Mitigation of Sight-Distance Problem for Unprotected Left-Turning Traffic at Intersections

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Sight-distance problems at intersections are often discussed in the context of visual obstructions caused by permanent objects such as trees, parked vehicles, and buildings. Very little investigation has been done on sight-distance problems engendered by queued vehicles. This type of problem poses safety and capacity deficiencies, particularly for unprotected left-turn movements at intersections. The available sight distance for a left-turning motorist on a major approach is shown to be dependent on the offset for opposing left-turn lanes, that is, the distance from the inner edge of a left-turn lane to the outer edge of the opposing left-turn lane. The model developed can be used to determine the minimum offset required for ensuring an adequate sight distance for left-turning traffic, given the design speed and the configuration of the intersection. A sensitivity analysis was undertaken to investigate the effects of changes in the noted offset on the available sight distance for left-turning traffic. It was determined that there was a strong correlation between the offset and the available sight distance for left-turning traffic. It is, therefore, possible to resolve this problem by incorporating in the intersection design some considerations for the minimum offset for opposing left-turning lanes.

Motorists turning at intersections are often confronted with situations that involve quick sequential decision making. These motorists must identify the layout of the intersection and all conflicting traffic movements and decide when to yield and when to execute a maneuver. Such decisions are made in a few seconds, and any misjudgment can result in side-impact accidents that could result in serious consequences. Therefore, in designing intersection geometry, it is important to consider the possible elimination of any hazardous conditions that may arise because of operational conditions. Such an approach would enable motorists to make safer decisions at intersections.

Over the years, substantial improvements have been made to traffic safety and capacity at intersections. Traffic signals, for example, eliminate most of the conflicts and confusion at busy intersections and, hence, improve traffic safety and intersection capacity. In addition, several safety elements are incorporated when designing intersections. One of the most important safety elements in intersection design is "sight distance," which refers to unimpeded vision along a roadway that is available to motorists on a given approach.

Several studies have been undertaken on sight distance requirements at intersections; a recent investigation was undertaken by Poe (*1*). The most complete single reference on sight distance, however, is the 1990 edition of the AASHTO *Policy on Geometric Design of Highways and Streets*, or the Green Book (*2*). Considered as the authoritative reference for geometric design of roadways, the Green Book contains all available relevant information about sight-distance requirements for highway and street (including intersection) design.

The determination of sight-distance requirements for turning vehicles at intersections has in the past concentrated mainly on the movement from the minor road to the major road. Clearly, adequate sight distance is important for safe execution of this movement; as the possible consequence of an accident between a vehicle traveling at a high speed on a major approach and a turning vehicle starting from a stationary position can be severe because of the speed difference and the angle of impact. Turning movements from minor roads to major roads, however, are not the only maneuver at intersections with a high degree of risk. Left-turn movements at intersections from major approaches (roads) to minor or cross streets can be very risky when visibility of oncoming vehicles is obstructed by queued opposing left-turning vehicles. This situation has been acknowledged as the most frequently occurring traffic conflict at intersections (*3*). This problem is also discussed briefly in the *Traffic Control Devices Handbook* (*4*), which recommends a striped island zone to separate through traffic lanes from the left turn bay. This problem has not been investigated in detail, so this paper identifies the risks that the condition poses and seeks possible remedies through an analytical approach. Current intersection design practice does not require evaluation of sight-distance requirements under this particular operational condition. However, during field review such problems are often identified and corrective measures undertaken.

In this paper, any left-turn maneuver made at an intersection that has no exclusive left-turn signal phase is referred to as an "unprotected left-turn maneuver." Such maneuvers are made at any unsignalized intersection or at signalized intersections with a permissive green phase. The obvious and intended implication of this terminology is that such maneuvers involve a risk that is nonexistent for those made during an exclusive left-turn phase.

