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INTERSECTION GEOMETRIC DESIGN AND OPERATIONAL GUIDELINES FOR OLDER DRIVERS AND PEDESTRIANS. VOLUME 3. GUIDELINES

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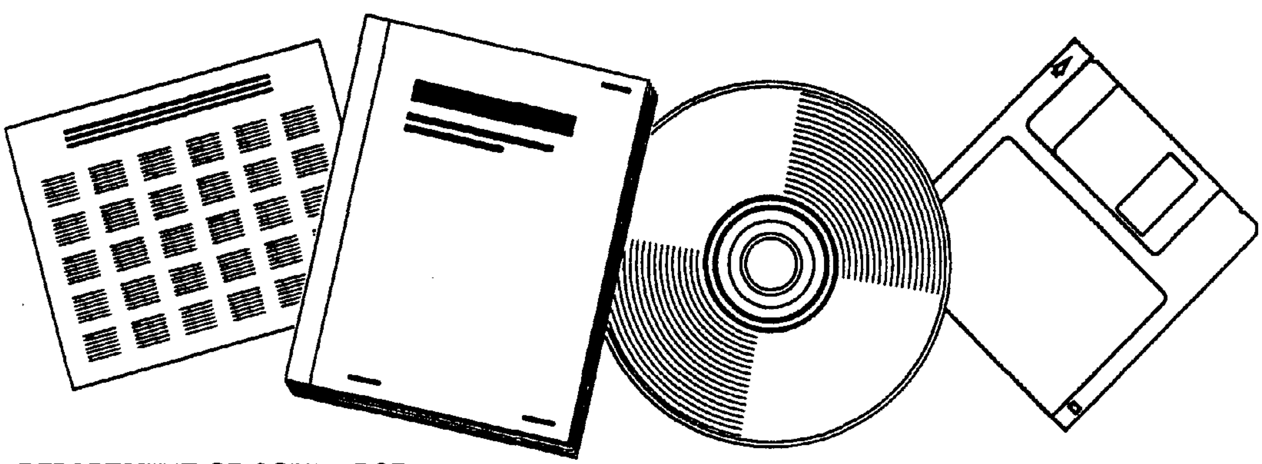

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Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians,

Volume III: Guidelines

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FOREWORD

This research produced guidelines and recommendations for the geometric design and operation of intersections that specifically address the needs and capabilities of older road users. Future research priorities that address issues or problems not presently amenable to design or operational solutions, or improvements in traffic control device use, are also identified.

This report will be of interest to researchers concerned with issues of older road user safety and mobility, and to transportation engineers, urban planners, and users of current AASHTO and FHWA policies on intersection geometric design and operations.

Copies of the report are being distributed to FHWA Regional and Division offices and to State highway agencies. Additional copies of this document are available from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161. A charge is imposed for copies provided by NTIS.

A. George Ostensen
Director
Office of Safety and Traffic Operations
Research and Development

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16. Abstract

This project was performed to develop guidelines for changes in the geometric design and operations at intersections with the greatest potential to aid in their use by older drivers and pedestrians. A literature review identified age-related diminished capabilities that affect performance at intersections, and examined current design standards and their adequacy for older road users. A set of problem identification studies (accident database analysis, task analysis, focus group discussions, field observations) were conducted to better define older persons' difficulties in intersection use, and an expert panel met to prioritize variables for more extensive laboratory and field studies later in the project. These studies subsequently focused on age (including both young-old and old-old groups) and the effects of opposite left-turn lane geometry (offset amount and direction), right-turn channelization and curb radius, and varying median pedestrian refuge island configurations, using both objective (performance) and subjective measures. A critique of the data obtained in these studies during a second expert panel meeting concluded that sufficient evidence exists to support guidelines for: (1) geometric design to ensure a minimum required sight distance for drivers turning left from a major roadway, and (2) operational changes to accommodate older drivers where (re)design of an intersection to meet sight distance requirements is not feasible. In addition, a revision of Case V in the AASHTO *Green Book* to determine sight distance requirements that reflect the perceptual task of gap judgment by a left-turning driver more accurately than the current assumptions in Case IIIB is recommended, and further research needs to enhance the safety and mobility of older road users at intersections are identified. This volume is the third in a series. The other volumes in the series are:

