MODELS FOR QUANTTITATIVE ASSESSMENTS OF VIDEO DETECTION SYSTEM IMPACTS ON SIGNALIZED INTERSECTION OPERATIONS

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Total Text: 3725
Total Figures and Tables: 13
Total Words: 6975

Submitted for Presentation and Publication at the 86th Annual Meeting of the Transportation Research Board

November 10, 2006

ABSTRACT

The paper presents various models for quantitative assessments of the impacts of video detection system applications at signalized intersections. The models are developed to mainly address the occlusion issue, one of the unavoidable phenomenons associated with video detection systems. Two types of occlusion scenarios and their potential impacts on intersection operations are analyzed based on typical parameter values and detection setup. The paper also addresses the limitations of video detection systems on providing advance detection. Occlusion in video detection systems can result in missing detections, false detections, and increased detector presence time, thus may affect intersection operations under actuated control. It is found that missing detections due to occlusion to the following vehicles are generally less than 5% when the approach volume is under 600 vphpl and the percentage of trucks is under 5%. At this traffic volume level, additional phase extension time caused by occlusion is generally less than 3 seconds. To minimize false detections due to occlusion to adjacent lanes, the horizontal offset between the camera and the travel lane should be at the minimum, with an ideal mast-arm mounting and positioning to the division line between the lanes. Due to limitations on the achievable camera height and mounting angle, using one camera is found to be difficult to satisfy the required advance detection for speeds above 50 mph. It should be noted that the paper does not address the impacts of physical limits of video detection systems such as pixel size, grayscale depth, lightning and shadows.

Keywords: Video detection, occlusion, signal operations

INTRODUCTION

Video detection systems possess several advantages over the traditional inductive loop detectors, such as easy installation, low maintenance costs and less disruption to traffic flow during intersection reconstruction. Despite these advantages, video detection systems also exhibit some unavoidable issues, one of which is occlusion. This paper discusses these issues and provides quantitative evaluations on the potential impacts on traffic operations at signalized intersections.

Occlusion is one of the major issues in video detection systems, which stems from a so-called *parallax* effect (*1*, *2*, *3*). Parallax effect refers to situations where measurement of distance relies on field of view (*4*). Parallax effect results in larger perceived images than their actual dimension. For example, video detection systems typically perceive vehicles with larger dimensions in length and width than their actual size. The perceived larger vehicle size can also result in various occlusion scenarios (*5*, *6*, *7*). Occlusion to a detector can result in increased detector occupancy, and can result in false detections when no vehicles actually exist at the detector location. Occlusion to a following vehicle can also result in missing counts.

Several studies have been conducted regarding video detection system applications at signalized intersections. Abbas et al. (*8*) developed a set of guidelines on deployment of video detection systems at signalized intersections, including detection design and configuration for design speeds less than 60 mph. A model to calibrate the effective vehicle length by the video systems was presented. Zheng et al. (*9*) applied video detection systems to detect cycle failures at signalized intersections. Applications of video detection systems have also been attempted to measure vehicle delays and other performance measures at signalized intersections (*10*, *11*, *12*, *13*). Grenard et al. (*14*) evaluated the performance of video detection systems at signalized intersections from the point of view of comparing differences of detector occupancy between video and inductive loops. Tian et al. (*2*) developed a model to calibrate the perceived detector location by video detection systems based on various geometric elements. Potential applications of the model were cited, but no detailed quantitative evaluations were conducted.

This paper provides a set of models which can be applied to conducting quantitative evaluations on the various issues related to video detection system applications at signalized intersections. It is not the intent of the authors to provide general quantitative results of the impacts, but rather to provide modeling tools and to demonstrate their applications if case-specific analyses are desired. The models focus on addressing various occlusions and their potential impact on signal operations, including impact on actuated signal operations, advance detection, missing detection, and false detection.

TYPES OF OCCLUSION

Practically speaking, occlusion is an unavoidable phenomenon for video detection systems. Because the magnitude of occlusion depends on several factors, minimizing occlusion has become a major objective while designing video detection systems. Occlusion can be categorized as either longitudinal occlusion, horizontal occlusion, or a combination of both, as illustrated in Figure 1 and Figure 2.

Longitudinal occlusion (Figure 1) occurs along the vehicle's travel lane. The consequence of longitudinal occlusion is perceived longer vehicles. As the camera mounting height reduces, the magnitude of occlusion increases until differentiation among vehicles becomes impossible. In this case, all the vehicles would be perceived as one long vehicle. Horizontal occlusion occurs when the camera is offset from the travel lane. The consequence of horizontal occlusion (Figure 2) can cause false detection when occlusion to the adjacent lane occurs. As shown in Figure 2, a false detection may occur when the left-turn phase is triggered by false detector calls when left-turn vehicles do not actually exist.

