ensure the alarm trigger will not reset if the stop bar was activated; for example, if a queue or stopped vehicle lands on the stop bar region after one of the extend-times from the per-lane detector is exceeded, the warning alarm trigger will still remain on. For our experiments, rather than utilizing the I/O port, the alarm trigger output state was represented visually by attaching a label detector to the output; it then displays "WARNING" when the output of the OR Boolean function state is "1" and is not displayed otherwise, thus emulating the warning signal.

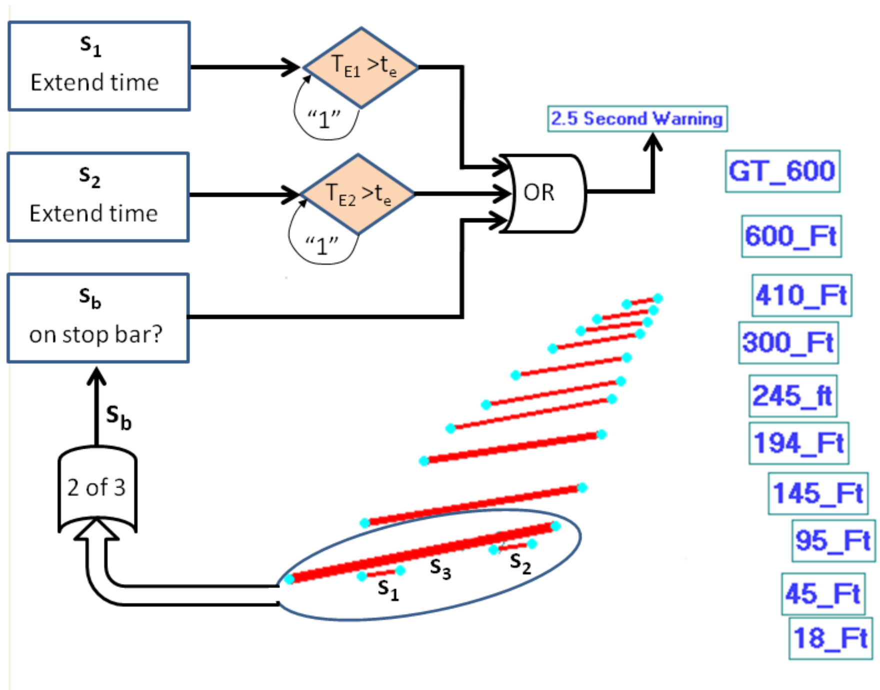


Figure 16. Presence detection logic used to monitor gap times between vehicles and the virtual stop bar at HWY 55 & Glenwood Ave. site.

To detect queue onset, a stop bar region is constructed using multiple presence detectors. Referring to Figure 16, the stop bar region is comprised of the lane specific presence detectors, S_1 and S_2 in addition to the presence detector that is placed over both lanes being monitored. Then, a "M of N" logic function is used which will output "1" (e.g., "true") if, any two of the three detectors (S_1 , S_2 , S_3) exceeded the threshold delay time, t_d previously described. The redundancy was required to address cross lane occlusion that occurred when monitoring multiple lanes.

The HWY 280 site provides a more simplified case since single lane monitoring does not produce cross lane occlusion; a single presence detector pair was used for the one lane. The warning trigger logic was identical to the intersections.

The detector layout on The HWY 55 & Rhode Island Ave. intersection proved to be substantially more challenging than the other two sites (Figure 17). On the first attempt, a presence detector with the delay state t_d, is placed across each lane being monitored, in addition to a presence detector, S_1, S_2, S_3, in each lane as in the other intersection, with the "M of N" logic function. In this situation, the extend time (e.g., gap time tolerance) is monitored for three lanes instead of 2. However, it was observed that occasionally the stopped vehicles would 'miss' these detectors. To account for vehicles that did not stop over the detectors, a second stop bar, S_6 in Figure 17, was placed within an approximate vehicle length upstream and ANDed together with the "M of N" Boolean logic function which grouped detectors S_1 , S_2, … S_5 (e.g, M=5, and N=2); If any two of the detectors exceeded the threshold, the output of the M-of-N will be "1". Second, cross-lane occlusion inadvertently triggered the specific lane detectors. To remedy this, the lane specific detectors, S_1, S_2, S_3 were aligned longitudinally with the lanes instead of orthogonally across them. They were also then positioned closer to the top of the lane to avoid cross-lane occlusions.

