Assessing the Effect of Heavy Vehicles on the Visibility of Traffic Signs at Multilane Highways

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Paper Submitted to the
Transportation Research Board 82nd Annual
Meeting, 12-16 January 2003

July 2002

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Word count: 7,747 word equivalent

ABSTRACT

Traffic signs are critical for the safe and efficient use of highway facilities. Occlusion of traffic signs by moving or stationary objects renders these important traffic control devices ineffective. Therefore, adequate visibility of traffic signs is an important safety concern on multi-lane highways in general and on limited-access facilities in particular due to the high proportion of heavy vehicles in the traffic stream. This paper presents an investigation into the different factors that affect sign occlusion by heavy vehicles on these highway facilities. Parametric analyses were conducted to explore these effects using a simulation model that was developed exclusively for this research. The variables investigated involved; legibility distance, maximum divergence angle, average speed of passenger cars, relative speed of trucks with respect to passenger cars, lateral offset of traffic sign, number of words in message, traffic level, and heavy vehicles' percentage. In general, research results showed that the occlusion of ground-mounted traffic signs by heavy vehicles was very significant for conditions that can be described as typical. Also, results suggest that the factors that have most significant effect on sign occlusion involve legibility distance, average speed of PCs, relative speed of trucks with respect to PCs, and number of trucks on the lane of interest. On the other hand, lateral offset and maximum divergence angle exhibited smaller effect on sign occlusion by heavy vehicles.

Keywords: traffic signs, heavy vehicles, occlusion, sign visibility

1. INTRODUCTION

Traffic signs are primarily intended for the safe and efficient use of highway facilities. These signs communicate traffic regulations to drivers, warn them of impending hazards, and provide directions for those who are not familiar with the route or area. Traffic signs become particularly important on multilane highways and limited-access facilities where a significant proportion of drivers are non-local drivers. For its important role, the design and placement of traffic signs is considered an integral part of highway design. This is clearly stated in the MUTCD *(1)* under "freeway and expressway signing principles":

> *The signing furnishes road users with clear instructions for orderly progress to their destinations. Sign installations are an integral part of the facility and, as such, are best planned concurrently with the development of highway location and geometric design. For optimal results, plans for signing are analyzed during the earliest stage of preliminary design, and details are correlated as final design is developed.*

Occlusion of traffic signs by moving or stationary objects renders these important traffic control devices ineffective. Therefore, adequate visibility of traffic signs becomes an important safety concern on multilane highways in general and on limited-access facilities in particular due to the high proportion of heavy vehicles in the traffic stream.

The investigation presented in this paper has two main objectives. The first is to assess the effect of heavy vehicles on the visibility of traffic signs under different traffic, geometric, and sign design conditions. This assessment is essential to estimate the magnitude of the problem. The second objective is to identify the factors that have most significant influence on sign visibility as concerned with the occlusion effect of heavy vehicles. This will help to develop design guidelines and other alternative strategies to minimize this undesirable effect.

This investigation is mainly restricted to tangent highway segments on two-lane or multilane highways (in one direction) and in particular limited-access facilities where heavy vehicles typically constitute a significant proportion of the traffic mix.

2. PROBLEM STATEMENT

Despite their smaller proportion of vehicular traffic, heavy vehicles are known for their impacts on the traffic stream. One important impact on traffic safety is the occlusion of ground-mounted traffic signs (at the roadside) by heavy vehicles due to their large dimensions and occupation of the rightmost lane(s). This negative impact on sign visibility is only minimal for traffic signs that are installed using overhead or cantilever structures. Therefore, the Manual on Uniform Traffic Control Devices *(1)*, the national guide for the design, use, and placement of traffic signs, regards high percentage of heavy vehicles as one of the conditions where the use of overhead signs should be considered. However, it also states: "the factors to be considered for the installation of overhead sign displays are not definable in specific numerical terms" and leaves much of this decision to engineering judgment. As such, there is no guidance in the current practice as to how the effect of heavy vehicles on sign visibility can be used as a criterion to select the proper type of sign installation.

Research is needed to assess the effect of heavy vehicles on the visibility of ground-mounted traffic signs. This assessment is essential in developing guidelines for the use of other types of sign installation particularly overhead signs. Also, this will help to investigate the effectiveness of the different strategies that are intended to minimize the impact of heavy vehicles on sign visibility.

3. PREVIOUS RESEARCH

The literature search suggests that there is little information in the literature that addresses the issue of sign visibility as related to the presence of heavy vehicles in the traffic stream.

Abramson *(2)* developed a mathematical formulation that addressed the occlusion of signs when a passenger car and a heavy vehicle happen to exist within the legibility area upstream of the traffic sign. The study modeled the geometry of the problem based on the shadow created by heavy vehicle(s) and derived probabilities for the passenger car being in the shadow, outside the shadow, or both.

Another study by Ullman and Dudek *(3)* provided an analytical approach to assess the potential impacts of vertical curves, horizontal curves, and heavy vehicles on Variable Message Sign (VMS) readability. The analyses were mainly based on the premise that each of these factors can significantly limit the distance at which a VMS can be read. This in turn translates into shorter available reading times and the need to display a shorter message with fewer units of information.

The literature survey found no other studies that investigated the effect of larger vehicles on sign visibility or the factors that affect the occlusion of traffic signs by heavy vehicles. However, several studies were identified that is related, in one way or another, to this investigation and therefore they are briefly discussed in this section.

One study examined the combined effect of letter size and the lateral sign placement (lateral distance from the traveled lanes) on legibility distance *(4)*. This study confirmed that increasing the legend size offsets the effect of lateral placement farther from the travelway. Another study (5) also investigated the effect of lateral and vertical sign placement on sign legibility at tangent and curved highway segments. Other studies investigated the day versus night legibility of traffic signs and the effect of luminance and contrast *(6, 7)*. Many other studies investigated the text content of traffic signs such as letter height, width, font, spacing, etc. *(7, 8, 9, 10 to name but a few)*.

4. MODELING OCCLUSION OF TRAFFIC SIGNS BY HEAVY VEHICLES

A simulation approach was utilized to model the occlusion of traffic signs by heavy vehicles on multi-lane highways. An analytical tool was developed where road geometry, traffic sign, and moving entities are simulated over space at any point in time. This tool dynamically models the movement and location of passenger cars and trucks on the facility upstream of the subject traffic sign and verifies the continuity of sightline between the subject driver and traffic sign. The model is presented in a companion paper, and therefore only a brief description of the model is provided in this section.

The proposed model estimates two measures 1) the probability of a traffic sign being occluded by heavy vehicles, and 2) the probability of a passenger car driver missing the ground-mounted traffic sign under certain traffic conditions. These measures are modeled in three steps:

- I- Modeling the amount of occlusion caused by one or more heavy vehicles that happen to be in the legibility zone upstream of the subject traffic sign. This is an imaginary zone upstream of traffic sign where the passenger car driver is able to read the sign.
- II- Modeling the probability of having one or more heavy vehicles within the legibility zone of that particular traffic sign
- III- Assessing the occlusion effect using results from steps I & II.