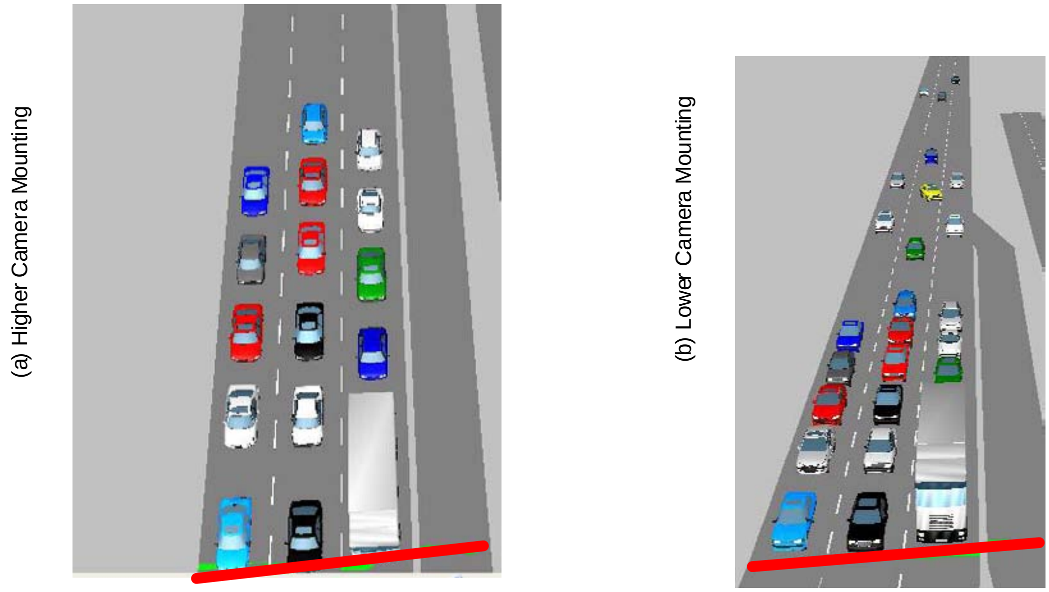


Figure 1 **Longitudinal occlusion**

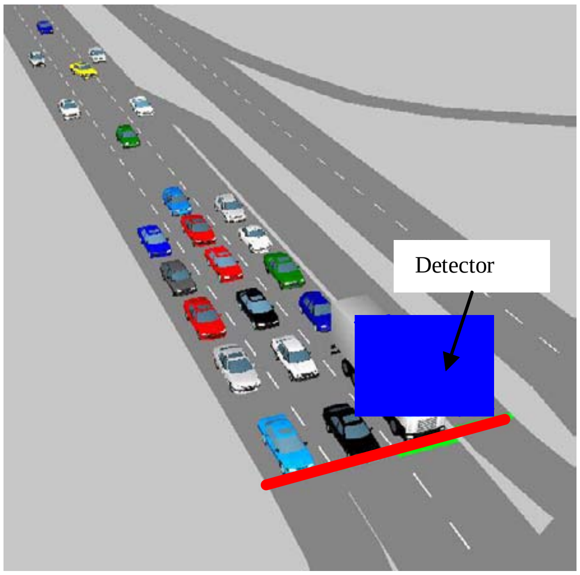


Figure 2 Horizontal occlusion

Several factors have been identified to affect occlusion. These factors include camera location defined longitudinally and horizontally, camera height, detector length and width, and vehicle dimension (length, width, and height). A complete geometric modeling approach to address the relationship among these factors should be pursued from a three dimensional perspective. Tian et al. (*2*) developed a generalized model called *video-image distance* model, taking into consideration all of these factors. The model was originally developed for calibrating *video-image distance*, a distance perceived by a video system, for the purpose of speed measurements. In this paper, models were developed based on simplified assumptions, such as uniform vehicle dimension and detector layout. Such simplifications can still provide valid results from the practical point of view. Figure 3 illustrates the major geometric elements to be addressed in the models.

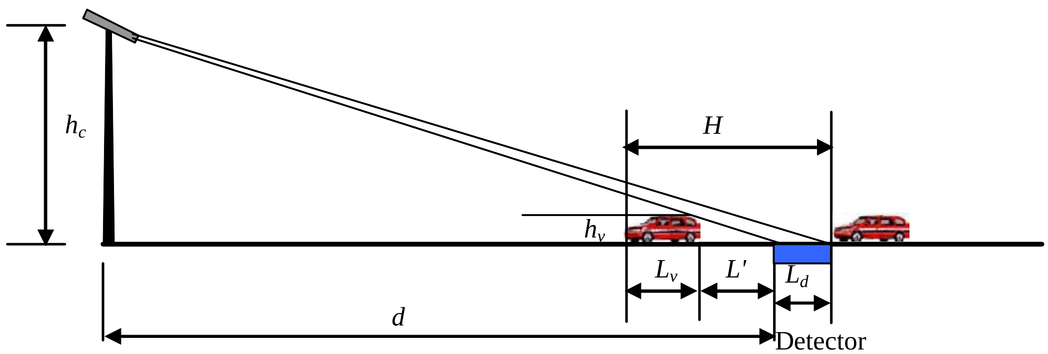


Figure 3 Illustration of geometric elements

The geometric elements shown in Figure 3 include the distance between the detector and the camera, d; the height of the camera, h_c; the length of the vehicle, L_v; the height of the vehicle, h_v; the length of the detector, L_d, the space headway, H, and the occlusion distance, L'. L' represents the magnitude of occlusion and can be used to explain the various occlusion effects. For example, the sum of L_v and L' can be interpreted as the perceived vehicle length by video detection systems. The detector would be continuously occupied until the rear end of the vehicle leaves the detector L' distance away. If another vehicle follows the subject vehicle at $L' + L_d$ distance or closer or if $L' + L_d$ is less than 1 pixel, video detection systems would consider them as one vehicle. Equation (1) can be established to address the relationship among some of the key elements:

$$L' = d\frac{h_v}{h_c} \qquad (1)$$

Equation (1) indicates that the further the distance is between the camera and the detector, the higher degree of occlusion would occur, which means that less accurate results would be achieved as detection zones are located far from the camera. Equation (1) also indicates that more occlusion could occur with the increase of vehicle height or the decrease of camera height.

