Comparison of Sight Distance Procedures for Turning Vehicles from a Stop-Controlled Approach

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The AASHTO Green Book intersection sight distance procedures for turning vehicles are based on the passenger car as the design vehicle. Highway design and operational criteria, however, should consider the characteristics of vehicles that can be expected to use a facility with reasonable frequency. Equations were developed to reproduce the intersection sight distance values presented in the 1984 Green Book. By using different values for certain parameters (i.e., truck acceleration instead of passenger car acceleration information), sight distance values for other conditions can be calculated. When truck characteristics from the Green Book are used in the equations, values over ½ mi in length for certain design speeds result. Operational and safety experiences at intersections indicate that sight distances of this magnitude are not needed for safe and efficient operations. Procedures based on actual operations at an intersection should result in values that better reflect sight distances drivers use. An intersection sight distance procedure based on the gaps a driver safely accepts during actual intersection operations is presented. Field data on the various intersection sight distance parameters and gap acceptance data were obtained from studies at six intersections. These data are used to develop intersection sight distance values from (*a*) the proposed gap acceptance procedure and (*b*) current parameter values used in the developed equations. These results are compared with both the 1984 and 1990 Green Book intersection sight distance values.

The 1990 edition of AASHTO's *A Policy on Geometric Design of Highways and Streets* (*1*) (known as the Green Book and as GB90 as used herein) contains stop-controlled intersection sight distance (ISD) procedures. The procedures for turning vehicles are based on consideration of the passenger car as the design vehicle. Highway design and operational criteria, however, should consider the characteristics of vehicles that currently use or anticipate using a facility with reasonable frequency.

This paper briefly reviews both the 1990 (GB90) and 1984 (GB84) AASHTO ISD procedures (*1,2*). Truck parameter values derived from AASHTO information are used in recently developed equations to illustrate the need to consider alternative procedures. One alternative procedure is to base ISD on the gaps that drivers typically accept during actual intersection operations. Data collected at several intersections are used in the "developed equations" and in the proposed gap acceptance procedure to produce values based on current vehicle performance. These values are compared with GB90 and GB84 ISD values.

This paper synthesizes several previous publications on intersection sight distance. Additional information can be obtained from several detailed publications including the Harwood et al. study on truck characteristics (*3*) and the work by Fitzpatrick on passenger cars (*4*). Previous Transportation Research Board publications report on the sensitivity analyses (*5*), the field studies (*6*), the reviews of ISD Case III (*7*) and ramp terminal (*8*) procedures, and the gaps accepted by truck and passenger car drivers (*9*).

AASHTO INTERSECTION SIGHT DISTANCE PROCEDURES

Three basic maneuvers occur at a stop-controlled intersection: traveling across the intersecting road by clearing traffic on both the left and the right of the crossing vehicle, turning left onto the intersecting road by first clearing traffic on the left and then entering the traffic stream with vehicles from the right, and turning right onto the intersecting road by entering the traffic stream with vehicles from the left. Consequently, there are three separate sight distance criteria for a vehicle stopped at an intersection. These conditions are referred to by AASHTO as Cases IIIA, IIIB, and IIIC, respectively. Sight distance values are shown in GB84 Figure IX-27 and GB90 Figure IX-40.

Case IIIA—Crossing Maneuver

As stated in the GB90, "the sight distance for a crossing maneuver is based on the time it takes for the stopped vehicle to clear the intersection and the distance that a vehicle will travel along the major-road at its design speed in that amount of time." The sight distance may be calculated from an equation or by using the GB90 Figure IX-39.

Case IIIB—Turning Left onto a Crossroad

A vehicle turning left onto a crossroad should have sight distance to a vehicle approaching from either the right or the left (see Figure 1). In the GB90, the turning vehicle should

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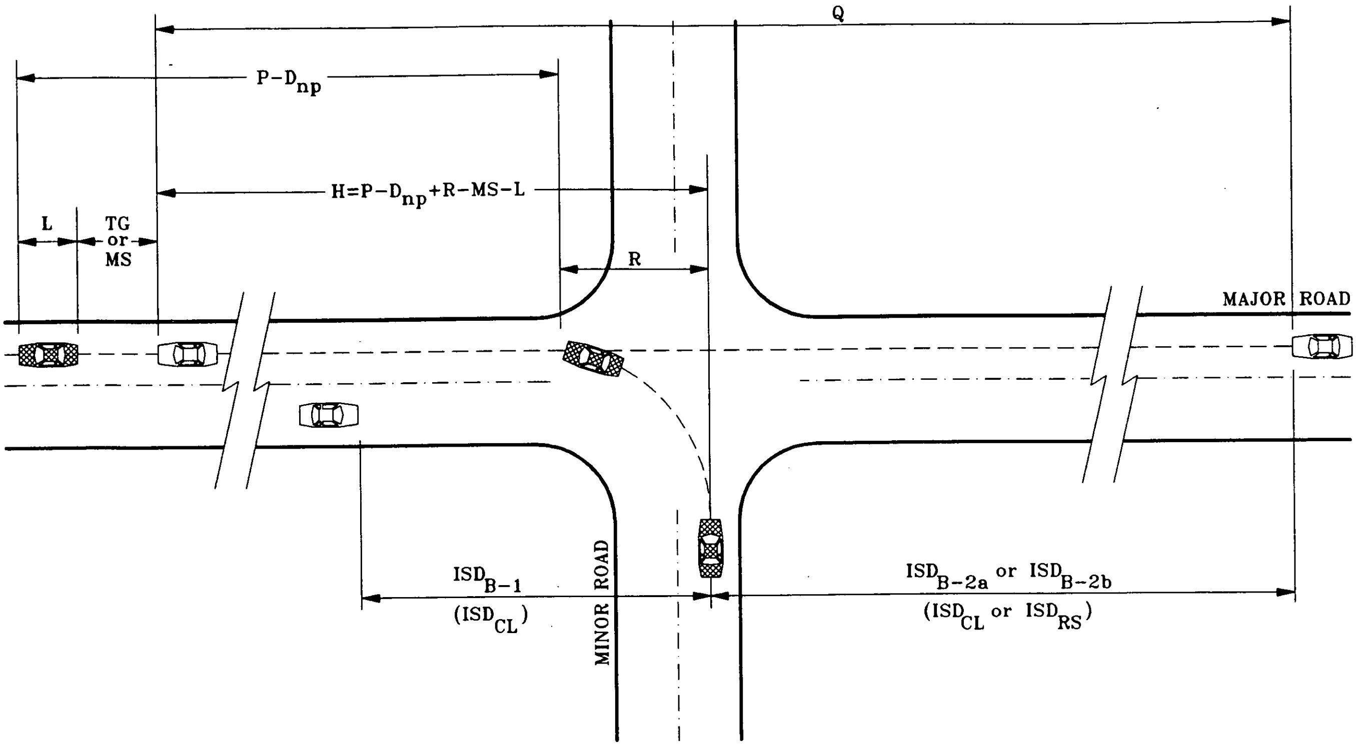