Figure 17. Presence detection logic used to monitor gap times between vehicles and stop bar at HWY 55 & Rhode Island Ave. site.

Under a deployment situation, the alarm can then be transmitted (wirelessly) to a remote driver information warning device upstream of the detection area, for example a variable message sign, or flashers. The location of the warning system must be determined using engineering judgment and other human factors considerations. The algorithm presented requires no extra hardware processing to implement, making potential actual field deployments cost effective and realizable. The next chapter will discuss the results of the experiments.

7 Design Modifications for Wireless Field Deployment

The design of the current apparatus can be modified to allow for real-time queue detection and wireless transmission using many techniques. Although a complete and actual deployment was beyond the budget and scope of the current project, the design modifications to achieve this are presented below. Individually, the components were tested in the lab to understand if they would be suitable for such actual deployments in the future. The Terra Rack Vision is integrated within the base enclosure of the portable apparatus, with the mast camera providing video input. As mentioned previously, the warning trigger output and queue length measurements can be directed to I/O channel bits on the TS1 port on the front panel of the Rack Vision unit as shown in figure 18. The open collector TTL I/O data can directly be communicated to portable message signs (PMS) using 900 MHz line of site radios (www.intuicom.com). Four I/O lines can each be transmitted/received by each radio pair ($4,400 = 2 x $2,200/radio).

If field deployment constraints complicate the deployment of the radios as above—for example the line of site between the upstream road side warning display device and the sensor is insufficient, then other wireless options can be used. We tested the utility of 3G communication with the current portable apparatus. Municipal WIFI services also can be used to transmit the data. However, very few municipalities support such a service.

A field test was conducted to provide insight to the power requirements that would be needed to sustain continous operation of the device, to provide surveillance and queue detection. A 3G field test determined that an additional 3.6 Watts are consumed (300 milliamps at 12 volts) during upload data transmission speeds of 39 Kbytes/sec (312 kbps) using a CradlePoint router and DC/DC converter. With the particular machine vision hardware used, the video can also be streamed live back to a remote traffic operations center that is responsible for monitoring the work zone and road facilities. Although a Terra system was not available for field deployment for this study, the latter capability was duplicated in the field test by streaming video from a remote intersection back to the laboratory continuously for 41 hours on a single 12 Volt deep cycle 55 Amp-Hr sealed gel lead-acid battery. The Terra streams MPEG4 video which was duplicated with a low-cost video streaming device (Monsoon Media) which consumed 800 to 900 milliamps at 12VDC during operation. Note that the Terra consumes approximately 5W at 12VDC (420 milliamps), less than the field configuration tested so we would expect a similar operational period. Wireless transmission of the data was ensured during this period by continuously leaving the viewer (VLC) open. If transmission is dropped for more than 2 seconds, the connection closed and therefore the video no longer displays.

The bandwidth for transmitting the alarm trigger is significantly less than for transmitting video data. The detector output from the current algorithm could be packed within one byte (alarm trigger = 1 bit, 7 other bits can be used to store detector length output states). An output rate of 10 bytes/sec. would be more than sufficient for this application. Figure 18 illustrates a proposed cost effective hardware configuration for transmitting the digital I/O to a message sign (for example, a relay activated VMS, with prestored messages). The red double lines represent IP communication over Ethernet.