ACTUATED SIGNAL OPERATIONS

Longitudinal occlusion results in longer perceived vehicle length by video detection systems and thus increases the detector presence time. To achieve similar objectives as inductive loops for actuated signal control, the passage gap (also called passage time, unit extension, vehicle extension) in the controller must be set at a reduced value in video detection systems (15). Equation (2) shows the relationship between passage gap and other parameters:

$$G = MAH - \frac{L_v + L' + L_d}{1.47u} \tag{2}$$

where

G = passage gap, sec

MAH = maximum allowable headway before gapping out a signal phase, sec

For example, assume MAH = 3.0 sec, d = 300 ft, h_v = 5 ft, h_c = 40 ft (luminaire pole mounting), L_v = 17 ft, L_d = 10 ft, u = 30 mph, then L' = 300×5/40 = 37.5 ft. The passage gap with video detection is calculated as

$$G_v = MAH - \frac{L_v + L' + L_d}{V} = 3.0 - \frac{17 + 37.5 + 10}{30 \times 1.47} = 1.5 \text{ (sec)}$$

The passage gap with an inductive loop system would have been:

$$G_l = 3.0 - \frac{17 + 10}{30 \times 1.47} = 2.4 \text{ (sec)}$$

The result indicates that for the same traffic flow condition and operating objectives, the passage gap in a video detection system should be set at a reduced value (in this case, 0.9 sec smaller than with inductive loop systems). The potential impact on traffic operations can also be addressed from the point of view of phase extension, which better relates to intersection capacity. Suppose a passage gap of 2.4 sec is used in the controller for the above example detector design, a video detection system would have higher *MAH*, which would result in more phase extension than that with an inductive loop system. *MAH* increases as L' determined by Equation (1) increases. The additional phase extension time is considered as a waste of the effective green time that could be used for serving other traffic movements, and can be translated into intersection capacity loss.

Phase extension, G_e, can be modeled by Equation (3) based on earlier work by Akcelik (16) and an assumed shifted negative exponential headway distribution with λ being the average flow rate in veh/sec, and Δ being the minimum headway in seconds.

$$G_e = \frac{1}{\lambda}\left[\frac{e^{\lambda(MAH-\Delta)}}{1-\Delta\lambda} - 1\right] \tag{3}$$

Figure 4 shows the differences in phase extension between the two types of detection systems based on different traffic flow levels and vehicle-to-camera height ratios. It can be seen that the additional phase extension by video detection systems increases with the increase of vehicle-to-camera height ratio and traffic volume. For a video system setting where h_v/h_c = 5/25 = 0.2, the resulting difference in phase extension is less than 3 sec when the traffic volume is less than 600 vph. This would translate into a 57 vphpl capacity difference assuming a 100-sec cycle and 1900 vphpl saturation headway.

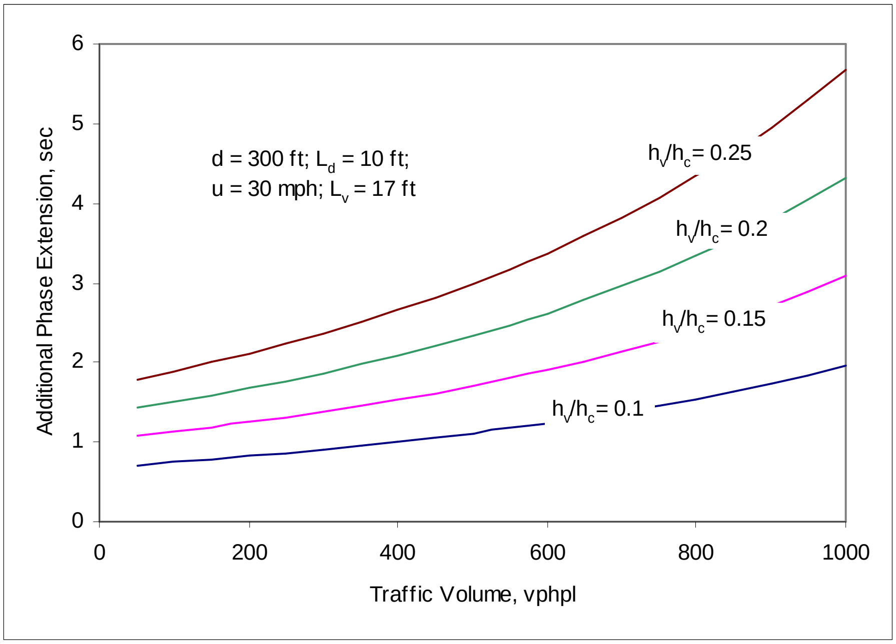
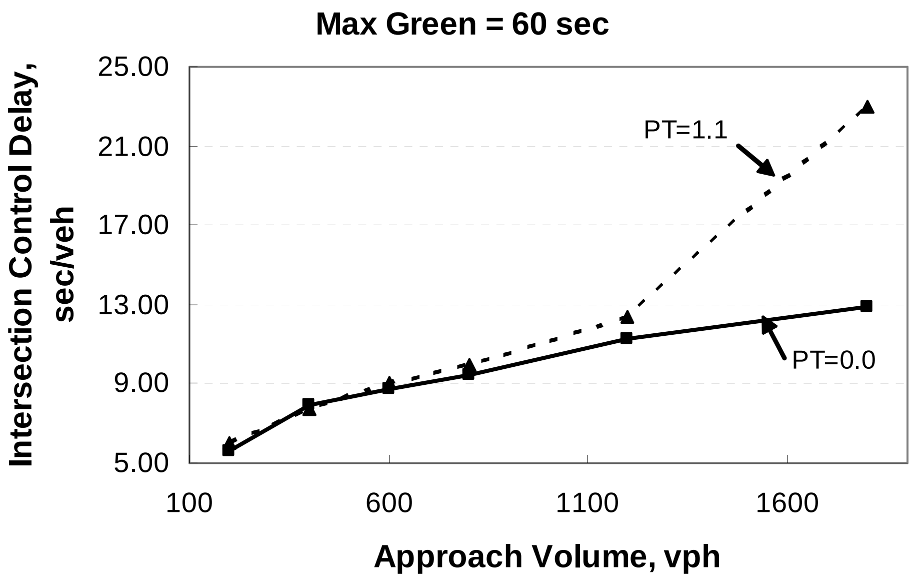
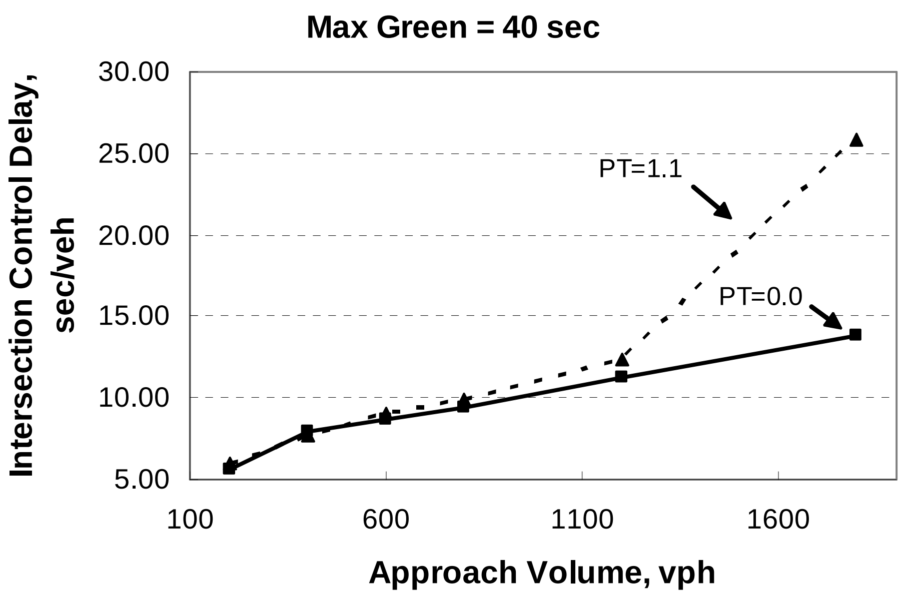