FHWA-RD-96-132 Volume I: Final Report
FHWA-RD-96-138 Volume II: Executive Summary

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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LIST OF ABBREVIATIONS

AASHTO .... American Association of State Highway and Transportation Officials
ADT .... Average Daily Traffic
ANOVA .... Analysis of Variance
DHV .... Design Hour Volume
FHWA .... Federal Highway Administration
IDOT .... Illinois Department of Transportation
ISD .... Intersection Sight Distance
MUTCD .... *Manual on Uniform Traffic Control Devices*
NCHRP .... National Cooperative Highway Research Program
NTIS .... National Technical Information Service
PRT .... Perception-Reaction Time
SSD .... Stopping Sight Distance
TCD .... Traffic Control Device
TRB .... Transportation Research Board
UFOV .... Useful Field of View

INTRODUCTION

The number of older, eligible (licensed) drivers in the United States is growing at a rate faster than the overall population. In 1988, 12 percent of the population was age 65 or older. By the year 2020, it is estimated that 17 percent of the population will be age 65 or older, and almost half of those persons will be age 75 or older. At the same time, use of the automobile as the primary means of transportation is increasing for this segment of the population. In 1977, 83 percent of the trips made by persons ages 65-74 and 73 percent of the trips made by persons age 75 or older were made by automobile. By 1983, these percentages had increased to 86 percent and 82 percent, respectively for the two older driver age groups (Transportation Research Board, 1988).

One of the principal concerns surrounding older road users—both drivers and pedestrians—is the ability of these persons to safely maneuver through intersections. Hauer (1988) reported that 33 percent of the fatalities and 51 percent of the injuries experienced by older pedestrians, and 37 percent of the fatalities and 60 percent of the injuries experienced by older drivers occur at intersections. For drivers age 80 or older, more than half of fatal accident involvements occur at intersections, compared to 25 percent or less for drivers up to age 45 (Insurance Institute for Highway Safety, 1988).

The fact that older drivers experience exaggerated difficulties with intersection use has been further documented in numerous recent accident analyses. Staplin and Lyles (1991) showed older drivers, ages 56-75 and age 76 or older, to be over-involved in both left-turn maneuver and crossing maneuver accidents, with the left-turn accidents being a much greater problem. When examining the left-turn accidents, it also becomes apparent that older drivers are involved to a much greater extent when they are the driver turning left as opposed to being the driver going straight. In both accident types, failure to yield right-of-way was the principal violation type and this increased as driver age increased.

Another recent analysis performed by Council and Zegeer (1992) confirms many of the above findings. Old-old drivers (age 75 or older) were more likely than younger drivers (ages 30-50) to be involved in left-turn accidents at urban signalized intersections and both young-old (ages 65-74) and old-old were more likely to be involved in left-turn accidents at rural signalized intersections. In both cases, the older drivers were more likely to be performing a left-turn maneuver than the younger drivers.

Council and Zegeer's analysis of accidents showed that older drivers were **not** over-involved in left-turn accidents at *unsignalized* intersections. However, they were over-involved in right-angle collisions at both rural and urban locations controlled by stop or yield signs. With respect to pre-crash maneuvers, older drivers were more likely than younger drivers to be performing a turning maneuver or starting from a stopped position. Examination of the citations issued in the various collision types showed that younger drivers more often were not cited with improper driving behavior, while older drivers more often were cited with either failure to yield or disregarding the signal. This generally held true at both rural and urban locations (both signalized and unsignalized).

The analysis by Council and Zegeer (1992) also included an examination of pedestrian accidents and the collision types in which older pedestrians were over-involved. The results showed that older pedestrians were over-represented in both right- and left-turn accidents. The young-old were most likely to be struck by a vehicle turning right, while the old-old were more likely to be struck by a left-turning vehicle. While older (versus younger) pedestrians' accident experiences may be concentrated at intersections because this group avoids crossing movements at other (e.g., midblock) locations, a number of problems related to performance deficits may also be cited: (1) increased exposure resulting from slower walking speed; (2) lack of understanding that vehicles may turn left (permissive left turn) or right (right turn on red) during their WALK interval; (3) inadequate searching for turning vehicles before stepping into the street; (4) inability to react quickly enough to avoid a turning vehicle; (5) reduced peripheral vision; (6) too much reliance on the pedestrian signal alone; and (7) large curb radii, resulting in high-speed right turns and, ultimately, less reaction time for pedestrians.