In the first step, the model updates the location of vehicles within the legibility zone every deci-second, evaluates the continuity of the sightline, and determines the status as being either clear or obstructed. Figure 1 shows the geometry of the problem and the important variables involved in this step. Of particular importance are the legibility distance and the legibility zone (mentioned earlier). Legibility distance is defined as the maximum distance along the driver’s sightline when he first becomes able to read the sign. The legibility zone is an imaginary zone upstream of traffic sign where the passenger car driver is able to read the sign. This zone, represented by the shaded area in Figure 1, is delineated by the legibility distance along the driver's sightline (upstream) and the line that represents the maximum divergence angle θ (downstream) beyond which the driver becomes practically unable to read the sign.

The model utilizes the speeds of the subject passenger car and heavy vehicles and the legibility distance to update the position of vehicles and evaluate continuity of sightline every deci-second. The model then estimates the amount of time when occlusion is in effect and derives the probability of occlusion and the probability of missing the sign during the time when one or more heavy vehicles occupy the legibility zone. Another important determinant of the amount of occlusion is the position of the heavy vehicle(s) at the time the passenger car arrives at the legibility zone. This variable, however, is fully random and has no meaning nor typical values in practice. The model considers 100 different positions within the legibility zone and takes the average occlusion for each particular run.

In the second step, the model estimates the percentage of time the legibility zone is occupied by one or more heavy vehicles. This event (occupying the legibility zone) was classified into two types; individual events and overlapped events. Figure 2 illustrates the two types of events. The model utilizes the shifted negative exponential distribution to estimate the number of individual versus overlapped events. Assuming constant speed for heavy vehicles, the individual events will occupy the zone for a constant period of time that is equivalent to the distance along the truck's path within the legibility zone plus one truck length divided by the average speed. For overlapped events, this time is variable and dependent on the headway between the leading and the following trucks. The model establishes a headway range for overlapped events and finds the minimum headway using one of the car-following theories, and the maximum headway as the time required for a single truck to traverse and clears the legibility zone (duration of one individual event). The model then divides this range into equal intervals (one deci-second) and the number of events in each interval is calculated. The model then calculates the percentage of time for individual and overlapped events separately. The main inputs to the second step are traffic volume, the percentage of trucks, and lane utilization factors that represent trucks' distribution over the traveled lanes.

The third step of the model combines results from steps I & II to estimate 1) the absolute probability of a traffic sign being occluded by a heavy vehicle, and 2) the absolute likelihood of a passenger car driver missing the sign.

5. STUDY DESIGN

The main drive for developing the model described in the previous section is to investigate the different factors that affect the impact of heavy vehicles on the visibility of traffic signs. The following typical scenario is considered by this investigation:

1. Two-lane or multilane directional roadway on tangent segment
2. Trucks travel on the rightmost lane
3. The subject passenger car travels on the adjacent lane (second from the right)

Several factors that are believed to affect sign occlusion by heavy vehicles were identified for inclusion in this investigation. These factors are:

1. Legibility distance
2. Maximum divergence angle
3. Average speed of passenger cars
4. Relative speed of trucks with respect to passenger cars (PC's)
5. Lateral offset of traffic sign
6. Number of words in message (determines the minimum time required to read the sign)
7. Traffic level

8. Percentage of heavy vehicles (HV's)

Appropriate ranges were established for these variables, and a default value was assigned to each. The default value is to be used when that variable is not investigated. In general, the default values were selected to represent typical values in practice. Table 1 shows the ranges, levels, and default values for the variables used in this investigation.

Two measures were used to assess occlusion. The first is the probability of occlusion at any point in time (P1) and the second is the probability of a passenger car driver missing the sign (P2). It is important to note that trucks and heavy vehicles will be used interchangeably in the following sections of this paper.

6. FACTORS AFFECTING OCCLUSION OF TRAFFIC SIGNS BY HEAVY VEHICLES

Several investigations were conducted to examine the effect of the above-mentioned factors using the simulation model described earlier. The results from these investigations are provided in this section.

6.1. Legibility Distance

This variable is expected to have a significant effect on sign occlusion by heavy vehicles, as it is one of the most important variables that define the geometry of the problem. This distance and the maximum divergence angle (defined in section 7.5) determine the amount of time it takes a passenger car or a truck to traverse the legibility zone.

Intuitively, the longer the legibility distance, the longer the time the PC spends in the legibility zone, and therefore the longer the time available to read the sign assuming all other variables constant.

The significance of this variable is mainly attributed to the fact that legibility distance can easily be influenced through sign design. The most important feature of sign design that affects the legibility distance is letter size. In general, the literature suggests that each inch of letter height would add 40-50 ft to the legibility distance. Besides sign design features, legibility distance is also a function of human vision characteristics and particularly vision acuity.

P1 investigation: Figure 3-(a) shows the relationship between the legibility distance and the probability of occlusion (P1) at different passenger car speeds. The general trend that is apparent in this figure is that P1 decreases as the legibility distance increases. The relationship is highly linear for the whole range of legibility distance investigated. In general, when the legibility distance increased from 400 ft to 800 ft, the amount of occlusion decreased in the range 24-33 percent. The second trend that can easily be identified in this figure is the significant reduction in P1 with the increase in average speed of passenger cars. This suggests that, the faster the passenger car, the less the amount of occlusion and the better the visibility of traffic signs.

P2 investigation: Figure 3-(b) shows the probability of a passenger car driver missing the sign for the same conditions exhibited in Figure 1-a using the default value for the # of words in message (3 familiar words). In general, the trends of P2 exhibited in this figure are somewhat similar to those of P1. Specifically, the longer the legibility distance and the faster the passenger car, the lower the probability P2. However, this figure also suggests that legibility distance has a much greater effect on P2 than that on P1. The reduction in P2 due to increase in legibility distance from 400 ft to 800 ft was in the range 76-81 percent while the corresponding reduction in P1 was in the range 24-33 percent. Also evident in this figure is the fact that the effect of the speed of PC's on P2 is less significant than its effect on P1.

An important observation that is common to the previous two figures is the significance of P1 and P2 under conditions that can be described as typical. For instance, at a legibility distance of 480 ft (10-12 inch letter height), P1 varied roughly in the range 0.14-0.21 for different speeds of PCs. This can be interpreted as; the percentage of time when occlusion will be in effect is in the range 14-21 percent. Also, the value of P2 varied in the range 0.18–0.25. This can be interpreted as; out of a hundred passenger car drivers on that particular lane, 18 to 25 drivers will miss the sign under the conditions investigated. This value is considered very high in terms of the potential impact on traffic safety.

6.2. Speed of Passenger Cars

This variable is important as it determines the amount of time required for the passenger car to traverse the legibility zone. In practice, average speeds of passenger cars and trucks can be influenced through traffic control by imposing speed limits. However, speed limit is usually affected by other considerations such as facility type, adjacent land uses, and site geometrics.

P1 investigation: Figure 4-(a) shows the value of P1 as a function of passenger car speed at different legibility distances. All other traffic and geometric variables were set to their default values. The trends shown in this figure confirm the finding that the higher the average speed of passenger cars, the less the probability of occlusion, and hence the better the visibility of the sign. Two factors with conflicting effects are behind this trend. On one hand, higher speed of PC's limits the time available for drivers to receive and process information by reducing the amount of time spent within the legibility zone. On the other hand, higher speed of PC's will result in a decrease in the amount of time the legibility zone is occupied by heavy vehicles (assuming constant relative speed between trucks and PC's). It seems that the effect of the second factor significantly outweigh the effect of the first factor, which explains the improvement in sign visibility.