Figure 4 Difference in phase extension for video systems and inductive loop systems

Figure 5 shows the intersection delay obtained from CORSIM simulation scenarios for different approach volume and different passage time. Past research suggested the stop bar video detector should be extended for up to 80 feet with zero passage time (and activating a function to disable the detector call after the queue clears) *(8)*. However, if different passage time was used, one can see the effect of the lost phase time on the intersection overall delay. It is therefore recommended that the passage time should be adjusted to account for the video detection operation characteristics.



a) Max Green equals 60 seconds



b) Max Green equals 40 seconds

Figure 5 Intersection control delay with different passage time

ADVANCE DETECTION

At intersections with high speed approaches where advance detection is necessary for dilemma zone protection, the detector needs to be placed some distance upstream of the camera location (*17*, *18*). The higher the vehicle speed, the further upstream it requires to place the detector, which may be restricted by both the camera height and the camera angle. Figure 6 illustrates typical camera and detector set up for advance detection.

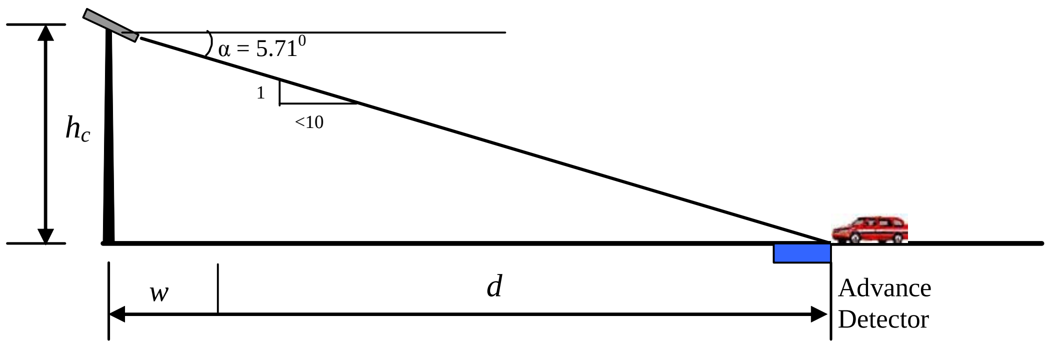


Figure 6 Camera and detector set up for advanced detection

Installation guidelines provided by the industry (*19*, *20*) and based on field experiences suggest that the minimum vertical viewing angle to the horizon should be greater than 10:1 (5.71º) to prevent sun glare. Of course, this required mounting angle would only apply if the positioning direction faces sunrise or sunset or the sky is in a significant portion of the image and is reasonably bright. But in any case, the further upstream the detector is located, the smaller the portion of the video image being viewed in pixels, and less accurate in detection. Equations (4) and (5) describe the relationship among all the elements shown in Figure 6, and some numerical results are illustrated in Figure 7.

$$h_c \geq d \times TAN(\alpha) \tag{4}$$

$$d - w = 1.47ut_0 + \frac{2.16u^2}{2\beta} \tag{5}$$

where

w = width of the intersection, ft

u = 85% speed, mph

t_0 = perception/reaction time, 1.0 second

β = deceleration rate, (11.2 fps^2 based on AASHTO method (*21*))

α = camera mounting angle, degree

$d - w$ = required stopping sight distance at the onset of yellow signal interval

In reality, the height of the camera is normally limited to a certain range depending on the type of camera mounting position. For example, a mast-arm mounting with a riser can usually achieve about 25 ft high. A camera mounted on a luminaire of a signal pole can achieve 25-35 ft, while a camera mounted on a luminaire pole can achieve 35-40 ft. Based on Figure 7, it can be seen that it is practically impossible to achieve the required advance detection setup for speeds above 50 mph with a single camera location. At the recommended minimum camera mounting angle of 5.71°, it would require the camera to be 40 ft or higher for speeds above 50 mph. Some states such as the State of Nevada have used an additional camera for advance detection (see Figure 8).