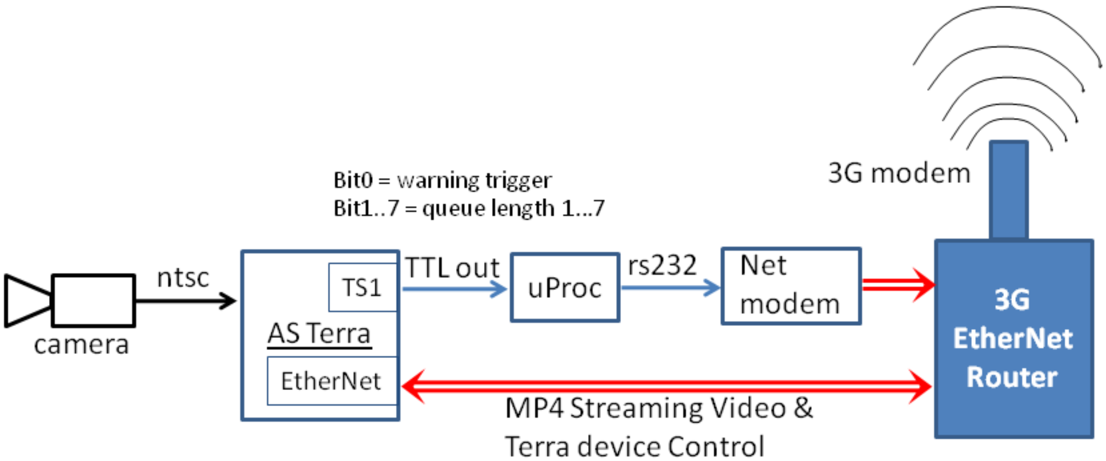


Figure 18. Hardware communication design for wireless transmission of detector and video surveillance data from the portable traffic measurement system.

An ARM7 (Amtel) single board micro computer (SBC) (ARMmite Pro, $29.00) can be programmed to read the I/O ports and translate the bit state to a RS232 serial byte-formatted output which then is sent through the wireless Ethernet using a low-cost RS232 serial to Ethernet modem, configured in bridge mode (for example, Multitech MTS2EA). The Terra RackVision unit is controlled directly over Ethernet.

On the upstream receiving end simply reverses the process in figure 18; the Net modem receives the serial data through the 3G EtherNet Router, with the microprocessor reading the received serial byte and multiplexing the bits back to the original open-collector TTL I/O bits output on the digital I/O ports, which can then be used directly by the VMS sign controller to trigger a pre-stored warning message (see for example, pp. 44-50 in the ADDCO controller manual for portable roadside Variable Message Signs, model DH250-FM).

To conclude, reliable, cost effective, wireless deployment to enable real-time transmission of the queue detection alarm, as well as remote surveillance of video data and machine vision sensor control, can be achieved using off-the-shelf components. The approach proposed here enables rapid deployment without concerns for line of sight, antenna adjustment, or multiple point-to-point communication relay stations. Note that service (and quality of service which determines deterministic data transmission bandwidth) is obviously dependent on provider coverage but the authors believe that this will continue to rapidly increase into the foreseeable future especially along major roadways within urban areas.

8 Conclusions and Recommendations

Timely and accurate warnings to upstream drivers potentially will reduce secondary crashes that arise when drivers unexpectedly encounter the queue tails upstream of work-zone areas. The objective of this study were to test the feasibility of a previously developed low-cost, portable, video-based traffic data collection device to detect and follow the progression of the tail of the queue and trigger an alarm that can be transmitted to warning devices located upstream of the device. Intersection sites were only selected because they provided frequent queue formations; the limited budget available did not allow deployments at more work zones that require lengthily deployments for incident recordings, queue formation for queue detection. In this feasibility study a logic trip-wire presence detector algorithm requiring no secondary processing hardware, minimal site preparation and calibration procedures, implemented on a widely available machine vision device was evaluated using traffic video data collected from two high-volume urban arterial intersection sites, and a work-zone site using a rapidly deployable, stand-alone, wireless, video-based traffic surveillance prototype. The algorithm provided real-time stopped vehicle detection (resulting from queues), a warning alarm trigger that can be used by upstream driver warning devices, and the length of the queue. The false positive rate for identifying queues of one or more stopped vehicles were very low for these experiments. The onset and termination of the warning alarm trigger was consistent over all experiments.

The second test site was used to test affects of non-ideal lateral view angles across three lanes of traffic on queue and stopped vehicle detection accuracy over three lanes of traffic. Queue length detection proved more challenging especially for situations where more than two lanes were being monitored, as done in the first test site, and the lateral camera offset produced a large lateral viewing angle to the front stop bar. Such a situation could occur when available roadside infrastructure such as luminaries or static road signs that can be used to attach the device are located at shoulder locations far from the desired lanes to be monitored; for example two near side discontinuous lanes and a far side continuous lane coming into the work-zone taper area.