These findings reinforce a long-standing recognition that driving situations involving complex speed-distance judgments under time constraints—the typical scenario for intersection operations—are more problematic for older drivers and pedestrians than for their younger counterparts (Waller, House, and Stewart, 1977). Accordingly, the specific objectives of this research were as follows:

- Identify the sensory/perceptual, cognitive, and physical (psychomotor) capabilities of both older drivers and older pedestrians that affect their ability to perform at intersections.
- Identify changes in the geometric and operational characteristics of intersections with the greatest potential to better accommodate the needs of older drivers and pedestrians, and develop and test alternatives as potential solutions to identified problems experienced by older road users at intersections.
- Develop specific guidelines for the geometric designs or operational improvements at intersections with the greatest potential to benefit older road users. Provide justification for each guideline and detailed documentation in a manner that will allow for direct application by transportation engineers, urban planners, and users of the American Association of State Highway and Transportation Officials (AASHTO) geometric design standards.
- Identify situations where it does not presently appear feasible to alleviate the problems of older road users through changes to geometric design or operations. Suggest future research objectives and approaches most likely to fill gaps in the present knowledge and resolve outstanding problems in this area.

The final report for this project (available from the National Technical Information Service [NTIS]) describes the major tasks and their outcomes: (1) summary of background information; (2) problem identification studies; (3) laboratory and field investigations of alternative intersection design elements; (4) sight distance design review and expert panel critique of project findings; (5) recommendations for intersection geometric design and operations to accommodate the needs of older road users; and (6) identification of future research priorities.

BACKGROUND AND RATIONALE

AGE-RELATED FUNCTIONAL DEFICITS AFFECTING INTERSECTION USE

A literature review examining characteristics of older road users that affect intersection use revealed that this population differs from their younger counterparts in a number of important ways. This group may experience greater difficulties at intersections as the result of diminished capabilities, which limit both *response initiation* and *movement execution.*

The safety and mobility of older road users at intersections are overwhelmingly vision-dependent. Static, geometric features, plus a wide array of dynamic targets, are relevant to drivers and pedestrians at intersections; these must be detected and recognized in a timely fashion to allow for the subsequent cognitive processing preceding response selection and action. Deficits in vision and vision-dependent processes likely to have the greatest impact on older road users at intersections include diminished capabilities in spatial vision, the functional or "useful" field of view (UFOV), and depth and motion perception.

Spatial visual functions, including acuity and contrast sensitivity, are probably the most important for detection/recognition of downstream geometric features at intersections. Tests of visual acuity, measuring response to high spatial frequency stimuli at contrast levels far above threshold, show a slow decline beginning during the forties that accelerates markedly during the sixties (Richards, 1972). Shinar and Schieber (1991) have argued that *dynamic* visual acuity—the ability to resolve targets by a moving driver, or moving targets by a standing pedestrian—should correlate more strongly with accident involvement, especially among older individuals. Though the loss of sensory response is greatest for high-frequency (over 24 cycles/degree) information, older road users' sensitivity to visual contrast at lower- and middle-range spatial frequencies (i.e., for 6-, 12-, and 18-cycle/degree targets) also declines steadily with increasing age over 40 (Owsley, Sekuler, and Siemsen, 1983). This is important because it is the larger, often diffuse edges defining lane and pavement boundaries, curb lines, and raised median barriers that are the priority targets in this research.

Next, the "useful field of view" (UFOV) measures the detection, localization, and identification of targets against complex visual backgrounds, i.e., the earliest stage of visual attention used to quickly capture and direct attention to the most salient events in a driving scene. Most importantly, tests assessing the useful field of view appear to be better predictors of problems in driving than are standard visual field tests. In one study, drivers with restrictions in UFOV had 15 times more intersection accidents than those with normal visual attention (Owsley, Ball, Sloane, Roenker, and Bruni, 1991).