FIGURE 1 Distance considered in a left-turn maneuver.

be able to clear the near lane by the time the major-road vehicle approaching from the left arrives (ISD_{B-1}), and the turning vehicle should be able to accelerate to 85 percent of design speed by the time the major-road vehicle approaching from the right is within a specified vehicle gap distance while traveling at 85 percent of design speed (ISD_{B-2b}). (GB90 Figures IX-36 and IX-37 contain the details of the procedure.) In the GB84, values were provided for the turning vehicle to be able to accelerate to the average running speed by the time the approaching vehicle is within a certain tailgate distance after reducing its speed to the average running speed, or the turning vehicle is able to accelerate to the design speed by the time the approaching vehicle is within a certain tailgate distance maintaining the design speed. (Figure IX-24 in the GB84 contains the details of the procedure.) Distances to the left that provided time for the turning vehicle to clear the near lane were also provided in GB84 Figure IX-27.

In both Green Book versions, AASHTO states that the required sight distances for trucks turning left onto a crossroad will be substantially longer than those for passenger cars. AASHTO further indicates that the sight distance for trucks can be determined using appropriate assumptions for vehicle acceleration rates and turning paths. The specific assumptions, however, are not detailed in AASHTO policy.

Case IIIC—Turning Right onto a Crossroad

In the GB90, the turning vehicle should be able to accelerate to 85 percent of design speed by the time the major-road vehicle is within a specified vehicle gap distance while traveling at 85 percent of design speed. (Figure IX-38 in the GB90 provides the details of the procedure.) In the GB84, a right-turning vehicle should have sufficient sight distance to vehicles approaching from the left to complete its right turn and to accelerate to either design speed or average running speed before being overtaken by traffic approaching the intersection from the left traveling at design speed or reducing to average running speed. (The Case IIIC policy is described in Figure IX-25 in the GB84.) Similar to Case IIIB, AASHTO indicates that sight distances for trucks need to be considerably longer than for passenger vehicles.

REPRODUCTION OF GB84 SIGHT DISTANCE VALUES

GB84 Figure IX-27 contains six sight distance versus design speed curves. Two of these curves are the upper and lower limits for stopping sight distance (SSD). The curve labeled A represents Case IIIA methodology and is the sight distance for a passenger car crossing a two-lane highway from a stopped position. Derivations for the SSD and A curves are included in the GB84 (and in the GB90).

The assumptions and procedures to derive the remaining three curves were not included in the GB84. Some discussions of these curves are included in the GB90, but again no derivation is given. These curves represent the sight distance required for the following maneuvers:

- Left-turning vehicle to clear the near lane (Green Book Case IIIB, B-1 Curve or "Clear Lane," CL, procedure),
- Turning vehicle to accelerate to design speed while major-road vehicle maintains a constant speed (Green Book Case

IIIB and C, B-2a & Ca Curve or "Constant Speed," CS, procedure), and

- Turning vehicle to accelerate to running speed while major-road vehicle reduces speed from design speed to running speed (Green Book Case IIIB and C, B-2b & Cb Curve or "Reduce Speed," RS, procedure)

Sufficient information to easily identify some of the assumed parameter values was missing in the GB84. Using the information that was provided, and making some reasonable assumptions for the missing information, Fitzpatrick and Mason (*7*) reproduced these curves within 8 percent accuracy. Table 1 gives the sight distance values calculated using truck characteristics in the equations developed by Fitzpatrick and Mason (hereafter referred to as the "developed equations") and the sight distance values from both Green Book editions.

The equations to reproduce the Reduced Speed procedure (B-2b & Cb Curve) are given in Table 2. Figure 1 shows the parameters used in the equations. The derivation of the equations and the equations to reproduce the other sight distance values (Clear Lane and Constant Speed procedures) are presented elsewhere (*3,4,7*).