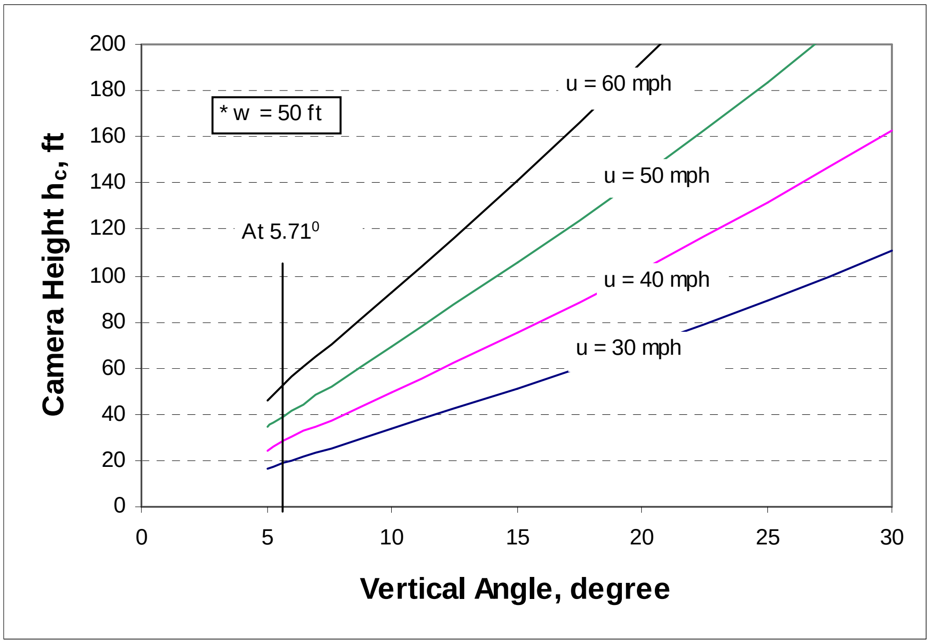
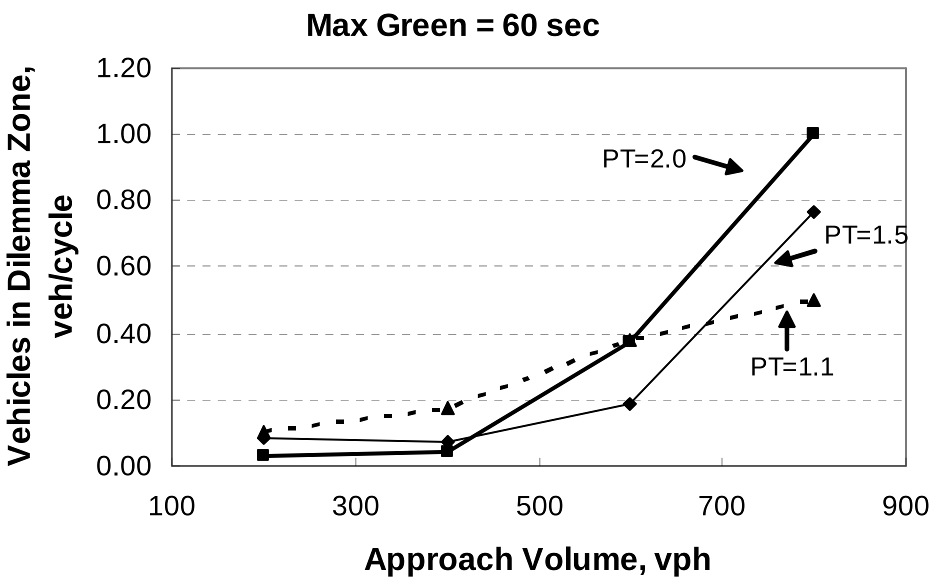


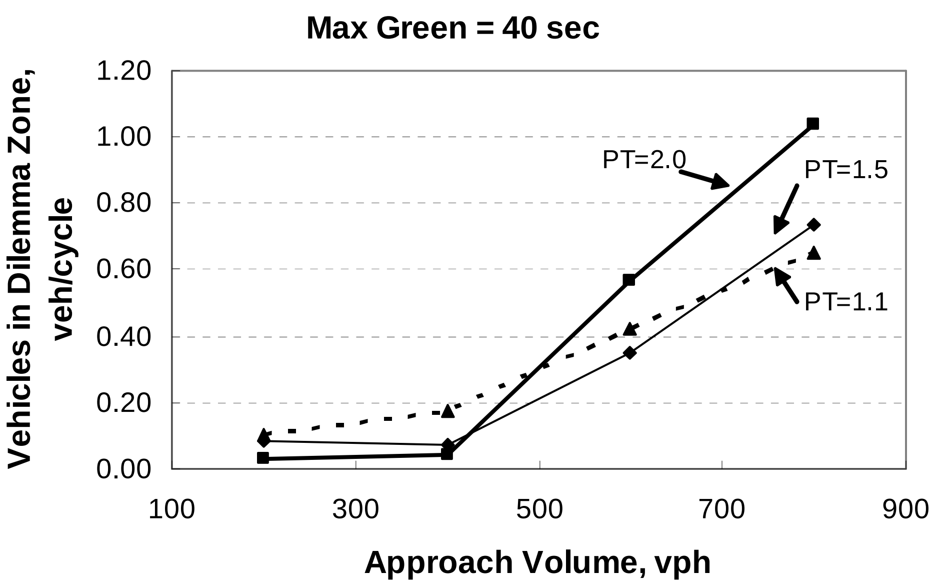
Figure 7 Required camera height for advance detection