This relationship is slightly nonlinear as exhibited by the curves shown in this figure. In general, more than 50% reduction in occlusion occurred when the average speed increased from 40 mph to 75 mph for the different legibility distances investigated. Expectedly, the amount of occlusion is higher for shorter legibility distances as was discussed in section 7.1.

P2 investigation: Figure 4-(b) shows the relationship between P2 and passenger car speed at different legibility distances. It is evident that P2 generally decreases with the increase in passenger car speed. However, the effect of passenger car speed on P2 is less significant than its effect on P1. Also, the legibility distance has much greater effect on P2 than that on P1 as illustrated in this figure.

6.3. Relative Speed of Trucks with Respect to Passenger Cars

This variable is a surrogate for the average speed of trucks at a given average speed of passenger cars. It is an important variable as it determines the time during which the legibility zone is occupied by heavy vehicles. It is also important as different states have different practices regarding speed limit policies on freeways and multilane highways. Specifically, some states utilize speed limits for trucks that are lower than those for passenger cars while other states apply one speed limit on all vehicle types.

P1 investigation: The relationship between P1 and the relative speed at different passenger car speeds is illustrated in Figure 5-(a). This relationship is slightly nonlinear particularly at slower passenger car speeds. This figure suggests that an increase in the relative speed (i.e. higher speed of trucks) will result in a decrease in the amount of occlusion. The effect of this variable is very significant, as the amount of occlusion was reduced roughly between 66% and 73% when the relative speed changed from –15 mph to +10 mph. However, while it is quite common for the average speed of trucks to be at or below the average speed of passenger cars, it is somewhat unlikely for the average speed of trucks to be higher than that of passenger cars. Again, higher speeds of passenger cars are generally associated with lower amount of occlusion.

P2 investigation: The relationship between P2 and the relative speed at different passenger car speeds is illustrated in Figure 5-(b). As shown, the effect of relative speed on P2 is remarkable. Specifically, by increasing the relative speed from –15 mph to +10 mph, the probability of missing the sign was reduced anywhere in the range 71%-100%. The figure also shows that lower passenger car speeds are associated with more significant decrease in P2 and that the effect of this variable on P2 is more significant than its effect on P1.

6.4. Lateral Offset

For a given legibility distance and divergence angle, this variable affects the distance along the center of the traveled lanes that falls within the legibility zone. Consequently, it affects the time available for passenger car drivers to read the sign and the time when the legibility zone is occupied by heavy vehicles. The importance of this variable is partly due to the fact that lateral offset is considered one of the important design factors of highway signage.

P1 investigation: Figure 6-(a) shows the relationship between P1 and lateral offset at different legibility distances. The general trend exhibited in this figure is the increase in the probability of occlusion with the increase in lateral offset. This suggests that the lateral offset should be kept to the minimum required by design standards to provide better visibility of traffic signs. This relationship is generally nonlinear with more significant effect occurring at longer legibility distances (a trend that is somewhat unexpected). However, the effect of lateral offset is relatively less significant than the effect of the other variables that were discussed previously.

P2 investigation: The effect of lateral offset on P2 at different legibility distances is illustrated in Figure 6-(b). In general, P2 increases as the lateral offset increases. However, this increase is generally nonuniform and occurs in abrupt changes as shown in three of the four curves exhibited in this figure.

6.5. Maximum Divergence Angle

This variable delineates the legibility zone thus affecting the distance along the path of passenger car where the sign can be read. This variable is more related to driver characteristics and therefore more difficult to control through sign design or traffic control.

P1 investigation: The relationship between P1 and the maximum divergence angle at different legibility distances is shown in Figure 7-(a). This figure suggests what seems to be an expected trend, i.e. occlusion decreases as the maximum divergence angle increases. This effect is generally more significant at shorter legibility distances. For instance, at 400 ft legibility distance, the reduction in occlusion due to the increase of the maximum divergence angle from 10° to 20° was in the proximity of 18 percent. The corresponding reduction for a legibility distance of 720 ft was in the proximity of 13 percent. Nonetheless, the effect of this variable on P1 is generally less significant than the effect of most variables investigated by this research.

P2 investigation: The effect of the maximum divergence angle on P2 at different legibility distances is illustrated in Figure 7-(b). The general trends shown in this figure suggest that, as the maximum divergence angle increases, the value of P2 decreases and that the reduction in P2 is significantly greater at shorter legibility distances. Another observation is that, except for a legibility distance of 720 ft, the effect of this variable on P2 is more significant than its effect on P1.

6.6. Number of Words in Sign (Message Size)

This variable is the main determinant of the minimum time required to read the sign and therefore it is only concerned with the probability of missing the sign (P2). This research utilized a formula by Mitchell and Forbes *(7)* in determining the time required to read the sign. The importance of this variable is that it represents one of the main aspects of sign design.

The effect of this variable on P2 at different legibility distances is illustrated in Figure 8. As shown in this figure, P2 generally increases as message size increases. However, in two of the curves, the increase is mostly uniform and has relatively small magnitude while the other two curves show a more significant increase in P2 that occurs in abrupt changes.

6.7. Traffic Level

This research utilizes volume-to-capacity (V/C) ratio as an indicator of traffic level. A capacity of 2350 pcphpl was assumed based on a free-flow speed of 65 mph. Intuitively, for a given truck percentage, the number of trucks in the traffic stream increases as traffic level increases thus increasing the amount of sign occlusion.

P1 investigation: the relationship between P1 and traffic volume at different truck percentages is illustrated in Figure 9-(a). In general, occlusion increases as traffic volume increases. This relationship is highly linear particularly at smaller truck percentages. As V/C increased from 0.3 to 0.9, P1 increased roughly in the range 150-200 percent.

P2 investigation: The effect of traffic level on P2 at different truck percentages is illustrated in Figure 9-(b). The trends shown in this figure are highly similar to those exhibited by Figure 7-a. Also, the percentage increase in P2 is very comparable to that for P1.

6.8. Percentage of Heavy Vehicles

At a given traffic level, the percentage of heavy vehicles in the traffic stream determines the number of trucks thus affecting the amount of sign occlusion.

P1 investigation: Figure 10-(a) shows the effect of the percentage of trucks on P1 at different traffic levels. As expected, the higher the truck percentage, the greater the probability of occlusion. In general, the effect of this variable on P1 is highly significant. Also, this relationship is almost linear at low traffic levels and becomes nonlinear at higher traffic levels. This trend is related to the distribution of headways in the traffic stream. At low truck percentages, the legibility zone is occupied by a single truck for most of the time and as truck percentage increases, the probability of two or more trucks occupying the legibility zone significantly increases thus resulting in a non-linear behavior.

P2 investigation: The effect of truck percentage on P2 at different traffic levels is illustrated in Figure 10-(b). The trends and the percentage increase in P2 are very similar to those shown in Figure 10-(a).