Truck characteristics used in the developed ISD equations frequently produced sight distance values greater than those at which drivers can normally detect motion. Tunnard and Pushkarev (*10*) state that an individual cannot perceive movement much beyond 800 ft or discern detail beyond 1,400 ft because the vehicle is too small and that a car at 2,000 ft appears the size of a pinhead held at 18 in. The Constant Speed procedure produced a sight distance for trucks of 3,200 ft for a 50-mph major-road design speed; the Reduce Speed procedure resulted in a sight distance for trucks of 2,500 ft for the same design speed. Operational experience at intersections indicates that sight distances of such magnitude are rarely necessary for safe and efficient operations.

Generally speaking, intersections currently operate with sight distance less than those calculated and, for practical reasons, ISD procedures should reflect actual field operations. For example, the individual parameter values used in the ISD procedures should represent current and/or future vehicle and driver characteristics. This can be accomplished by explicitly considering gaps in the major-road traffic that are accepted by minor-road drivers. Gap acceptance involves the evaluation of available gaps in an opposing traffic stream and the decision to carry out a specific maneuver within a particular gap. At a stop-controlled intersection, drivers observe the gaps in the traffic streams and then join or cross the major-road traffic stream within the length of the selected gap. Gap acceptance data are, therefore, suggested for use to determine the required sight distance at intersections.

EQUATIONS FOR GB90 SIGHT DISTANCE VALUES

The GB90 contains equations either within the Case IIIB and IIIC discussions or on the figures that describe the cases (see GB90 Figures IX-36, 37, and 38). These equations and a description for each parameter are given in Table 3. Where terms are similar to the previous set of developed equations (see Table 2) but have different values (for example, the new PC acceleration values), "1990" is added after the term to avoid confusion between the two sets of equations. When the GB90 equations were used, the authors of this paper calculated B-2 & Cb intersection sight distance values between 11 and 16 percent less than the values shown in GB90 Figure IX-40. Even though the GB90 indicates that the major-road vehicle decelerates during the minor-road vehicle's turning maneuver, no terms for time at design speed or time for deceleration are included in the GB90 equations (see Table 3). When these terms are considered (the equation for Q distance in Table 2 was used with appropriate GB90 parameter values), the calculated sight distances are 8 percent greater than the previous attempt at reproducing the GB90 values. Expressed in another manner, the calculated values that con-

TABLE 1 Intersection Sight Distance Values

Speed (mph)	Green Book Sight Distance Values (ft)					Calculated Sight Distance Values for Trucks[d] (ft)		
	B-1 Curve		B-2a & Ca Curve[a,c]	B-2b & Cb Curve		B-1-WB50 Clear Lane	BT-2a & Ca Constant Speed	BT-2b & Cb Reduced Speed
	GB84[a]	GB90[b]		GB84[a]	GB90[b]			
20	300	210	250	250	240	687	670	670
25	350	260	340	325	300	858	903	903
30	425	310	450	425	370	1,030	1,179	1,179
35	500	360	580	525	470	1,202	1,516	1,213
40	550	420	750	660	570	1,374	1,938	1,549
45	625	470	950	825	710	1,545	2,483	1,971
50	675	510	1,190	1,025	850	1,717	3,199	2,516
55	750	570	1,440	1,225	980	1,889	* [e]	3,232
60	825	620	1,730	1,475	1,150	2,060	*	*
65	875	670	2,100	1,725	1,350	2,232	*	*
70	950	710	2,500	2,000	1,550	2,404	*	*

[a] Values from GB84 Figure IX-27.
[b] Values from GB90 Figure IX-40.
[c] Concept is briefly discussed in the GB90, however, no values or procedures are provided.
[d] Calculated using equations developed to reproduce GB84 values [7]. Truck characteristics are based on GB84 information.
[e] Acceleration time and distance information not available.

TABLE 2 Equations Developed to Reproduce GB84 ISD Values

$ISD_{B\text{-}2b\ \&\ Cb}$ or $ISD_{RS} = Q - H$ $Q = 1.47\ V_{ds}\ t_{ds} + D_{dec} + 1.47\ V_{rs}\ t_{rs}$ $H = P - D_{np} + R - TG - L$	$t_{rs} = t - t_{ds} - t_{dec}$ $t = t_t + J$ $t_{ds} = J + t_{pr}$	$t_{dec} = (2 * D_{dec}) / (1.47\ V_{ds} + 1.47\ V_{rs})$ $D_{np} = \pi * R/2$ $TG = 1.47\ V_{rs}\ t_{TG}$

$ISD_{B\text{-}2b\ \&\ Cb}$ or ISD_{RS}	=	sight distance along the major roadway's far lane to the right for left turns and along the near lane to the left for right turns. This condition assumes that the major road vehicle reduces speed from design speed to running speed during minor road vehicle's turning maneuver (ft), see Figure 1
Q	=	distance traveled by the major road vehicle during the minor road vehicle's turning maneuver (ft)
V_{ds}	=	design speed of major road vehicle (mi/h)
t_{ds}	=	time major road vehicle is at design speed during turning maneuver (sec)
D_{dec}	=	distance traveled during deceleration (ft), data can be derived from GB84 Figure II-13 or GB90 Figure II-17
t_{dec}	=	time major road vehicle is decelerating (sec)
V_{rs}	=	running speed of major road vehicle (mi/h), assumed as design speed when design speed is 30 mi/h or less, as 5 mi/h below design speed for design speeds of 35 to 65 mi/h, or as 10 mi/h below design speed when design speed is 70 mi/h
t_{rs}	=	time major road vehicle is at running speed during turning maneuver (sec)
H	=	major road vehicle's distance from intersection when at assumed tailgate distance to minor road vehicle (ft)
t	=	time for a stopped minor road vehicle to move into traffic stream and accelerate to design speed (sec)
J	=	sum of perception time and time required to actuate the clutch or automatic shift (sec), assumed: $J = 2.0$ sec
t_t	=	acceleration time for the minor road vehicle to complete the turning maneuver (sec), data can be derived from GB84 Figure IX-22 or GB90 Figure IX-34 and IX-34A
t_{pr}	=	perception-reaction time for the major road driver (sec), assumed: $t_{pr} = 2.0$ sec
P	=	total distance traveled by minor road vehicle from stopped position to location when the reduced speed is achieved (ft), data derived from GB84 Figure IX-22 or GB90 Figure IX-34
D_{np}	=	distance minor road vehicle traveled during the turning maneuver that is not parallel to major highway (ft)
R	=	radius of turn for minor road vehicle (ft)
TG or MS	=	tailgate or minimum separation distance (ft)
L	=	length of minor road vehicle (ft)
t_{TG} or t_{MS}	=	tailgate or minimum separation time (sec), assumed: $t_{TG} = 1.0$ sec