BACKGROUND OF PROBLEM

Under normal circumstances, unprotected left-turning vehicles at an at-grade intersection execute their turning maneu-

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vers only when gaps acceptable to the drivers become available. For left-turning vehicles from a major road to a minor road, the conflicting traffic movement is the opposing through and right-turning traffic. To evaluate effectively the available gaps and to choose those that are adequate for safe manuevers, left-turning motorists should be able to see a sufficient distance along the opposing approach.

Field observations have shown that most intersections with unprotected left-turning movements in opposite directions operate poorly because left-turning motorists at the major approaches suffer sight-distance problems due to obstructed vision by queued opposing left-turning vehicles. For safe execution of left-turn maneuvers, it is common for motorists to either wait for the opposing queue to dissipate or slowly move toward the center of the intersection to increase their sight distance. In both cases, excessive time is used by left-turning motorists to execute the turning manuever, which consequently contributes to capacity deficiencies at such intersections. In addition, there is a definite safety concern associated with such sight-distance problems. Aggressive or impatient motorists are sometimes tempted to accept gaps on the available sight distance, which may not be adequate for the speed of the oncoming traffic. However, because this is an operational condition that occurs frequently, it should be given more consideration during the intersection design and also before installation of permissive green signal phases for major approaches.

OBJECTIVE

The objective of this paper is to use a theoretical approach to determine design criteria for ensuring minimum safe sight-distance requirements for unprotected left-turning vehicles from major roads to minor roads, given the geometric configuration of the intersection and the major approach design speed.

ASSUMPTIONS AND NOTATION

Figure 1 shows a simplified geometric configuration of an at-grade intersection with two unprotected opposing left-turning vehicles: vehicles V1 and V2. As shown in this figure, the major road is a four-lane divided road and is assumed to run east-west. The minor road is a two-lane road that runs north-south. The alignments of major intersection approaches are assumed to be tangent and level. The curb-to-curb distance of the minor road is denoted W_n, and the lateral distance from the side of vehicle V1 to the curb on eastbound approach, W_x.

The analysis is based on the available sight distance for left-turning motorists on the eastbound approach. However, the same analysis and results can be applied to the westbound left-turn approach.

It is assumed that left-turning motorists tend to maximize their sight distance of the opposing approach by staying as close as possible to the inner edge of the lane. The separation between the side of a left-turning vehicle and the inner edge of the left-turn lane is denoted X_t. According to the Green Book, an X_t value of 2 ft can be assumed for design purposes.

In Figure 1, X_d is the lateral distance between the line of sight of the driver of vehicle V1 and the left edge of vehicle V1. The value of X_d would depend on the type and size of the vehicle. For example, most compact cars would have smaller X_d values than larger cars and trucks. The distance from the