7. SUMMARY OF FINDINGS

An investigation into the effect of the different factors that affect the occlusion of ground-mounted signs by heavy vehicles was presented in this paper. This investigation is deemed important as some of the factors investigated are within the control of traffic and highway engineers or those involved in sign design. Further, this investigation is essential in developing strategies to improve sign visibility as related to sign occlusion by heavy vehicles. The most important findings are:

1. In general, occlusion of ground-mounted traffic signs by heavy vehicles is very significant for conditions that can be described as typical. This finding was supported by the different analyses presented in this paper.
2. Factors that have most significant effect on sign occlusion involve legibility distance, average speed of PC's, relative speed of trucks with respect to PC's, traffic level, and proportion of heavy vehicles in the traffic mix.
3. The effect of the lateral offset and the maximum divergence angle on sign occlusion is less significant than that of the other factors investigated by this research.
4. Longer legibility distances provide for better visibility of traffic sign. In other words, increasing letter size will considerably reduce the probability of sign occlusion.
5. At a given traffic sign, higher average speeds of passenger cars and heavy vehicles result in lower amount of occlusion. Also, the higher the relative speed between trucks and passenger cars, the less the amount of occlusion. This suggests that the practice of applying different speed limits for passenger cars and trucks on interstate highways increases sign occlusion by heavy vehicles.
6. In general, the number of trucks on the lane(s) of interest has considerable effect on sign occlusion. This effect is almost linear for low to moderate number of trucks and becomes increasingly nonlinear as this number increases.

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TABLE 1 Ranges, Levels, And Default Values for Study Variables

	Legibility Distance (ft)	Speed of PCs (mph)	Relative Speed (mph)	Lateral Offset of Sign (ft)	Maximum Divergence Angle φ (Degree)	# of Familiar Words in Sign	Volume-to-Capacity Ratio	Percent HVs
Default	480	65	-10	15	15	3	0.7	20%
Levels								
	400	40	-15	10	10	2	0.3	5%
	480	50	-10	15	13	3	0.5	10%
	560	55	-5	20	15	4	0.7	15%
	640	60	0	25	17	5	0.9	20%
	720	65	5	30	20			25%
	800	70	10	35				30%
		75						
Range	400-800	40-75	-15 - +10	10-30	10-20	2-5	0.3-0.9	5%-30%

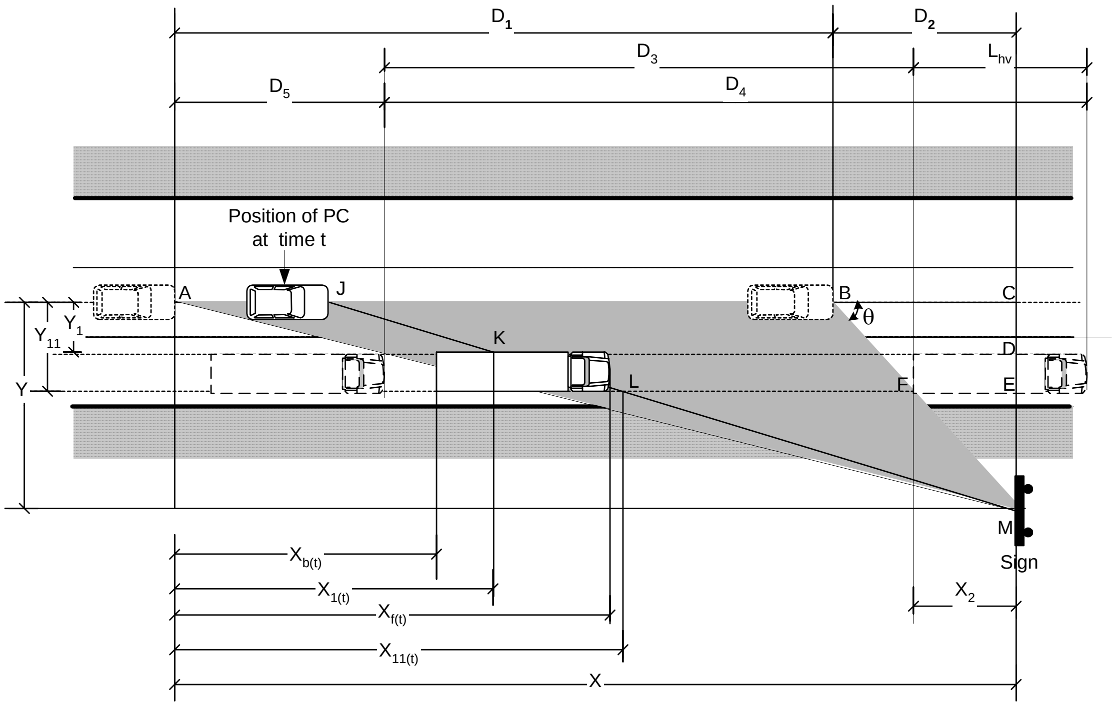


FIGURE 1 Static layout for the occlusion problem with main geometric variables.