Figure 8 Video detection system with an advance camera

Using a longer passage time for advance detection typically results in extending the main street through phase duration. This extension would also usually result in more frequent phase max-outs, and therefore more vehicles caught in their dilemma zone as a result. To show the effect of advance detection setup, Figure 9 shows the number of vehicles caught in their dilemma zone due to different setting of passage time. It is clear from the figure that the higher the passage time, the higher the number of vehicles caught in their dilemma zone. The effect becomes even more pronounced when the volume on the main approach increases, and the max green time decreases. These results suggest that the passage time should be adjusted using Equations (4) and (5) to improve the intersection safety.



a) Max Green equals 60 seconds



b) Max Green equals 40 seconds

Figure 9 Vehicle caught in dilemma zone for different passage time

EFFECT OF OCCLUSION ON MISSING DETECTION

One of the effects of longitudinal occlusion is the result of missing counts. Missing counts may be critical for signal operations where discrete volume count information is used. One such a case is the adaptive left turn control (<u>22</u>) where selection of a protected or permitted left turn phase is based on real-time gap counts for the opposing through movement. At a signalized intersection approach with video detection, a missing count occurs when the condition in Equation (6) satisfies:

$$H_v \le \frac{L_v + L' + L_d}{1.47u} = \frac{L_v + d\,\dfrac{h_v}{h_c} + L_d}{1.47u} \qquad (6)$$

where

H_v = time headway for normal vehicles, (e.g., passenger cars), sec

u = vehicle speed, mph

All other variables are defined earlier, and the units are in feet

Equation (6) suggests that missing counts are related to the same factors affecting occlusion. Assume the following parameter values: h_v = 5 ft for cars, h_c = 25 ft (typical mast-arm mounting), d = 300 ft, L_d = 10 ft, L_v = 17 ft, and u = 35 mph, we obtain for passenger cars, $H_v \le 1.7$ sec, indicating that a missing detection would occur to a vehicle following a passenger car with a headway of equal to or less than 1.7 sec. If we assume h_T = 12 ft and L_T = 60 ft for trucks, we obtain for trucks, $H_T \le 4.2$ sec, indicating that a missing counts would occur to a vehicle following a truck with a headway of equal to or less than 4.2 sec. This is to say that missing counts occurs more often (i.e., occurs at larger headways) with more trucks in the traffic stream.

The probability or the proportion of missed detections can be determined based on the following probabilistic calculations. A shifted-negative exponential distribution is assumed for the vehicle headways in the traffic stream. The probability of missing counts, P_σ, can be determined by Equation (7):

$$P_\sigma = P_T P\{t \le H_T\} + P_v P\{t \le H_v\} \qquad (7)$$

where

P_T = probability of a vehicle being a truck, i.e., the percentage of trucks in the traffic stream

P_v = probability of a vehicle being a car, i.e., the percentage of cars in the traffic stream, and $P_T = 1 - P_v$

H_T = headway below which a missing detection would occur if the leading vehicle is a truck

H_v = headway below which a missing detection will occur if the leading vehicle is a car

$P\{t \le H_T\}$, $P\{t \le H_v\}$ = the probabilities of a headway being less than or equal to H_T and H_v, respectively, and are calculated by Equations (8) through (10).

$$P\{t \le H_T\} = 1 - P\{t > H_T\} = 1 - e^{-(H_T - \Delta)\lambda} \tag{8}$$

$$P\{t \le H_v\} = 1 - P\{t > H_v\} = 1 - e^{-(H_v - \Delta)\lambda} \tag{9}$$

$$\lambda = q / 3600 \tag{10}$$

where

q = traffic volume, vphpl

Δ = minimum headway in a traffic stream, sec

Figure 10 is the plot of P_σ based on different truck percentages and traffic volumes using the same parameter values shown in the figure.

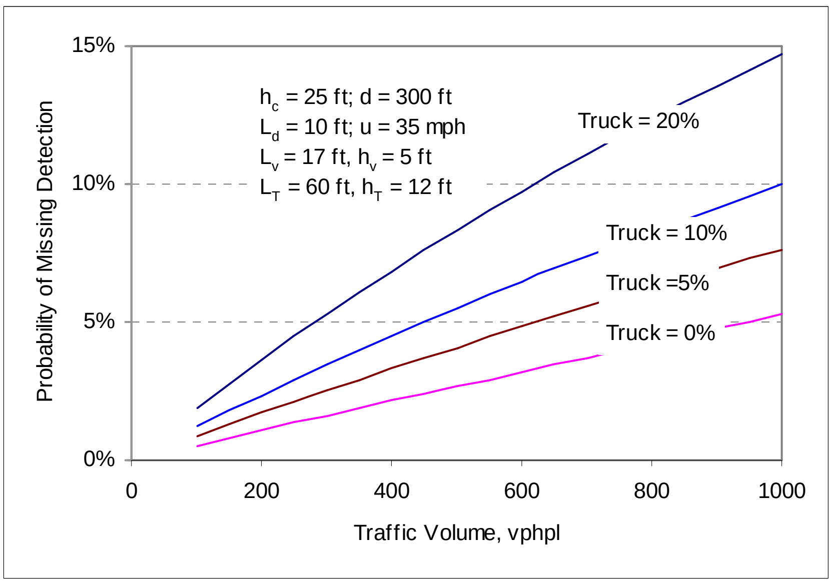


Figure 10 Probability of having missing detections (Trucks = 0%, 5%, 10%, and 20%)

As shown in Figure 10, higher percentage of trucks and higher traffic volumes would result in increased number of missing counts. Based on the set of parameter values used in the figure, missed counts are generally less than 5% when volume is less than 600 vphpl and the percentage of trucks is less than 5%.