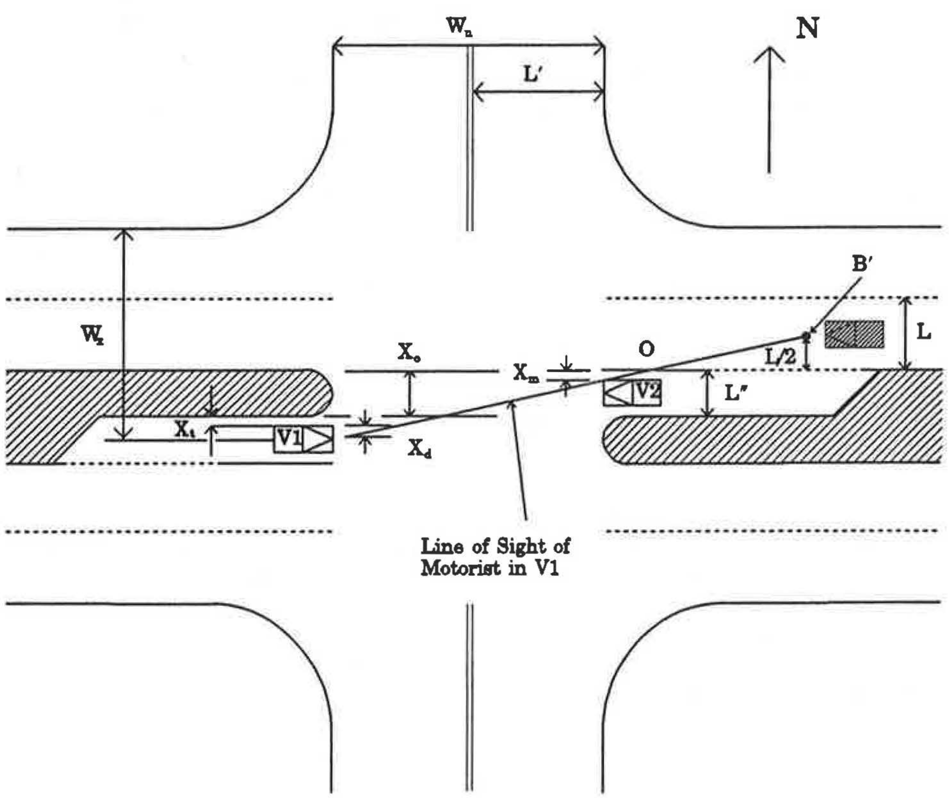

FIGURE 1 Intersection configuration.

outer edge of the westbound left-turn lane to the inner edge of the eastbound left-turn lane is denoted by X_o; and the distance from the right side of vehicle V2 to the outer edge of the westbound left-turn lane by X_m. Like X_d, the value of X_m is dependent on the type and size of the vehicle. The variable X_o is the offset between opposing left-turn lanes. When X_o is zero, the left-turn bays are aligned directly opposite one another.

In Figure 1, the point B' is taken to be the farthest point at which an oncoming westbound vehicle becomes visible to the driver of vehicle V1. This point is where the driver's line of sight intersects the centerline of the nearest westbound through lane traveled by the oncoming vehicle. This is based on the assumption that to identify an oncoming vehicle at least half that vehicle's frontal view should be visible. This may not be true for all drivers and all lighting conditions. However, this is a reasonable assumption that at worst would introduce a factor of safety into the following analysis. The driver of vehicle V1 can see only objects left of this line of sight because vehicle V2 and other queued vehicles impede his vision to the right. Therefore, for an adequate view of all oncoming westbound traffic, the distance from the stop line of the westbound approach to Point B′ must be equal to or greater than the minimum required safe sight distance. In other words, a safe left-turn maneuver is one in which a vehicle turning left can safely move across all opposing lanes before any unobserved opposing vehicle reaches the intersection.

Figure 2 shows the assumed path P1–P2–P3–P4 of the eastbound left-turning vehicle V1. Here the assumption is that P1–P2 is a circular curve with radius R. Many motorists executing such left-turn maneuvers tend to follow a path closer to the chord from P1 to P2, to reduce the travel path and hence the time to execute the maneuver. Others tend to move into the intersection to get a better view of oncoming traffic (i.e., increase sight distance) and to reduce crossing time. The circular path assumption P1–P2 in the following analysis results in a more conservative approach erring on the side of safety. Before the vehicle initiates the turning maneuvers, it is parallel to the centerline of the lane of travel and will be parallel to the centerline of the receiving lane on the minor road at the end of the maneuver. In other words, the centerline of the receiving lane is tangential to the assumed circular curve (see Figure 2). Therefore, the arcs P2–P3 and P3–P4 are assumed to be linear.

As shown in Figure 2, W_m is the distance from edge of the southbound approach to the centerline of the innermost northbound lane, and W_x is the distance from the center of vehicle V1 to the far edge of eastbound approach.

Based on the P1–P2 circular path assumption, for all conditions in which $W_x > W_m$, the radius R can be expressed by Equation 1.

$$R = \max\{W_m, 24 \text{ ft}\} \tag{1}$$

where

L' = width of the northbound lane on the minor road, and

$W_m = W_n - (0.50)(L')$.