TABLE 3 Equations for the GB90 ISD Procedure

$ISD_{B\text{-}2b\ \&\ Cb,1990} = Q_{1990} - h_{1990}$ $Q_{1990} = 1.47\ V_{85\%ds,1990}\ (t_{1990} + J)$	$h_{1990} = P_{1990} - 16 - VG - L$ $VG = 1.47 * V_{85\%ds,1990} * t_{VG}$

$ISD_{B\text{-}2b\ \&\ Cb,1990}$	=	sight distance along the major roadway's far lane to the right for left turns and along the near lane to the left for right turns (ft)
Q_{1990}	=	distance traveled by the major road vehicle during the minor road vehicle's turning maneuver (ft)
$V_{85\%ds,1990}$	=	85 percent of design speed of major road vehicle (mi/h)
h_{1990}	=	major road vehicle's distance from intersection when at assumed vehicle gap distance to minor road vehicle (ft)
J	=	sum of the perception time and the time required to actuate the clutch or automatic shift (sec), assumed: $J = 2.0$ sec
t_{1990}	=	acceleration time for the minor road vehicle to reach 85 percent of design speed from a stopped position (sec), data from GB90 Table IX-7
P_{1990}	=	total distance traveled by minor road vehicle from stopped position to location when 85 percent of design speed is achieved (ft), data from GB90 Figure IX-34
16	=	the distance (in ft) that the minor road vehicle traveled during the turning maneuver that is parallel to the major road, determined using the following equation: $\pi R/2 - R$ where R is the radius of turn for the minor road vehicle (ft)
VG	=	vehicle gap distance (ft)
L	=	length of minor road vehicle (ft), assumed: $L = 19$ ft
t_{VG}	=	vehicle gap time (sec), assumed: $t_{VG} = 2.0$ sec

sider deceleration are found to be between 3 and 10 percent less than the values in GB90 Figure IX-40.

The sight distance values in the GB90 are between 4 and 23 percent less than the values in the GB84 edition. Changes between the two Green Book editions in the Reduced Speed procedure include the following:

- The distance or time to accelerate by a minor-road passenger car in the GB90 has been updated. Figures showing truck acceleration characteristics did not change.
- The vehicle gap (previously known as "tailgate" or "minimum separation") time between the turning vehicle and the major-road vehicle is assumed to be 2 sec in the GB90; it was estimated as 1 sec in the GB84 developed equations.
- In the GB90, the major-road vehicle decelerates to (or travels at) 85 percent of design speed, whereas Fitzpatrick and Mason used a 0 mi/hr reduction for design speeds of 30 mi/hr or less, a 5 mi/hr reduction for design speeds between 35 and 65 mi/hr, and a 10 mi/hr reduction for design speeds of 70 mi/hr to reproduce the GB84 values.

• As discussed in the previous paragraph, it has not been determined whether the GB90 procedure implicitly accounts for the time that the major-road vehicle is at design speed or is decelerating.

The reduction in sight distance values between the GB84 and GB90 editions can be primarily attributed to updated "distance" and "time to accelerate" values.

SURVEY OF INTERSECTION SIGHT DISTANCE PROCEDURES

To measure the acceptance of the GB84 ISD procedures, a letter was sent to the highway agencies of 50 states, Puerto Rico, and the District of Columbia in October 1988 requesting a copy of the pertinent intersection sight distance section in their agency design manuals (*4*). The following summarizes the responses:

- Twenty agencies indicated that they apply the ISD policies as presented in the GB84.
- Fifteen states' design manuals included portions of the policy discussed in the GB84.
- Seven states did not respond to the request.
- Four states used variations or portions of the GB84 procedures.
- Three states use SSD as the minimum sight distance values and either Curve B-1 SD values, twice SSD values, or values developed from field studies conducted by the state as the desirable ISD values.
- Two states use a gap acceptance procedure (7.0 and 7.5 sec).
- One state's design manual said "the location of each approach should be reviewed to ensure that sight restrictions do not create a hazardous condition."

FIELD STUDIES

Details of the field studies for both cars and trucks were documented previously (*3,4,6*); the following discussion provides a synopsis of the analytical procedures and results.