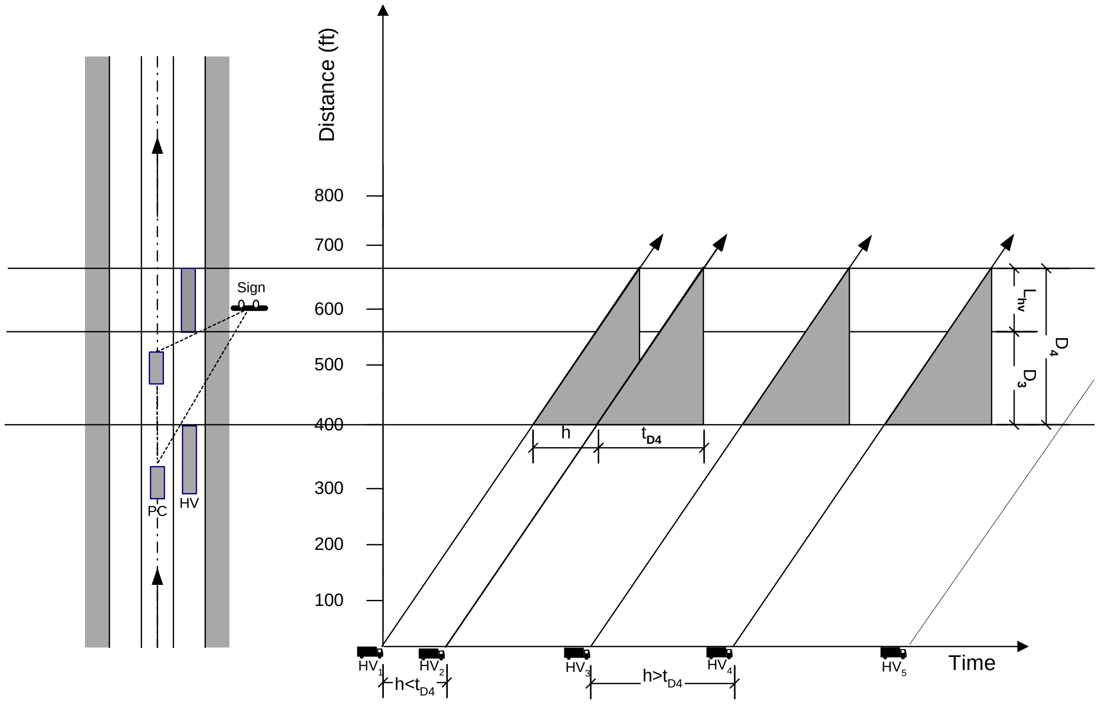
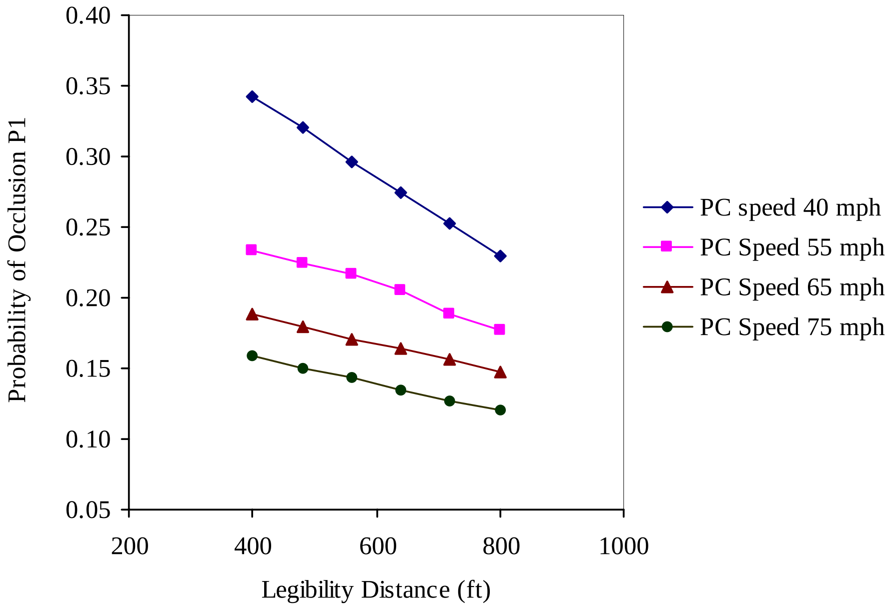
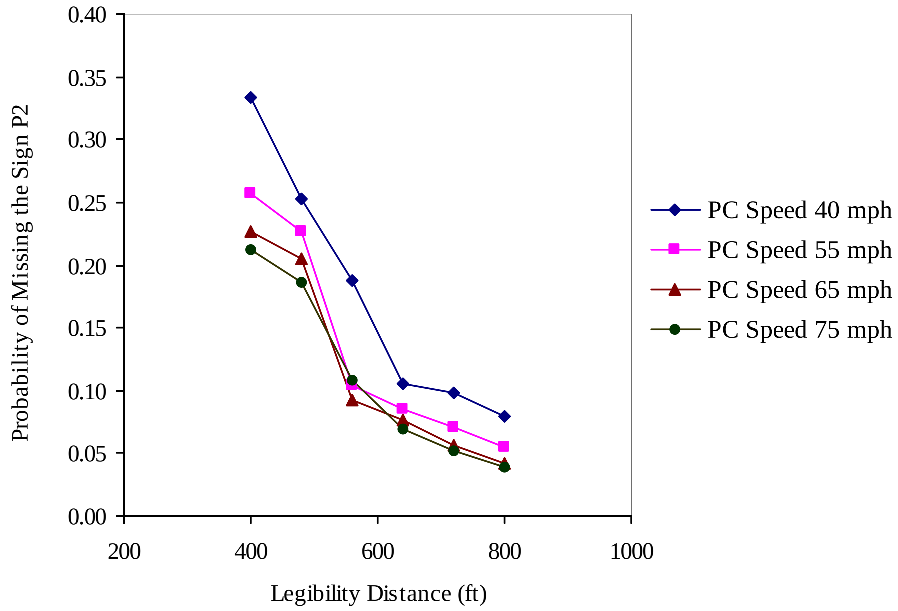


FIGURE 2 Individual and overlapped events.



(a)



(b)

FIGURE 3 Measures of occlusion as a function of legibility distance at different passenger car speeds (a) probability of occlusion (b) probability of missing the sign.