In Equation 1, the minimum turning radius of 24 ft specified in the Green Book for Type P design vehicle is preserved.

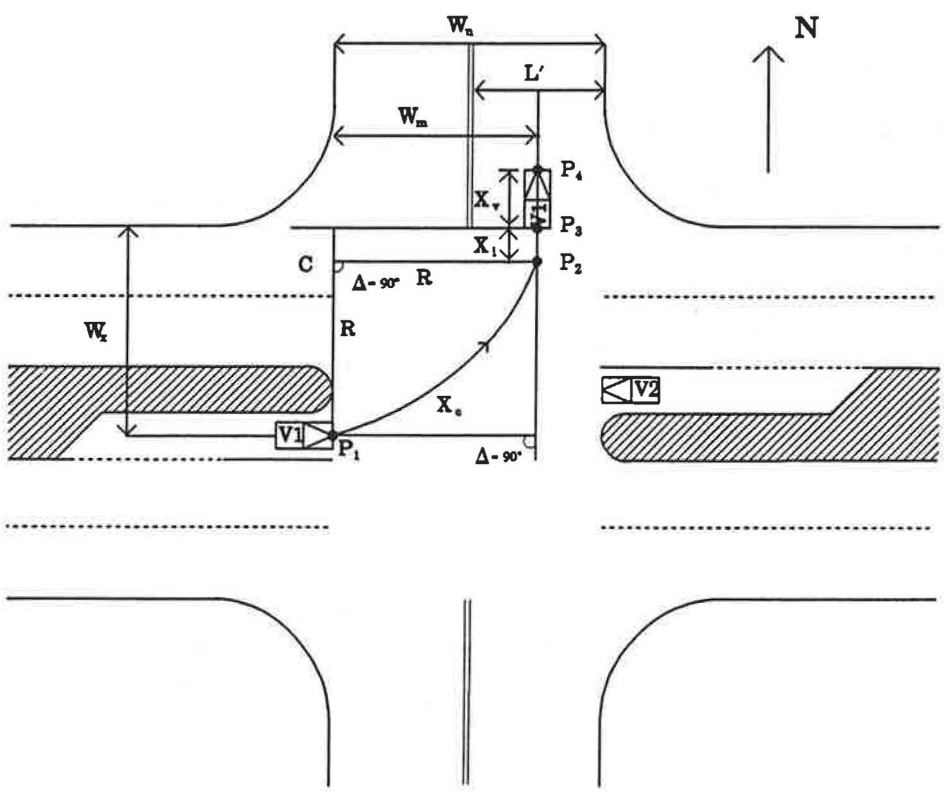

FIGURE 2 Travel path of left-turning vehicle V1.

In Figure 2, the distance X_t from P2 to P3 is the difference between W_x and W_m or W_x and 24 ft (whichever is larger); where $W_x \geq W_m$. The distance X_v from P3 to P4 is the length of the turning vehicle. The total distance traveled by vehicle V1 to clear the intersection safely, therefore, is the sum of X_c, X_t, and X_v. The distance X_c or the length of the circular curve P1–P2 can be expressed as

$$X_c = (\pi \Delta R)/180 \tag{2}$$

where Δ is the angle of deflection of the circular curve; for the case analyzed, this angle is equivalent to the internal angle formed by the intersection of the major approach and the minor approach traveled by the left-turning vehicle (see Figure 2).

The value of Δ depends on the geometric configuration of the intersection. However, for most intersections, it is reasonable to assume Δ as 90 degrees. If $\Delta < 90$ degrees, the circular arc could be defined as above. However, if $\Delta > 90$ degrees, then the point at which the circular arc would terminate may occur on the northbound approach clear of westbound approach.