Finally, age differences in the use of visual cues for depth and motion perception deserve emphasis. A recent study indicated that the angle of stereopsis (seconds of arc) required for a group age 75+ to discriminate depth using a commercial vision tester was roughly twice as large as that needed for an 18- to 55-year-old group to achieve the same level of performance (Staplin, Lococo, and Sim, 1992). Also, it has been shown that older persons require up to twice the rate of movement to perceive that an object's motion-in-depth is approaching, and require significantly longer to perceive that a vehicle is moving closer at a constant speed (Hills, 1975). A recently completed study investigating causes of older driver over-involvement in turning accidents at intersections, building on the previously reported decline for detection of angular expansion cues, did **not** find evidence of over-estimation of time-to-collision (Staplin et al., 1992). At the same time, a relative insensitivity to the speed of an approaching vehicle was shown for older versus younger drivers; this result supports the notion that older drivers rely primarily or exclusively on perceived distance to perform gap-acceptance judgments, reflecting a reduced ability to integrate time and distance information with increasing age. Thus, a principal source of risk at intersections is the error of an older, turning driver in judging gaps in front of fast vehicles.

Compounding the varied age-related deficits in visual performance, an overall slowing of mental processes has been postulated as individuals continue to age into their seventies and beyond (Cerella, 1985), and a decline has been demonstrated in a number of specific cognitive activities with high construct validity in the prediction of driver and pedestrian safety. The cognitive functions included in this processing stage perform attentional, decisional, and response selection functions crucial to maintaining mobility under current conditions, on current system facilities. Complementary functions essential to the safe and effective use of intersections are selective attention, attention switching, and divided attention, which together comprise the core of what is often termed "situational awareness." Older drivers appear to benefit disproportionately from interventions that compensate for divided attentional deficits during a high-workload task such as negotiating an intersection; this includes cuing drivers with advanced notice of protected versus permissive movement regulations through a redundant upstream posting of advisory signs (Staplin and Fisk, 1991). Related studies suggest that if older drivers must increase their attention to inconspicuous or confusing geometric features to make appropriate maneuver decisions during an intersection approach, a deficit in the discrimination of peripheral targets (e.g., other vehicles or pedestrians) is likely (Brouwer, Ickenroth, Ponds, and Van Wolffelaar, 1990).

Finally, the execution of vehicle control movements by an older driver, or walking movements by an older pedestrian, is likely to be slowed due to a number of factors. A study by Goggin, Stelmach, and Amrhein (1989) linked response slowing by older individuals to abbreviated stimulus exposure times and interstimulus intervals. The spacing of vehicle control movements required of drivers to negotiate intersection geometries therefore may be expected to strongly influence the ability of older individuals to respond in a safe and timely manner; thus, designs which require weaving or successive lane changes within a restricted timeframe are clearly undesirable. Slower reaction times for older versus younger adults when response uncertainty is increased have been demonstrated (Simon and Pouraghabagher, 1978), indicating greater risk when older road users are faced with two or more choices of action. Also, research has shown that older persons will have greater difficulty in situations where planned actions must be rapidly altered (Stelmach, Goggin, and Amrhein, 1988), and corrections during movement execution are slower and much less efficient (Goggin and Stelmach, 1990). Again, a need to avoid geometric designs that increase the likelihood that older road users will be called upon to execute multiple responses in quick succession is underscored.

Perhaps most common is the age-related decline in head and neck mobility. Joint flexibility has been estimated to decline by approximately 25 percent in older adults (Smith and Sethi, 1975) due to arthritis, calcification of cartilage, and joint deterioration. This restricted range of motion reduces an older driver's ability to effectively scan to the rear and sides of his/her vehicle to observe blind spots, and can also hinder the timely recognition of conflicts during turning and merging maneuvers at intersections (Ostrow, Shaffron, and McPherson, 1992). Reduced neck flexibility also penalizes older pedestrians, who must detect potential conflicts without unreasonable delay to accomplish intersection crossings within a protected signal phase.