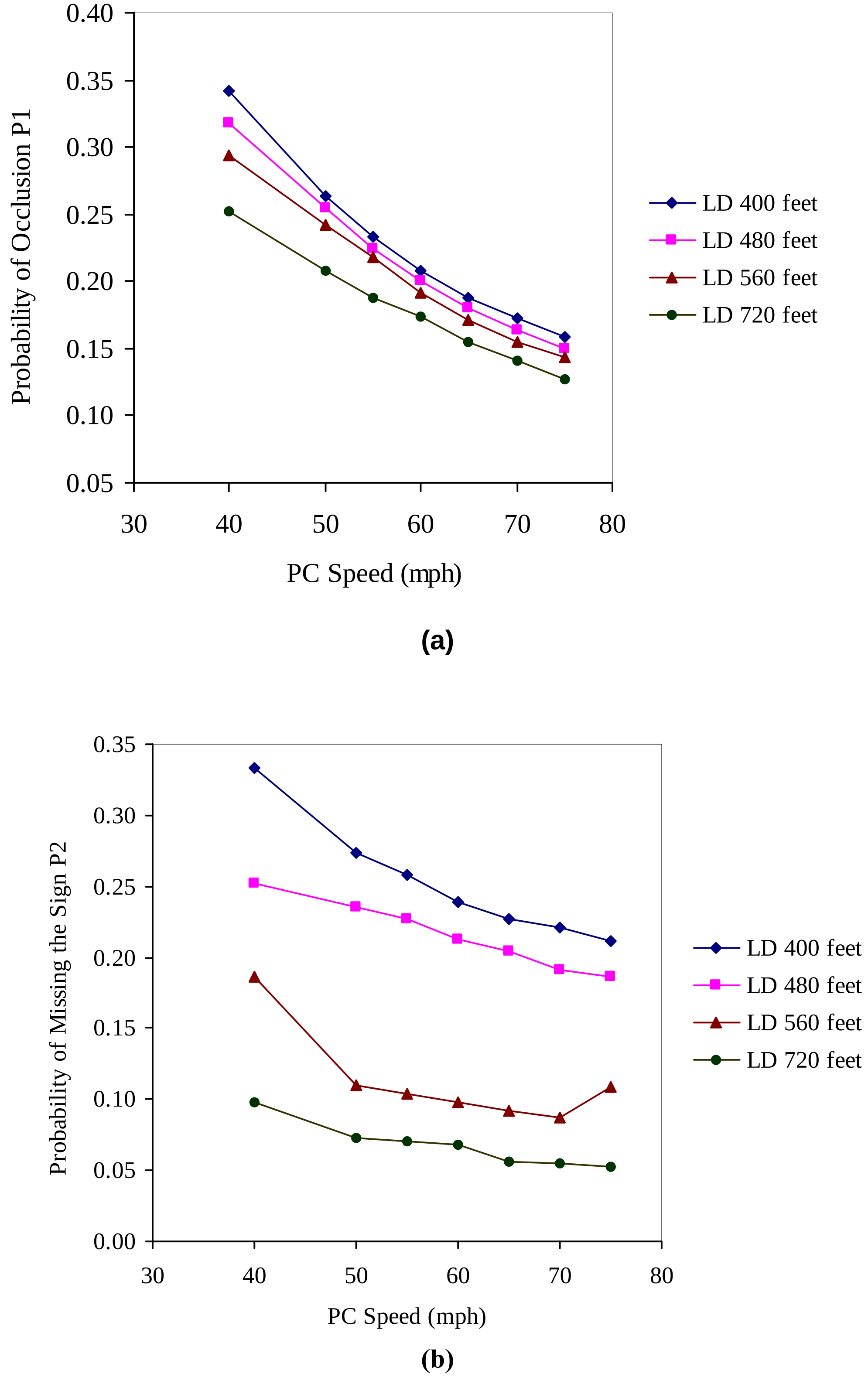
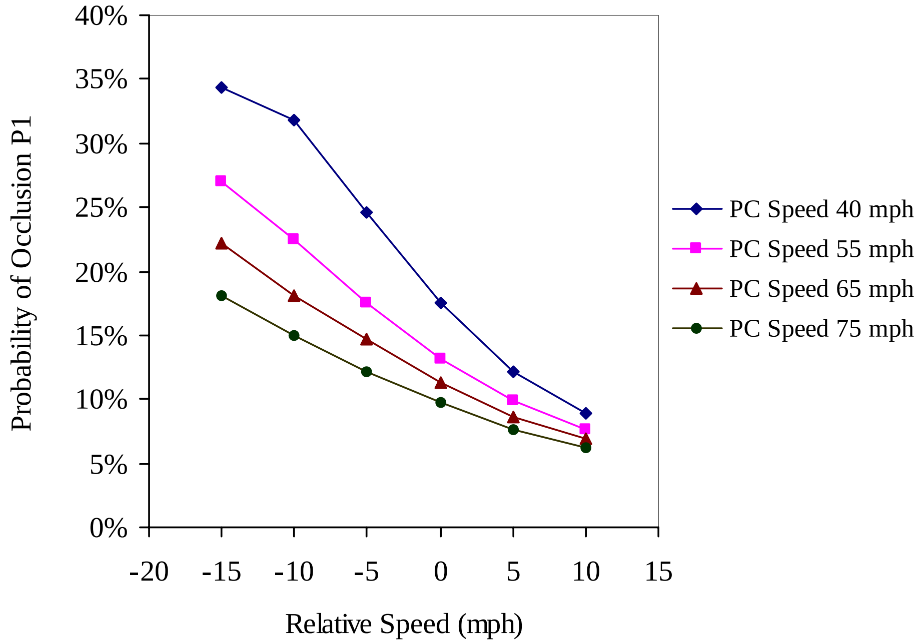
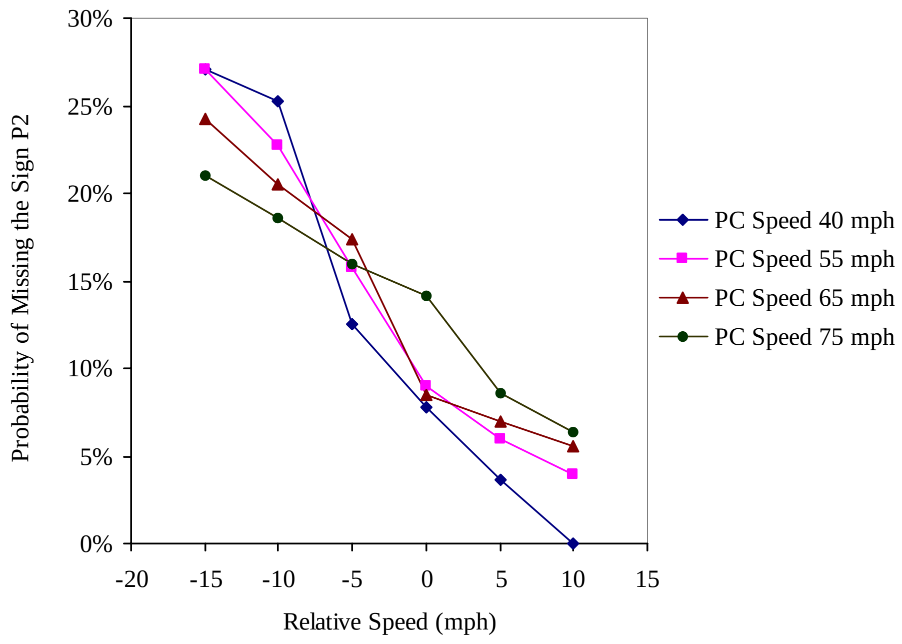


FIGURE 4 Measures of occlusion as a function of pc speed at different legibility distances (a) probability of occlusion (b) probability of missing the sign.



(a)



(b)

FIGURE 5 Measures of occlusion as a function of relative speed at different passenger car speeds (a) probability of occlusion (b) probability of missing the sign.