Gap Acceptance

The logistic function was selected on the basis of a literature review of statistical methods to evaluate the gap data obtained in the field studies. Detailed discussions on previous gap acceptance studies, statistical procedures to evaluate data, and the determination of the 50 percent and 85 percent probability of accepting a gap is contained elsewhere (*9*). The findings from the field studies compared favorably with other studies. The generalized results used in this paper for passenger cars and trucks are as follows:

	Passenger Car (sec)	*Five-Axle Trucks (sec)*
50%	6.5	8.5
85%	8.25	10.0
85% (low volume)	10.50	15.0

Acceleration

The time between departure from the intersection and arrival at specific increment points for an accelerating vehicle was determined from videotaped field data. Time data at each increment point were averaged in each intersection/vehicle/maneuver combination file. Several regression analyses were performed on each data set and the best fit equation was selected. The regression equation coefficients and limits and the number of vehicles used in the average are given in Table 4. The basic form of the regression equation is

$$D = \beta_1 t_a + \beta_2 t_a^2 \quad (1)$$

TABLE 4 Acceleration Regression Equation Coefficients

Intersection Characteristics	Turn Maneuver	Vehicle Type	Data Sets	β_1	β_2	Max. Time (sec)*
Low-volume, Rural	right	3- & 4-axle	8	9.351	0.516	24.39
	left	3- & 4-axle	26	2.432	0.767	20.44
Low-volume, Rural (Truck Stop)	right	5-axle	44	6.366	0.311	26.55
High-volume, Urban	right	5-axle	41	1.523	0.967	23.37
	left	5-axle	4	8.726	0.638	23.03
	right	PC	75	7.755	1.801	14.62
	left	PC	47	8.150	1.708	15.27

*The limits of the regression equations are from 0 sec to the value listed in this column. The values are the maximum acceleration time from the intersection data.

where

β_1, β_2 = regression coefficients,
D = distance to accelerate (ft), and
t_a = time to accelerate (sec).

Speed reached at a specific time was calculated by taking the first derivative of the regression equation. For example, a right-turning passenger car at a high-volume, urban intersection would reach 25 mi/hr after accelerating for 8.05 sec, as shown in the following calculations:

Time-distance equation:

$$D = 7.755t_a + 1.801t_a^2 \quad (2)$$

First derivative:

$$\frac{dD}{dt} = V = 7.755 + (2 * 1.801 * t_a) \quad (3)$$

Speed reached (V) when t = 8.05 sec:

$$V = 7.755 + (2 * 1.801 * 8.05)$$
$$= 36.75 \text{ fps} = 25.0 \text{ mi/hr} \quad (4)$$

Deceleration

An average speed was estimated for an approaching major-road vehicle at each 100-ft increment. These average speeds were examined to identify where a maximum deceleration rate or speed reduction occurred. Vehicles were not considered in the analysis if they had less than a 5-mi/hr speed reduction through the observation area or if the data displayed erratic or extreme speed variations. The minimum value of 5 mi/hr for speed reduction was selected on the basis of the estimated accuracy of the reduced data.

Table 5 gives the 50th and 85th cumulative deceleration rates and speed reduction values occurring before the intersection for major-road vehicles. These values typically represent a 200- to 400-ft total deceleration distance ending 50 to 150 ft before the intersection. Table 5 also gives the speed reduction for each 5-mi/hr rounded initial speed increment.

Minimum Separation

Minimum separation is the shortest distance between the rear bumper of the turning vehicle and the front bumper of a vehicle approaching on the major roadway at any point during the turning maneuver. Minimum separation can be approximated by comparing the acceleration data for the minor-road vehicle with the deceleration data for the vehicle approaching on the major roadway. The minimum time (or distance) difference between estimated acceleration and deceleration curves was determined from plots of the respective data. The available information on minimum separation distances was very limited; nonetheless, an attempt was made to establish a probable range of values for right-turning vehicles.

This limited analysis indicated a minimum separation time value of approximately 1 sec for right-turning passenger cars and for the trucks turning onto a low-volume, rural road.

TABLE 5 Deceleration Rates and Speed Reductions for Major-Road Vehicles

Cumulative Deceleration Rates and Speed Reductions

Major Road Vehicle Reacting to			Deceleration Rate (mi/h/sec)		Speed Reduction (mi/h)	
Turn	Vehicle	Lane	50 percent	85 percent	50 percent	85 percent
Right	5-axle	onto	3.67	5.85	21.2	38.1
Right	PC	onto	2.62	3.75	12.3	16.2
Left	PC	cross	2.05	3.07	15.3	20.1
Left	PC	onto	1.48	2.36	8.3	13.1

Estimated Speed Reductions by Rounded Initial Speed

Rounded Initial Speed (mi/h)	Estimated Speed Reduction in Response to			
	Left-Turning Passenger Car		Right-Turning	
	Onto Lane (mi/h)	Cross Lane (mi/h)	Passenger Car (mi/h)	Truck (mi/h)
25	12*	**	**	**
30	**	**	**	**
35	14	7	**	15
40	16	10	11	15
45	18	13	11	20
50	20	13*	13	25
55	**	25	14	30*
60	**	**	16*	35
65	**	**	16*	35*
70	**	**	**	40*

*Value based on two or less observations.
**No data available.

Higher values were generally found for five-axle trucks at an intersection on a high-volume, urban road. Drivers appeared to select a larger separation distance between their vehicle and the turning vehicle if available, but accepted 1 sec or less on some occasions. (A 1-sec tailgate or minimum separation time represents a 15-ft minimum separation distance for each 10 mi/hr increment.)

INTERSECTION SIGHT DISTANCE PROCEDURES

Another objective of this paper is to compare the AASHTO ISD values with the results from (*a*) a gap acceptance procedure and (*b*) the field study findings used in the developed ISD equations. The field study findings included gaps accepted by the minor-road driver, minor-road vehicle acceleration, major-road vehicle deceleration and speed reduction, and minimum separation findings.

Gap Acceptance Procedure Results

Sight distance values for both left- and right-turning vehicles given in Table 6 were calculated on the basis of design speed and gap acceptance times of 7.0, 8.25, and 10.5 sec for passenger cars and 8.5, 10.0, and 15.0 sec for trucks.