FALSE DETECTION

Horizontal occlusion can result in a false detection when a vehicle gets into the view of the adjacent lanes, causing occlusion to the detector and false call to the related signal phase. For example, when occlusion occurs to the left-turn lane while no left-turn vehicles are present, a false detection would occur to the left-turn phase. Horizontal occlusion and false detection occur when the camera is not mounted directly above the travel lane, such as on an elongated signal pole or a separate luminaire pole, typically located on the far right-hand corner of the intersection. Cameras mounted at such a location are to achieve the required camera height for minimizing longitudinal occlusion. Left-turn lane occlusion can be avoided by mounting the camera on a mast-arm and to position the camera to the division line between the left-turn lane and the through lane.

Figure **11** shows a plane view where occlusion occurs to the left-turn lane. In this figure, the camera is located on the far right-hand corner of the vehicle's traveling direction. A stop-line detector is used for the left-turn lane.

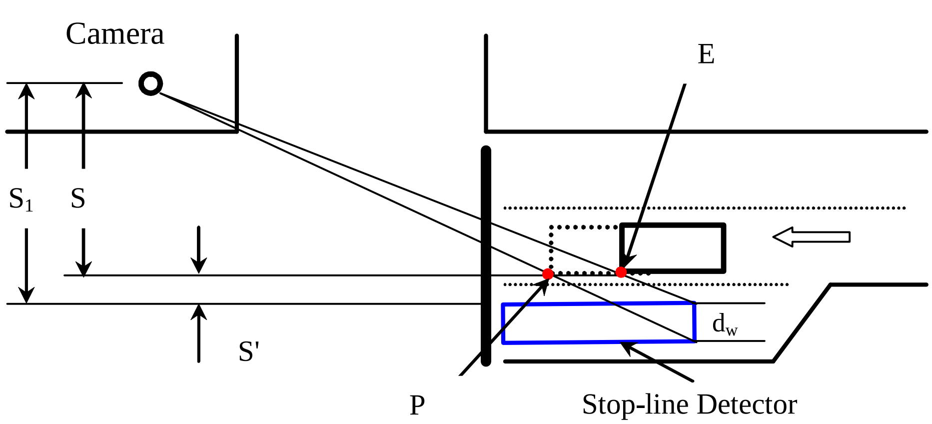


Figure 11 False detection due to adjacent lane occlusion

The condition that vehicle occlusion to the left-turn lane occurs can be described as when the vehicle's height is equal to or greater than the *critical height* at either point E or point P. *Critical height* at a point is the minimum vehicle height that would block the view to the detector, resulting in detector occlusion and activation. Points P and E represent the two possible detector occlusion points. Depending on the vehicle dimension and detector width, either P or E could be occluded first, which would result in the first detector actuation. Detailed derivation of the equations can be found in the cited literature (*2*). The critical height at point E, h', can be obtained from Equation (11):

$$h' = \frac{h_c S'}{S_1} \tag{11}$$

The critical height at point P, h'', can be obtained from Equation (12):

$$h'' = \frac{h_c(S' + d_w)}{S} \tag{12}$$

Where

S	= horizontal offset between camera and edge of vehicle, ft
S_1	= horizontal offset between camera and edge of detector, ft
S'	= spacing between vehicle and detector, ft
d_w	= width of the stop-line detector, ft

It can be proved that h'' is greater than h'; therefore, occlusion would always first occur at point E. Therefore, the critical height at point E is used to derive the condition of horizontal occlusion and false detection. Substitute in Equation (11) the critical height, h', with the vehicle height, h_v, the following equation can be obtained:

$$h_c = \frac{h_v S_1}{S'} = \frac{h_v(S' + S)}{S'} = h_v\left(1 + \frac{S}{S'}\right) \tag{13}$$

The camera height, h_c, obtained from Equation (13) represents the required camera height for avoiding horizontal occlusion and false detection, which is affected by the height of the vehicle, h_v, the spacing between detector and vehicle, S', and the horizontal offset of the camera S. Figure 12 and Figure 13 illustrate the relationship among these parameters.