The total distance from point P1 to P4 is denoted by D. When a left-turning vehicle has moved from P1 to P4, it has also cleared all conflicting vehicle paths. The safe left-turn maneuver, therefore, is one in which the left-turning vehicle can reach P4 before a westbound vehicle reaches the intersection. Equation 3 shows the components of D.

$$D = X_c + X_t + X_v \tag{3}$$

or

$$D = (\pi \Delta R)/180 + (W_x - W_m) + X_v \tag{4}$$

The time-acceleration-distance relationship provided in the Green Book can be used to determine the time t_c required by the left-turning vehicle V1 to clear the intersection. This information can then be used to evaluate the adequacy of the sight distance available to a left-turning vehicle.

MODEL FORMULATION

Figure 3 is a simplified representation of the dimensions and geometrics, as identified in Figure 1, pertaining to the problem. Two opposite triangles are formed by vehicle VI driver's line of sight and the lane line AB between the westbound through and left-turn lanes. By definition, the distance from Point A to Point B is the available sight distance, parallel to the road centerline, for driver of vehicle V1. In addition, a sight-distance problem exists only if $X_m < X_t + X_d + X_o$. For values of $X_m < X_t + X_d + X_o$, the following relationships hold:

$$(W_n + S)/(X_t + X_d + X_o) = S/X_m \tag{5}$$

$$S/(X_m) = T/0.5L \tag{6}$$

$$S = [W_n(X_m)]/(X_t + X_d + X_o - X_m) \quad \text{for } X_t + X_d + X_o \geq X_m \tag{7}$$

$$T = [W_n/(X_t + X_d + X_o - X_m)]0.5L \tag{8}$$

where S is the distance from the front end of vehicle V2 to Point O; that is, the point at which the line of sight of driver of vehicle V1 intersects with Line AB; and T is the distance from Point O to Point B (see Figure 3).

Recall that Point B' is where the line of sight of driver of vehicle V1 intersects the middle of the innermost westbound through lane. Point B, therefore, represents the available sight-distance limit on the nearest westbound through lane. This is the sight distance that controls.

On this basis, the available sight distance (SD) can be determined from Figure 3 as follows:

$$\text{SD} = W_n + S + T \tag{9}$$

Substituting the values of S and T from Equations 7 and 8 in Equation 9 results in the following equation:

$$\text{SD} = W_n + [W_n(X_m)]/(X_t + X_d + X_o - X_m) + [W_n/(X_t + X_d + X_o - X_m)]0.5L \tag{10}$$

Simplified further, Equation 10 results in

$$\text{SD} = [W_n/(X_t + X_d + X_o - X_m)] \times [(X_t + X_d + X_o) + 0.5L] \quad \text{for } X_t + X_d + X_o \geq X_m \tag{11}$$

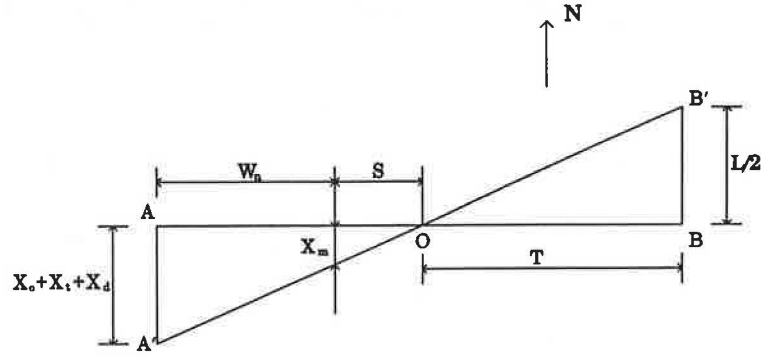

FIGURE 3 Geometric representation of design variable relationships.

Equation 11 can be used to evaluate the available SD for a given left-turn approach on a major road or to determine the appropriate value(s) of the offset X_o for a safe SD.