Several recommendations for future improvements and strategies to ensure optimal algorithm performance can be considered in light of the aforementioned results from the second site. For others to utilize the stopped vehicle/queue detection, a reliable 'start of queue' detection area should be located in the bottom region of the image where a stop bar can be drawn horizontally completely crossing the lanes to be monitored and far enough upstream to mitigate cross-lane occlusion. Cross-lane occlusions were somewhat problematic for sensing queues in any of three lanes because moving vehicles triggers a stop bar detector defining the stop bar region. Adding additional detectors and setting time-on-detector thresholds to be above the calibrated occupancy delay threshold value reduces the problem but increased the latency time to detect queues somewhat. Therefore, if the system must be deployed with a lateral offset exceeding two lanes, monitoring two lanes of traffic (with the camera offset equal to 25 ft (7.6m) from the center near lane) might be considered the practical limit for this approach. To reiterate, these recommendations were based on the results of the second intersection test site.

Third, such a portable apparatus may require additional hardware for some work-zone sites since appropriate infrastructure to attach the system on the roadside is lacking. For these cases, an efficient, cost effective solution would utilize a trailer-mounted base, as a suitable deployment enhancement.

As noted earlier, queue dissipation and subsequent return to previous uncongested traffic flow conditions is dependent on actual upstream demand, which cannot be measured by a single system. Instead the algorithm utilized a traffic flow measure that was utilized by Liu et. al (2009) to determine the point of queue dissipation where traffic flow conditions are restored to previous non-queue state. The results indicated that this approach is reliable.

The warning trigger performance was relatively robust even for queues which extended well beyond the detection area as observed by the Glenwood Ave. intersection test site**.** Work-zone queues can rapidly grow to lengths, which significantly longer than the observed conditions used for the intersection sites tested. Under such circumstances, the queue tail will continue to propagate beyond the detection area of the machine vision sensor; traffic flow may be detected as being restored when in fact, upstream it is not. As mentioned earlier, the system cannot detect queues that start beyond the designated stop bar. Multiple systems would need to be deployed upstream to extend beyond observed or expected queues tail locations if the system were to warn upstream drivers of a propagating queue tail.

One possible improvement to the algorithm is to design and test trigger delay occupancy threshold time that is varied as a function of the detector distance from the camera. The approach would integrate occlusion and gap headway analysis similar to [28] with time headway distributions characterized within different actual work-zone configurations [29]. Understanding distribution of the gap times between vehicle types (trucks/buses and private vehicles), for example could then be used to estimate expected distribution of occupancy time over the detectors during non-queue traffic conditions [29], in order to minimize false positive queue identifications. The data itself, which could be collected with one or more of the portable traffic measurement systems, would be useful for practitioners to guide new sensor design requirements and further understand traffic dynamics in work zones in order to improve work-zone safety and safety mitigation measures.

To conclude, the portability of the system and algorithm approach proved to be feasible. Further study is warranted to determine utility and performance in actual work zones. Such deployments would require collecting data from work zones with different characteristics over an extended period in order to harvest sufficient queue events under different traffic dynamics. In this regard coordination with construction crews to allow the portable system to be moved to different locations should be established. And as noted above, multiple systems that provide sufficient coverage from the start of the buffer or work area, through the end of the taper zone would be required in order to catch queues resulting from rapid stops or crashes within the work area (Garber and Zhao, 2002). The number of systems is highly dependent on the nature of the road facilities and work zone that would be studied. For high-speed arterial traffic (55 mph, for example) Minnesota Manual on Uniform Traffic Control guidelines recommends minimum taper zones of 700 ft. and one or more advanced warnings starting at 750 ft. intervals beyond the taper [24]. These are minimum requirements. Considering the present length of the detection area studied here in, three systems would be needed for testing, as well as portable observation camera placed well upstream to provide data on queue length dynamics well beyond such a test area.

Regardless of traffic sensing technology used, the emergence of high bandwidth cell carrier communication may prove to be a cost effective and scalable alternative to more expensive point-to-point wireless communication equipment used in practice to transmit warning alarm trigger states to one or more upstream warning devices (VMS, flashers, etc.). It also mitigates issues with line-of-site requirements which may be impossible to overcome for some deployments.

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