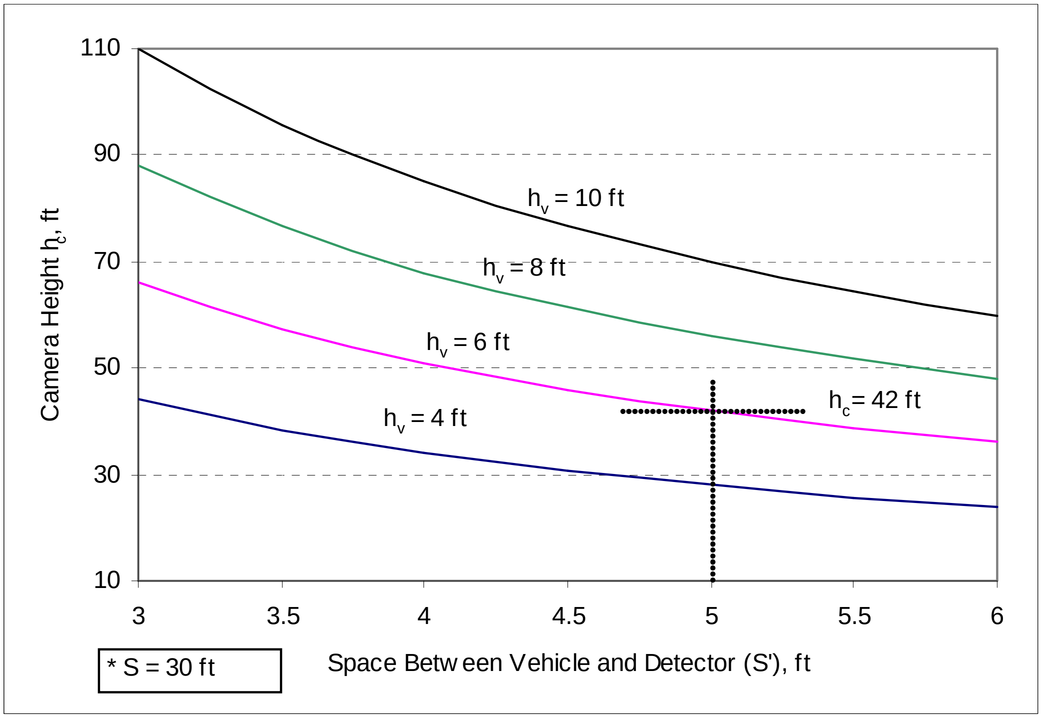


Figure 12 Required **c**amera height with respect to *S′*

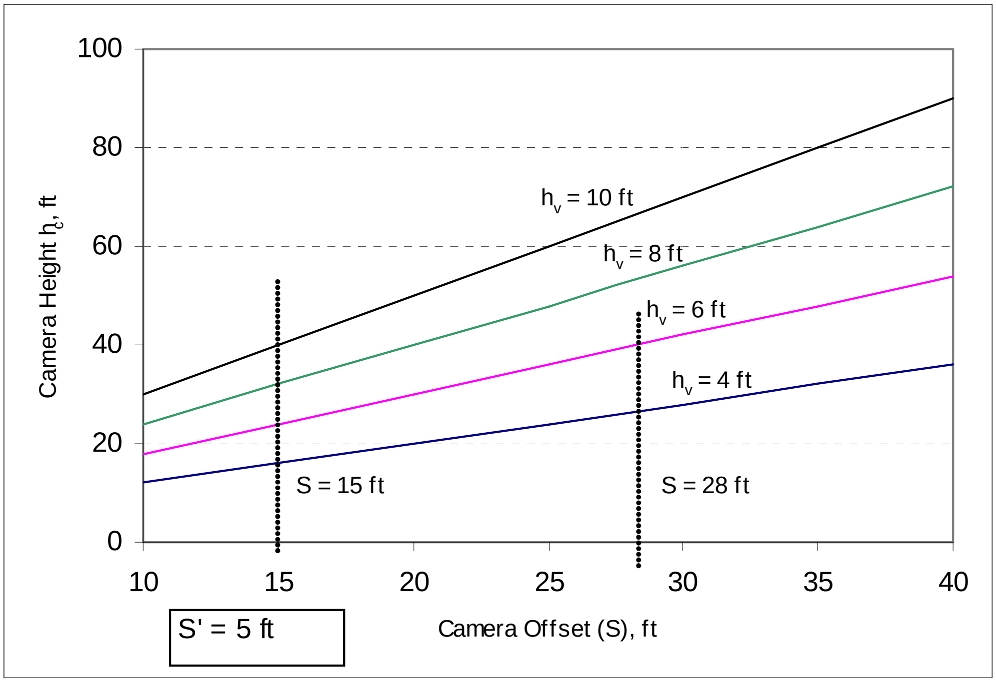


Figure 13 Required camera height with respect to *S*

Figure 12 and Figure 13 indicate that the required camera height for avoiding occlusion and false detection increases as: (a) the height of the vehicle increases; (b) the spacing between detector and vehicle decreases; and (c) the horizontal offset of the camera increases. This is equivalent to say that horizontal occlusion can be reduced by either reducing the horizontal camera offset (ideally, to place the camera directly above the travel lanes), or to increase the camera height, thus Equation (13) can be used to assess the tradeoffs between camera height and offset. Mounting the camera in a mast-arm can reduce horizontal offset, while mounting the camera on a luminaire pole can increase camera height.

Here we use a typical two-lane approach with an exclusive left turn lane as an example. Assume *S* is 30 ft, S' is 5 ft, the required camera height is then at least 42 ft if the vehicle is 6 ft high (see Figure 12). If the vehicle is 10 ft high, the required camera height is then at least 70 ft high in order to avoid occlusion and false detection for the left-turn phase. With a camera height typically less than 40 ft (see Figure 13), the horizontal offset of the camera (S) should be less than 28 ft when a vehicle's height is 6 ft. *S* should be less than 15 ft when a vehicle's height is 10 ft less.

SUMMARY AND CONCLUSIONS

The paper provides various models for assessing the impacts of video detection system applications at signalized intersection operations. Various occlusion scenarios are modeled and examples are presented to illustrate how the models can be used to provide quantitative assessments on the operational impacts. The paper, however, does not address the impacts of physical limits of video detection systems such as pixel size, grayscale depth, lightning and shadows.

The following summarizes the major findings and conclusions reached from this study.

Longitudinal occlusion to a following vehicle results in missing detections. With an approach volume under 600 vphpl and the percentage of trucks under 5%, the probability of having missing counts is normally less than 5%. Longitudinal occlusion also results in increased detector presence time, thus require reduced passage gap setting in the signal controller. If the same passage gap is used, video detection systems would result in longer phase extension than inductive loop systems; however, the difference in phase extension between the two detection systems is generally less than 3 seconds with traffic volume under 600 vphpl. To minimize false detections due to horizontal occlusion to an adjacent lane, the camera is better positioned at a minimal offset. An ideal position would be at the division line between the lanes, which is possible with a mast-arm camera mounting. When the camera is offset from the travel lanes, it requires higher camera setup, which is achievable with a luminaire mounting. Due to limitations on camera mounting height and positioning angle, the required advance detector location may not be satisfied for high speed approaches. With normal system settings, it is found that video detection systems are difficult to satisfy the advance detector placement for speeds above 50 mph. At higher speed approaches, an additional camera is necessary for providing advance detection.

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