SIGHT-DISTANCE EVALUATION

The minimum safe SD required at the intersection is the distance traveled by an oncoming vehicle during a time t_c that would be required for a left-turning motorist to clear the intersection safely; that is, to travel a distance D (see Equation 4). The available time to make this maneuver, on the basis of available SD and approach design speed V_x, denoted by T_g, is given by Equation 12.

$$T_g = \mathrm{SD}/V_x \qquad (12)$$

The time (t_c) it will take a left-turning vehicle from a stopped position to complete a turning maneuver can be estimated by making some assumptions about the acceleration rates of the vehicle and the perception-reaction time of the driver. For design purposes, these values can be obtained from the Green Book. The value of t_c can then be determined from Equation 13.

$$t_c = J + t_a \qquad (13)$$

where J is the sum of the perception time and the time required to actuate the clutch or actuate an automatic shift (in seconds), and t_a is the time required to accelerate and traverse the distance D.

The value of t_a can be obtained from the relationship between t_a and distance traveled D, shown in Figure 4, for Type P vehicles. This curve is based on Figure IX-33 of the Green Book (*3*).

For safe completion of left-turn maneuvers, SD must yield values for T_g that satisfy $T_g > t_c$. In other words, mitigation measures are necessary if $T_g \leq t_c$.

MITIGATION MEASURES

As noted earlier, a left-turning motorist tends to maximize sight distance by staying as close as possible to the inner edge of the turn lane. In view of this, X_m can be considered as a function of the width of the left-turn lane and can be estimated as

$$X_m = L'' - (X_t + w) \qquad (14)$$

where

L'' = width of the westbound left turn lane,
w = width of the opposing left-turning vehicle, and
X_t = separation between the edge of the vehicle and the outer edge of the westbound left-turn lane (as noted earlier, X_t can be assumed to be 2 ft).

Substituting the value of X_m from Equation 14 into Equation 11,

$$\mathrm{SD} = \{(W_n)/[X_t + X_d + X_o - L'' + (X_t + w)]\} \times [(X_t + X_d + X_o) + 0.5L] \qquad (15)$$

Simplifying Equation 15 further,

$$\mathrm{SD} = [W_n/(2X_t + X_d + w + X_o - L'')] \times [(X_t + X_d + X_o) + 0.5L] \qquad (16)$$

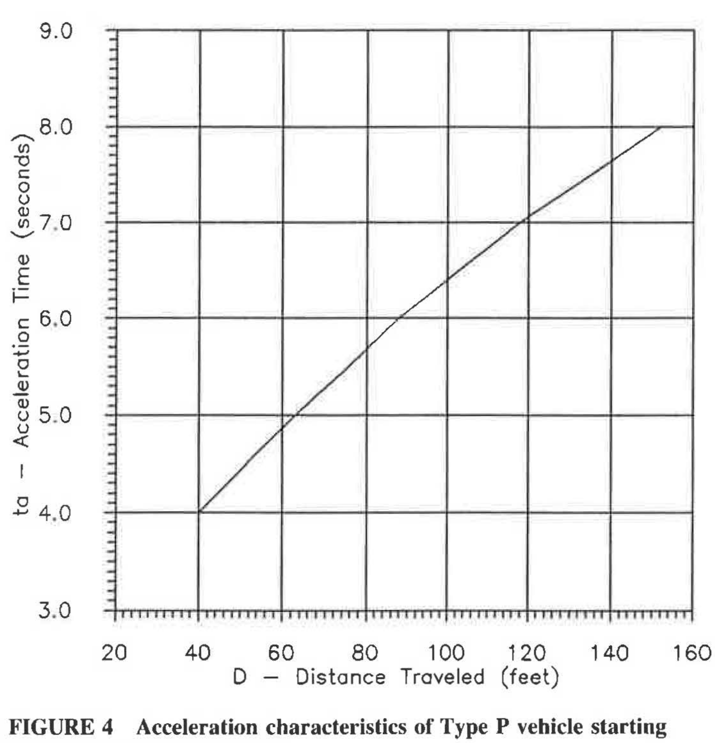

FIGURE 4 Acceleration characteristics of Type P vehicle starting from stop (*1*, Figure IX-33).