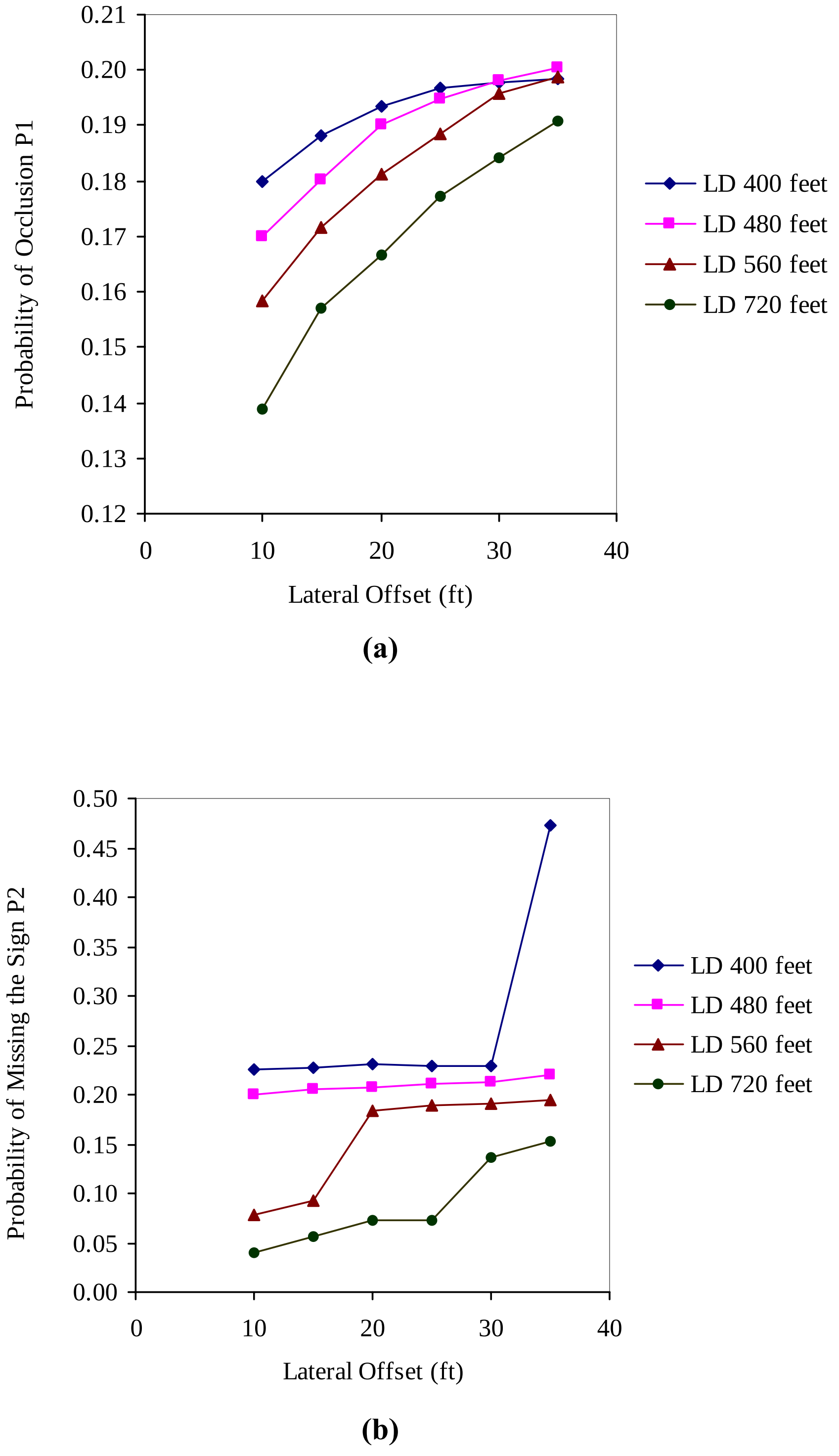
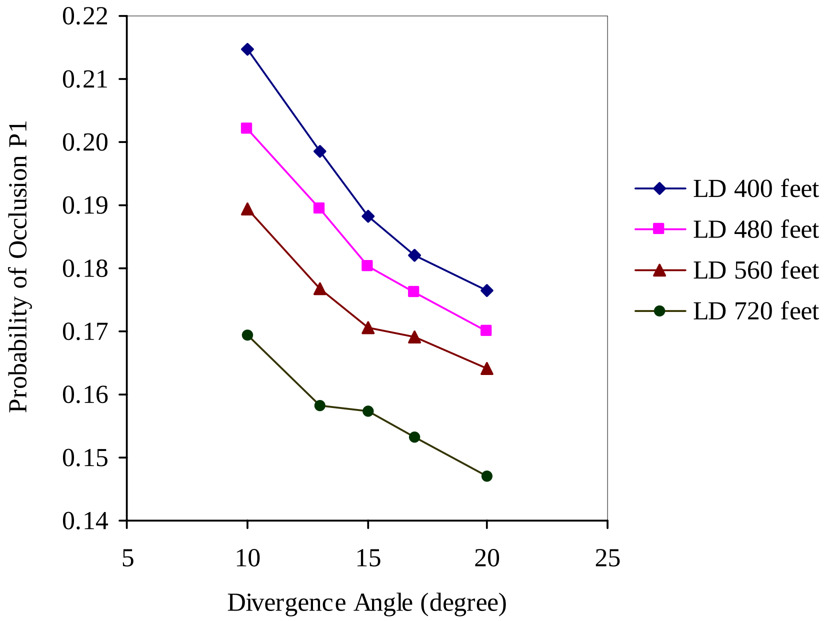
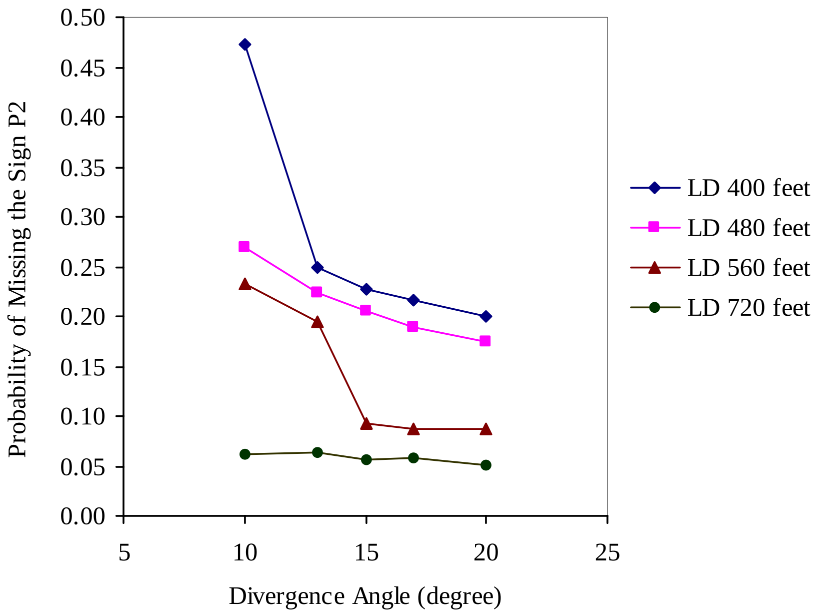


FIGURE 6 Measures of occlusion as a function of lateral offset at different legibility distances (a) probability of occlusion (b) probability of missing the sign.



(a)



(b)

FIGURE 7 Measures of occlusion as a function of maximum divergence angle at different legibility distances (a) probability of occlusion (b) probability of missing the sign.