Passenger Cars

The 7.0-sec gap was selected on the basis of GB84 and GB90 discussions of local roads, findings from the field study, and results of the agency survey. The GB90 states that a "minimum of 7 sec should be available to the driver of a passenger vehicle crossing the through lanes" on a local road or street and that the resulting "sight distance should be sufficient to permit a vehicle on the minor leg of the intersection to cross the travel way without requiring the approaching through-traffic to slow down" (*1*).

The 7.0-sec gap is also greater than the 50 percent probability of a passenger car driver accepting a gap for both left and right turns (6.50 sec). Two states also use a similar value in their gap procedure to calculate ISD; California uses 7.5 sec, and Michigan cites 7.0 sec. The 8.25-sec gap is the 85 percent probability of accepting a gap for both right- and left-turning passenger cars at moderate- to high-volume (intersection ADT between 10,000 and 22,000 vehicles) intersections. The 10.5-sec gap represents the 85 percent probability of accepting a gap at an intersection where the accepted gaps were influenced by low to moderate volumes (intersection ADT less than 10,000 vehicles) and by the intersection geometry.

Trucks

The 50 percent probability of accepting a gap for left- and right-turning five-axle trucks at a high-volume intersection was generalized as 8.5 sec. The 10-sec gap was selected on the basis of the 85 percent probability of accepting a gap at a high-volume location for five-axle trucks, whereas the 15-sec gap was based on the 85 percent probability of accepting a gap at a low-volume intersection for five-axle trucks.

Field Study Findings Used in the Developed ISD Equations

The results of the field study findings substituted in the developed equations can be used to demonstrate the implications of the field study findings. The utility of the results is limited because field findings were based on only a few intersections. The equations developed on the basis of the GB84 ISD values allow for the inclusion of the observed speed reduction by the major-road vehicle. Equations in the GB90 do not include any terms for the deceleration of the major-road vehicle (even though the GB90 Figure IX-36 states that the sight distance allows for the major-road vehicle to reduce speed from design speed to 85 percent of design speed). The initial speed of the major-road vehicle was used in the design speed term in the equations.

Two sets of results were determined: one for passenger cars and the other for five-axle trucks (see Table 7). Sight distance values for right- and left-turn maneuvers were not separately determined because the calculated values would be very similar. Acceleration characteristics are similar for each turn ma-

TABLE 6 Sight Distances Based on Gap Acceptance Procedure

Speed (mi/h)	Passenger car sight distances (ft)			Truck sight distances (ft)		
	Gap accepted (sec)			Gap accepted (sec)		
	7.0	8.25	10.5	8.5	10.0	15.0
20	206	243	309	250	294	441
25	257	303	386	312	368	551
30	309	364	463	375	441	662
35	360	424	540	437	515	772
40	412	485	617	500	588	882
45	463	546	695	562	662	992
50	515	606	772	625	735	1,103
55	566	667	849	687	809	1,213
60	617	728	926	750	882	1,323
65	669	788	1,003	812	956	1,433
70	720	849	1,080	875	1,029	1,544

TABLE 7 Passenger Car and Five-Axle Truck Sight Distances Using Findings from the Field Studies

Speed V_s (mi/h)	Speed Reduction (mi/h)	Reduced Speed V_{rs} (mi/h)	Acceleration* Time t_t (sec)	Acceleration* Distance P (ft)	Deceleration Distance D_{dec} (ft)	Deceleration Time t_{dec} (sec)	Field Results FPC or FT (ft)	AASHTO B-2b&Cb or BT-2b&Cb (ft)	Percent Difference
Passenger Cars									
20	5	15	3.97	59	49	1.91	166	240	31
30	5	25	8.05	179	77	1.91	298	370	19
40	11	29	9.69	244	213	4.20	430	570	24
50	13	37	12.95	403	317	4.96	624	850	27
60	16	44	**	**				1,150	
70	20	50	**	**				1,550	
Five-Axle Trucks									
20	5	15	16.61	125	35	1.36	299	670	55
30	10	20	14.41	223	100	2.72	457	1,179	61
40	15	25	18.21	349	195	4.09	654	1,549	58
50	25	25	18.21	349	376	6.81	792	2,516	69
60	35	25	18.21	349	596	9.54	971	**	
70	40	30	22.01	502	801	10.90	1246	**	

* Acceleration time and distance values were determined from the following regression equations:

Passenger Car	$P = 7.755\, t_t + 1.800\, t_t^2$	limits = 0 to 14.62 sec
Five-axle Truck	$P = 1.524\, t_t + 0.967\, t_t^2$	limits = 0 to 23.37 sec

** Speed is beyond data limit.

neuver, and the increase in sight distance that the longer left, minimum turning path creates is less than 2 percent. Values selected for use in the calculations represent either the more conservative findings from the left- or right-turn maneuver or the findings that were based on a substantially greater amount of data.

The following study data were used to calculate intersection sight distances for turning five-axle trucks and passenger cars:

- Speed reduction values were based on observations made at two intersections with a high volume of five-axle truck traffic (one of which is a high-volume, urban intersection). The values used are given in Table 7.
- Vehicle acceleration time and distance values are from field observations of right-turning five-axle trucks and passenger cars at a high-volume, urban intersection. The values and regression equations are given in Table 7.
- The distance and time to decelerate values were determined using the 50 percent cumulative deceleration rate for major-road vehicles. Deceleration rates used for drivers reacting to a five-axle truck or passenger car are 3.67 and 2.62 mi/hr/sec, respectively. The 3.67 mi/hr/sec rate is within the range of comfortable rates listed in the GB84 and GB90.
- Minimum separation time between the rear bumper of the turning vehicle and the front bumper of the major-road vehicle was assumed to be 1.0 sec.