By decreasing the offset X_o while maintaining all other variables constant, Equation 16 yields longer SD values. Therefore, an effective mitigation measure for the sight-distance problem discussed here is to decrease the offset (X_o) for opposing left-turn lanes. The same end result would be achieved by increasing the dimensions of L'' or L, or both.

PRACTICAL APPLICATIONS

It must be recognized that the minimum value that can be provided for the offset X_o is 0 ft. This occurs when the two left-turn lanes are aligned directly opposite to one another. Although, theoretically, negative values for X_o would increase sight distance, intersection geometry based on negative X_o values would result in unsafe conditions. At locations where a wide median is available on the intersection approaches, the left-turn bay could be widened with a painted island separating it from through lanes (*4*). The model is based on the assumption that major intersection approaches are tangent and level. This assumption simplified the analysis. However, in reality, intersection approaches may contain curvilinear alignment that would make this particular sight-distance problem more pronounced. Therefore, in using this model or approach for evaluating an existing intersection, both the horizontal and vertical alignment on the approaches must be considered. The following example illustrates how this model can be used for a safety evaluation of sight distance at an existing intersection.

Example: Evaluation of Available Sight Distance for Left-Turn Traffic

The following parameters are based on as-built plans of the intersection:

- $X_o = 6$
- $L = 12$ ft
- $L' = 11$ ft
- $L'' = 12$ ft
- $W_x = 33.5$ ft
- $W_n = 33$ ft
- $X_t = 2$ ft
- $X_v = 19$ ft
- $X_d = 1.5$ ft

Design values for vehicle and driver parameters are assumed as $w = 7$ ft and $J = 2$ sec. Design speed for major approach is $V_x = 66$ ft/sec (45 mph).

Problem

Is the sight distance available for a left-turning vehicle (in the presence of an opposing left-turning vehicle) adequate for making a safe maneuver?

Analysis

$X_m = 12 - (7 + 2) = 3$ft (from Equation 14)
SD $= [33/(4 + 1.5 + 7 + 6 - 12)][(2 + 1.5 + 6) + 0.5(12)] = 78.6$ ft (from Equation 16)

$W_m = R = W_n - (L'/2) = 33 - 5.5 = 27.5$
$D = [\pi(90)(27.5)]/180 + (33.5 - 27.5) + 19 = 68.2$ ft (from Equation 4)

From Figure 4, t_a for $D = 68.2$ ft is estimated to be 5.2 sec. Therefore, from Equation 13, total time t_c required to clear the intersection is $5.2 + 2 = 7.2$ sec.

From Equation 12, $T_g = 78.7/66 = 1.2$ sec.

In the preceding example, $T_g < t_c$. Therefore, it is clear that the available sight distance is not adequate. The available sight distance may be increased by decreasing the offset X_o. For this example, if X_o is reduced to 0 ft, it can be shown that SD will increase to 627 ft. Alternatively, the width L'' of the opposing left-turn lane or the width L of the opposing through lane can be slightly increased to obtain similar results. In some situations this evaluation may indicate that it is not possible to provide the required minimum sight distance without a major redesign of the intersection. In such cases the overall intersection safety can be improved by the following actions:

1. At signalized intersections at which this problem occurs during the permissive green phase, eliminate this phase and provide an exclusive left-turn phase.
2. At unsignalized intersections, reduce the offset as much as possible and enforce a reduced speed limit on the opposing approach.

Sensitivity Analysis

A sensitivity analysis based on the model formulated earlier was undertaken to investigate the effect of the offset on sight distance. In Equation 16, by holding other variables constant, X_o was gradually varied to evaluate the corresponding effect on the available SD.