DRIVER PERFORMANCE AS A FUNCTION OF OPPOSITE LEFT-TURN LANE GEOMETRY

The present research and other recent, related studies have provided data necessary to determine: (1) the minimum required sight distance for a driver turning left from a major roadway to a minor roadway, as a function of major road design speed; (2) the offset value needed to achieve the minimum required sight distance; and (3) the offset value which will provide unlimited sight distance. The major laboratory and field studies conducted in the present project are described next, along with related research. This body of evidence provides the justification for the design and operational recommendations which follow.

Laboratory Study

The laboratory study evaluated left-turn gap acceptance by drivers waiting in a left-turn storage bay to turn left across a stream of opposing traffic during the permissive (green ball) signal phase. The purpose was to measure driver age differences in performance under varying traffic and operating conditions, as a function of varying degrees of offset of opposite left-turn lanes at suburban arterial intersections. The degree of offset for opposite left-turn lanes refers to the distance from the inner edge of a left-turn lane to the outer edge of the opposite left-turn lane. The alignment of opposite left-turn lanes and the horizontal and vertical curvature on the approaches are the principal geometric design elements which determine how much sight distance is available to a left-turning driver. Operationally, vehicles in the opposite left-turn lane waiting to turn left can also restrict the (left-turning) driver's view of oncoming traffic in the through lanes. The level of blockage depends on how the opposite left-turn lanes are aligned with respect to each other.

Restricted sight distance can be minimized or eliminated by offsetting opposite left-turn lanes so that left-turning drivers do not block each other's view of oncoming through traffic. When the two left-turn lanes are exactly aligned, the offset distance has a value of zero. Negative offset describes the situation where the opposite left-turn lane is shifted to the left. Positive offset describes the situation where the opposite left-turn lane is shifted to the right. Positively offset left-turn lanes and aligned left-turn lanes provide greater sight distances than negatively offset left-turn lanes, and a positive offset provides greater sight distance than the aligned configuration. However, while increasing the sight distance to through traffic may provide safety benefits to left-turning drivers, increasingly positive offset geometries also result in longer crossing distances for pedestrians.

Four levels of offset left-turn lane geometry were studied in the laboratory: (a) 3.6-m (12-ft) "full positive" offset; (b) 1.8-m (6-ft) "partial positive" offset; (c) aligned (no offset); and (d) 1.8-m (6-ft) "partial negative" offset. These geometries are diagrammed in Figure 1.