Other assumptions made for the analysis include the following:

- Perception-reaction time is 2.0 sec.
- Minimum turning vehicle radius is 40 ft for passenger cars and 60 ft for five-axle trucks.
- Length of vehicle is 19 ft for passenger cars and 55 ft for five-axle trucks.

Table 7 contains the analytic "field" results for passenger cars (FPC) and trucks (FT). Also given in Table 7 are the GB90 B-2b & Cb Curve intersection sight distance values as shown in GB90 Figure IX-40 and the results using the Green Book truck characteristics in the developed equations (BT-2b & Cb) (*7*). The passenger car results based on the field findings are between 19 and 31 percent less than the GB90 B-2b & Cb Curve. Truck results are between 55 and 69 percent less than the values from using the Green Book truck data in the developed equations (BT-2b & Cb values).

COMPARISON OF INTERSECTION SIGHT DISTANCE PROCEDURE RESULTS

Passenger Car Findings

The results from the gap acceptance procedure (G-7.0, G-8.25 and G-10.5) and the field studies (FPC) are shown in Figur 2. Also included in the figure are SSD from the GB90 an findings from field studies conducted by the Special Studie Unit of the Connecticut Department of Transportatio (ConnDOT) (*11*).

The field results (FPC) are between SSD and the 7.0-se gap results for speeds less than 40 mi/hr. Between 40 and 5 mi/hr, the field results are greater than both the SSD and th 7.0-sec gap results but are less than or near the 8.25-sec ga results. The 8.25-sec gap yields less than 800-ft sight distanc (for speeds less than 70 mi/hr), which is the value that Tunna

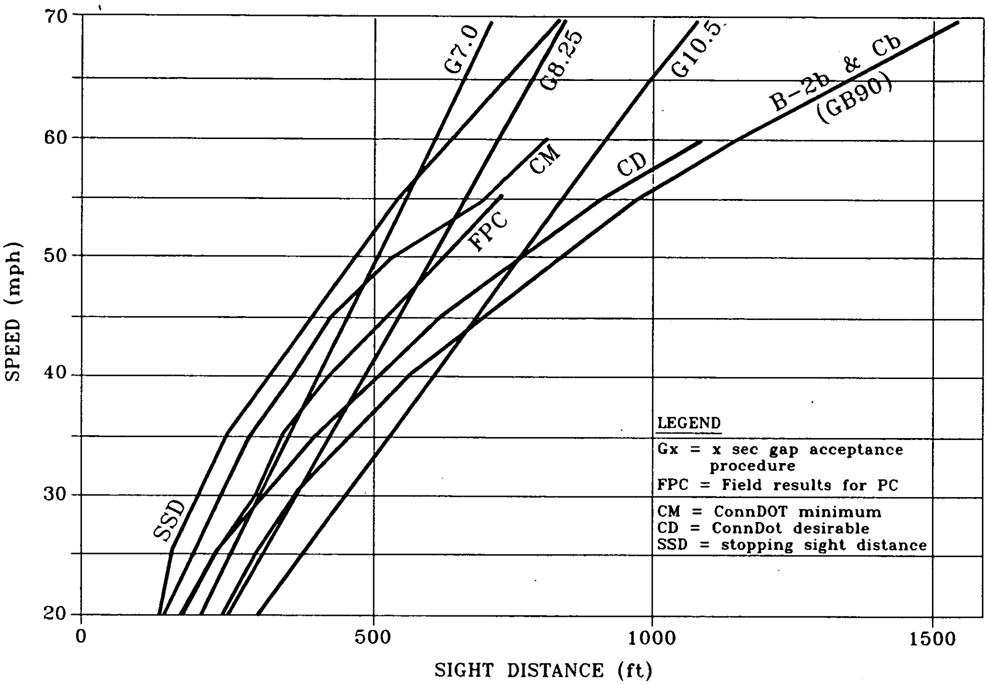

FIGURE 2 Comparison of passenger car sight distances.

and Pushkarev state is the limit of an individual's perception of vehicular movement (*10*).

ConnDOT's desirable ISD values are also based on field studies. In addition to the desirable values, minimum sight distance values based on stopping sight distance are cited. The 8.25-sec gap procedure produces sight distances that are higher than ConnDOT's minimum values for speeds less than 50 mi/hr and higher than ConnDOT's desirable values for speeds less than 35 mi/hr.

Truck Findings

Figure 3 shows the curves from the field results for trucks (FT) and the results from gaps studies (G-8.5, G-10.0, and G-15.0). The figure also has the GB90 passenger car SSD values (to represent the distance needed by a major-road passenger car to come to a stop on a wet pavement).