The analysis was undertaken for a Type *P* design vehicles with $w = 7$ ft, and the results are shown in Table 1. It can be deduced from Table 1 that the available sight distance is very sensitive to X_o. Therefore, it is possible for the designer to define intersection layout so that adequate sight distance is provided for left-turning traffic. The designer, for example, can maximize available sight distance by minimizing the value of the following expression:

$$2X_t + X_d + w + X_o - L'' \qquad (17)$$

Because X_t, X_d, and w are assumed to have fixed minimum values, the above expression can be minimized by decreasing X_o or increasing L'' or doing both.

SUMMARY AND CONCLUSION

Sight-distance problems are associated with many safety and capacity deficiencies. In this paper, a relationship is established between the available sight distance, which is a reduced value due to one or more queued left-turning vehicles in the opposite direction, and the offset distance between opposing left-turn lanes at the major approaches of a typical at-grade intersection. This is a common operational problem in urban areas. The model formulated to analyze this problem used a

TABLE 1 Lane Offset and Sight-Distance Relationship

Xo	L	L"	SD
12.0	11.0	11.0	51.3
6.0	11.0	11.0	66.0
4.0	11.0	11.0	78.0
2.0	11.0	11.0	103.7
1.0	11.0	11.0	132.0
0.0	11.0	11.0	198.0
12.0	12.0	12.0	56.8
6.0	12.0	12.0	78.7
4.0	12.0	12.0	99.0
2.0	12.0	12.0	151.8
1.0	12.0	12.0	231.0
0.0	12.0	12.0	627.0
12.0	12.0	13.0	61.7
6.0	12.0	13.0	93.0
4.0	12.0	13.0	127.3
2.0	12.0	13.0	253.0
1.0	12.0	13.0	693.0
0.0	12.0	13.0	Unlimited

Note: All above dimensions are given in feet

Wn	=	33.0 feet
Xt	=	2.0 feet
Xd	=	1.5 feet
Xv	=	19.0 feet
w	=	7.0 feet

simplified intersection geometry with level and tangent approaches and a 90-degree angle of intersection. Therefore, it applies only to intersections with similar geometric features. However, this analytical approach can be used, with appropriate modifications to the model, to evaluate the margin of safety for such left-turn maneuvers at any existing intersection.

In the model formulation, two major assumptions were employed; that is, the tendency of left-turning motorists to maximize their sight distance by staying as close as possible to the median, and the circular arc formed by the path of the left-turning vehicle. To be consistent with other aspects of intersection geometric design, all values related to design vehicle dimensions, acceleration rates, and other design elements were based on current design practice.

For the assumed intersection configuration, opposing approach speed, and design vehicle, the available sight distance is shown to be dependent on the lane offset. Equations were also developed for the available time gap for crossing, on the basis of available sight distance, and the required time for crossing. This model can be used to determine the offset required to ensure adequate sight distance for left-turning motorists at major approaches of similar intersections. The optimum condition for sight distance is shown to exist when this offset is zero. At existing intersections, large offset distances may be reduced by increasing the width of opposing left-turn lanes. This can also be achieved by providing a striped island to reduce the offset, thereby reducing the overall level of risk associated with left-turn maneuvers. For example, the outer portion of a left-turn lane could be striped so that the through traffic does not encroach on the opposing left-turning traffic. Such measures to decrease any existing offset will also reduce the median width.

The analytical approach presented can be used to generate suitable criteria for intersection design. It could also be used as a methodology for safety evaluation of existing intersections at which this operational condition is likely to occur. It would also be a valuable tool for determining the possible safety implications of providing a permissive left-turn signal phase, at locations with opposite left-turn bays.

Finally, the model discussed here has not been subjected to empirical testing. However, it is the authors' opinion that favorable results could be obtained because the model is sensitive to critical traffic and geometric factors related to this sight-distance problem. The implications of horizontal and vertical curvature on the approaches are also not considered in the analysis. It is the authors' hope that the discussions prompted by this paper lead to more comprehensive analyses that provide solutions to this common intersection safety problem.

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