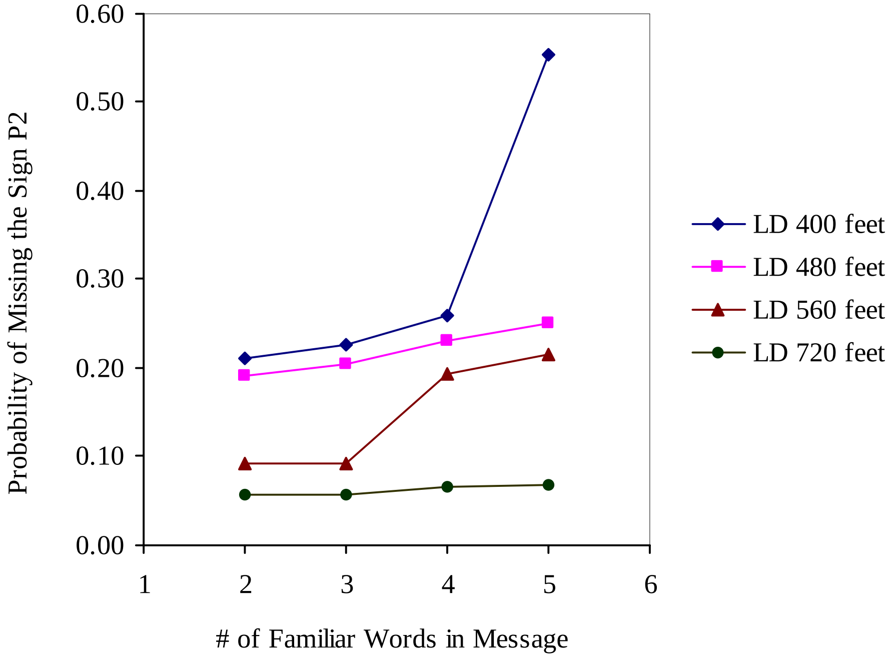
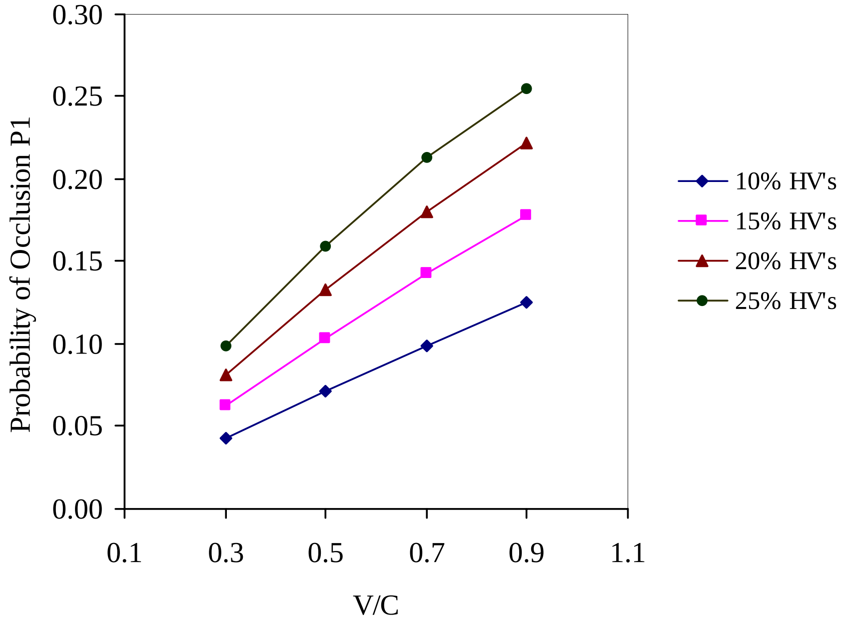
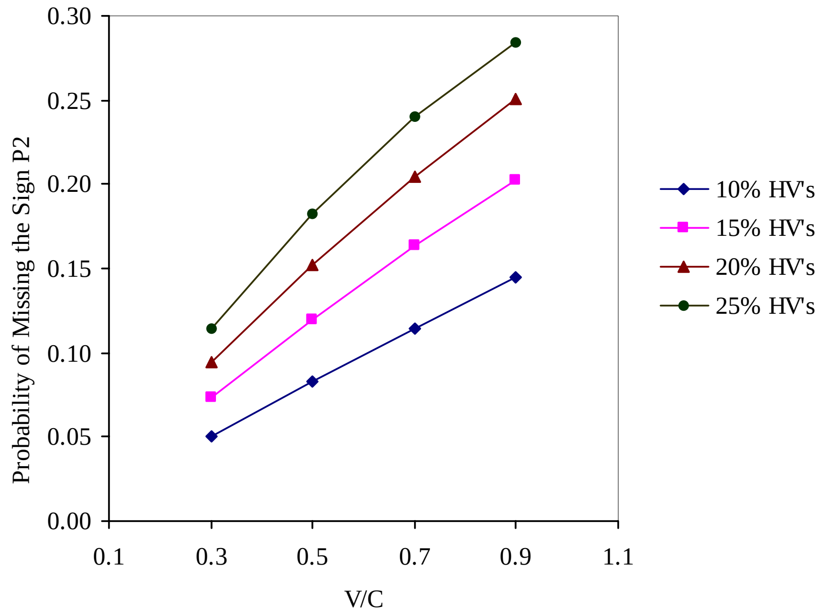


FIGURE 8 Probability of missing the sign as a function of # of familiar words in message at different legibility distances.

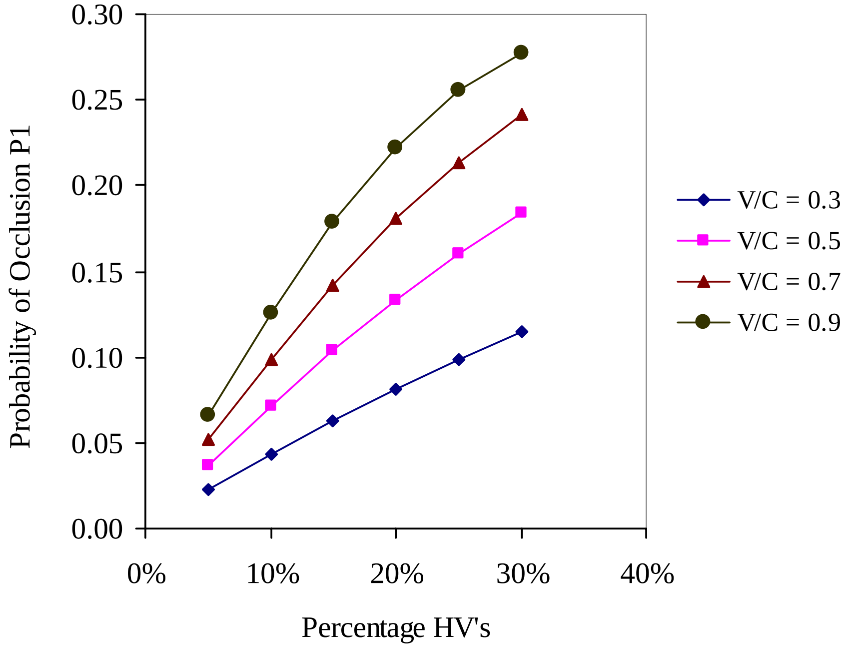


(a)

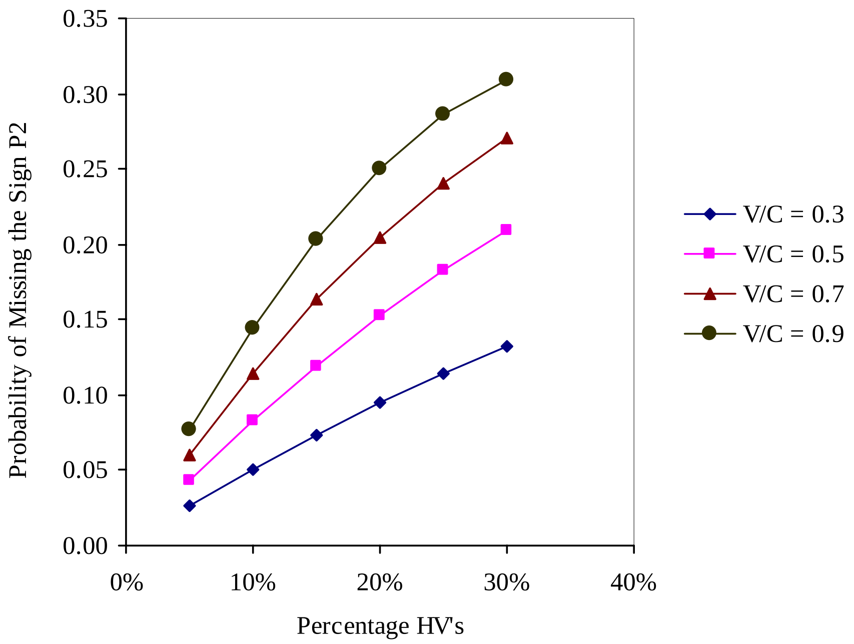


(b)

FIGURE 9 Measures of occlusion as a function of traffic level at different percentages of heavy vehicles (a) probability of occlusion (b) probability of missing the sign.



(a)



(b)

FIGURE 10 Measures of occlusion as a function of percentage of heavy vehicles at different traffic levels (a) probability of occlusion (b) probability of missing the sign.