The field sight distance results are near the 10.0-sec gap results for speeds less than 55 mi/hr. They are also greater

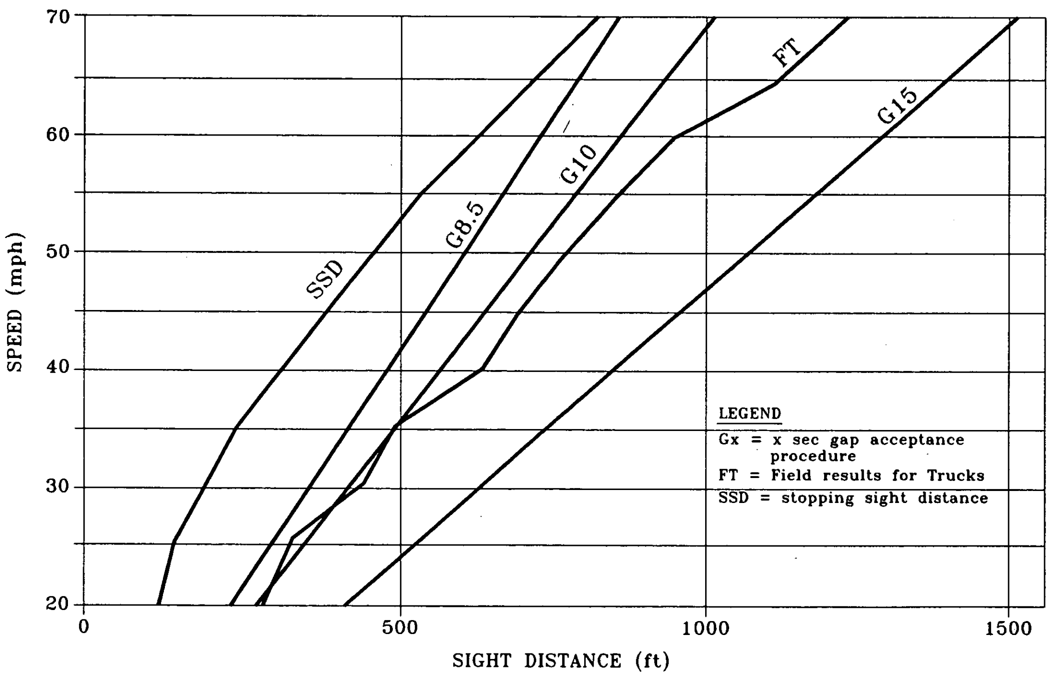

FIGURE 3 Comparison of five-axle truck sight distances.

than the SSD values. The 15.0-sec gap procedure produces significantly larger sight distance values than the results from the field observations. The gap procedure using a 10.0-sec gap produces sight distances less than 800 ft for major-road speeds less than 55 mi/hr.

SUMMARY

The Green Book states that after a vehicle has stopped at an intersection, the driver must have sufficient sight distance to make a safe departure through the intersection area. AASHTO sight distances for passenger cars and the sight distances for trucks (generated using the truck characteristics in the Green Book) produce values that are too conservative. These sight distances are approximately 35 percent greater than what passenger car drivers use and 63 percent greater than what truck drivers use as indicated by data from field studies.

An alternative approach may be to base the criteria on gap lengths safely accepted by the side-road vehicles. An initial field study at a few intersections indicates that representative sight distances are obtained using a critical gap of 8.25 sec for passenger cars and 10 sec for trucks. These gap values produce sight distances that are near the results developed from a field study in the developed ISD equations, which (with different input data) approximately reproduce the AASHTO ISD criteria. The 8.25- and 10.0-sec gaps represent the 85 percent probability of accepting a gap for both right- and left-turning vehicles at a high-volume, urbanized intersection.

CONCLUSION

Current sight distance procedures are a series of equations representing several interrelated maneuvers. To determine intersection sight distance, the user must make several assumptions on individual driver and vehicle performances (for example, perception and reaction time, acceleration, and deceleration) that are then combined to produce the sight distance value. An error or poor assumption for one parameter can have a major influence in the sight distances calculated. Several parameters are in need of frequent updating as the vehicle fleet changes. A gap acceptance procedure could simplify the process while implicitly considering the interrelated maneuvers being performed. Any future alternative procedures for determining intersection sight distances should also consider the driver's visual limitations.

Specifically, the following conclusions were determined from this research:

- Existing ISD procedures are difficult to reproduce, which can cause difficulties if input parameters need to be varied (for example, if a significant number of large trucks are expected at the intersection or if the cross street intersects a multilane highway).
- Input parameters could be in need of frequent updating to reflect the current vehicle fleet.
- A gap acceptance procedure for intersection sight distance for stop-controlled approaches would simplify the process.
- A comprehensive study should be conducted to determine the actual gap values on the basis of more data from sites with varying conditions, such as geometry, traffic characteristics, and volume levels, and from different driver groups such as inexperienced and older drivers.
- Further review is needed of driver visual limitations and factors (known and presently unknown) that could be used to select adequate ISD values before possible inclusion into future editions of the Green Book.

RECOMMENDATIONS FOR FUTURE RESEARCH

The field study methodology provided a practical and reasonable means for establishing estimates of the parameters used in the Green Book ISD procedures. Weaknesses lie in the limited data set and the loss of accuracy in visually detecting vehicles farther than 500 to 600 ft from the intersection. Nonetheless, the data needed to formulate ISD criteria can be established from actual field studies. A more comprehensive study would overcome the weaknesses in this study and provide additional support to modify the Green Book ISD procedures, select parameter values, and critically evaluate the feasibility of adopting intersection sight distance criteria based on gap acceptance.

Some of the critical gap values determined at several of the intersections were influenced by geometric or traffic characteristics. Additional research is necessary to measure the impact of different characteristics (e.g., rural versus urban location of the intersection, high versus low volume, grades on minor road, night versus daylight conditions) on the gap acceptance value. Additional research on the effects of different drivers, such as older drivers, on gap acceptance is needed, along with an evaluation of what percentile gap value should be selected (e.g., 50th percentile versus 85th percentile versus 99th percentile). Such findings could be incorporated into a descriptive gap acceptance model, which would provide design flexibility while ensuring that the attributes of functional classification are satisfied.

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