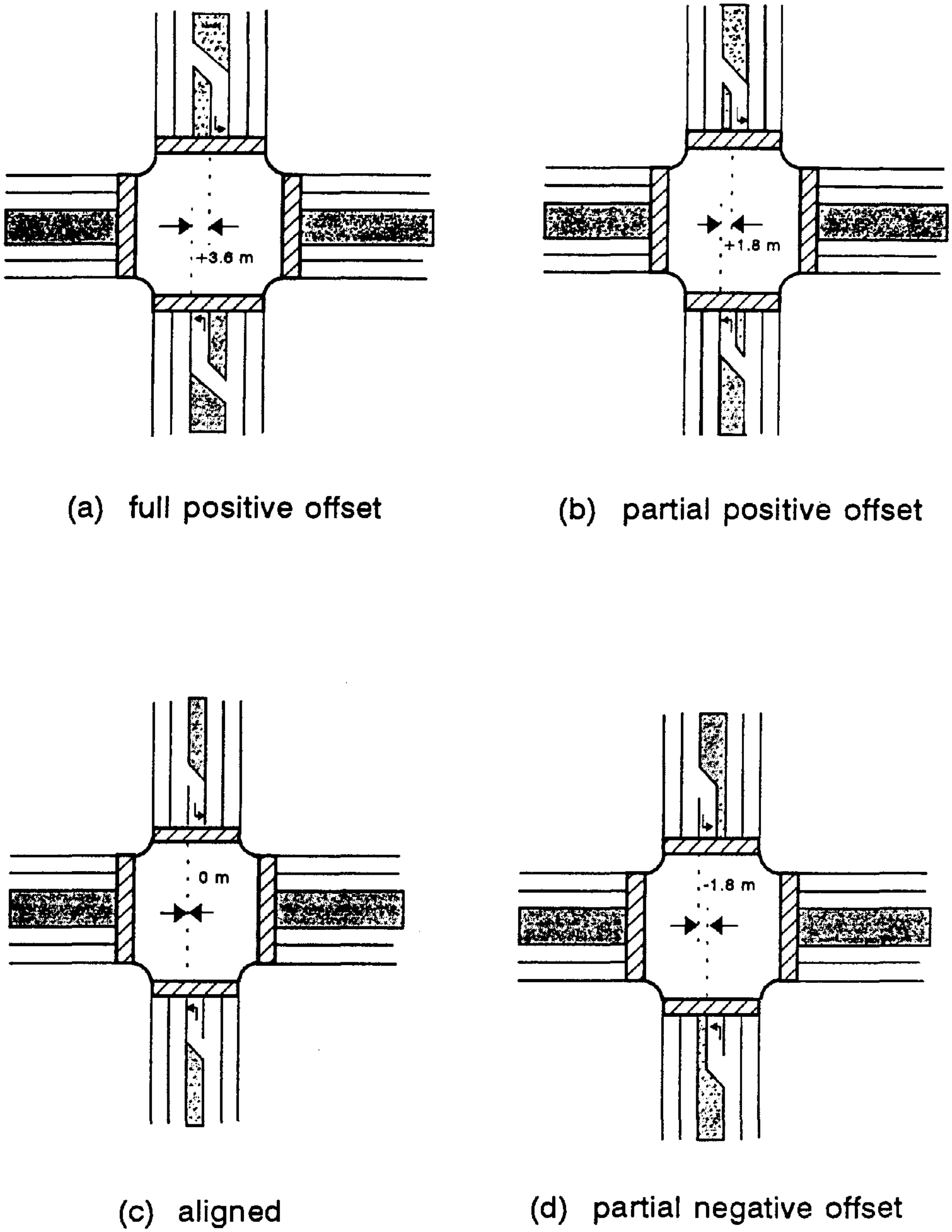


Figure 1. Alternative intersection geometries examined in the laboratory.

In addition, the traffic operational factors varied in the laboratory included: (1) oncoming (through) traffic vehicle type (passenger car versus semi-tractor trailer), (2) oncoming traffic speed (56, 72, and 88 km/h [35 mi/h, 45 mi/h, and 55 mi/h]); (3) oncoming traffic density (spacing between successive vehicles in the opposing through-traffic stream at nine spacings, from 30.5 m [100 ft] to 274.4 m [900 ft], in 30.5-m [100-ft] increments); and (4) opposite left-turn queue composition (a passenger car or semi-tractor trailer at the front of the queue).

The measures of effectiveness for the laboratory study included:

(1) *Critical Gap Size*: A measure of the gap size at which the number of accepted gaps and the number of rejected gaps were equal, derived using the PROBIT model from the continuous gap judgments subjects made in response to a continuous stream of through (opposing) traffic, i.e., reflecting subjects' judgments of whether it was "safe" or "unsafe" to proceed with a left turn from a stationary position at the stop bar of a left-turn bay.

(2) *Last Safe Moment to Turn*: The distance of the oncoming vehicle during a single approach from the farthest separation when a subject indicated that it would no longer be safe to proceed with a left turn. This measure was obtained when there was no vehicle in the opposite left-turn lane to block the driver's view.

(3) *Frequency of Unsafe Gaps Accepted*: A measure derived from the continuous gap acceptance judgments, calculated using a threshold distance which was established for each oncoming vehicle speed, where a turning driver must initiate the turning maneuver and then complete the turn (assuming a fixed clearance interval) to allow the oncoming vehicle to proceed through the intersection without braking or swerving.

(4) *Ratings of the Perceived Level of Hazard*: An integer value assigned to each geometry ranging from 1 to 7, where 1 = "extremely safe; not hazardous at all" and 7 = "extremely hazardous."

Seventy-two subjects participated in the laboratory driver study, with 24 between the ages of 25-45 ("young/middle-aged group"), 24 between the ages of 65-74 ("young-old" group), and 24 subjects age 75 or older ("old-old" group). A repeated measures-research design was used in which all subjects generated responses to all dependent measures for all geometries and test conditions studied.

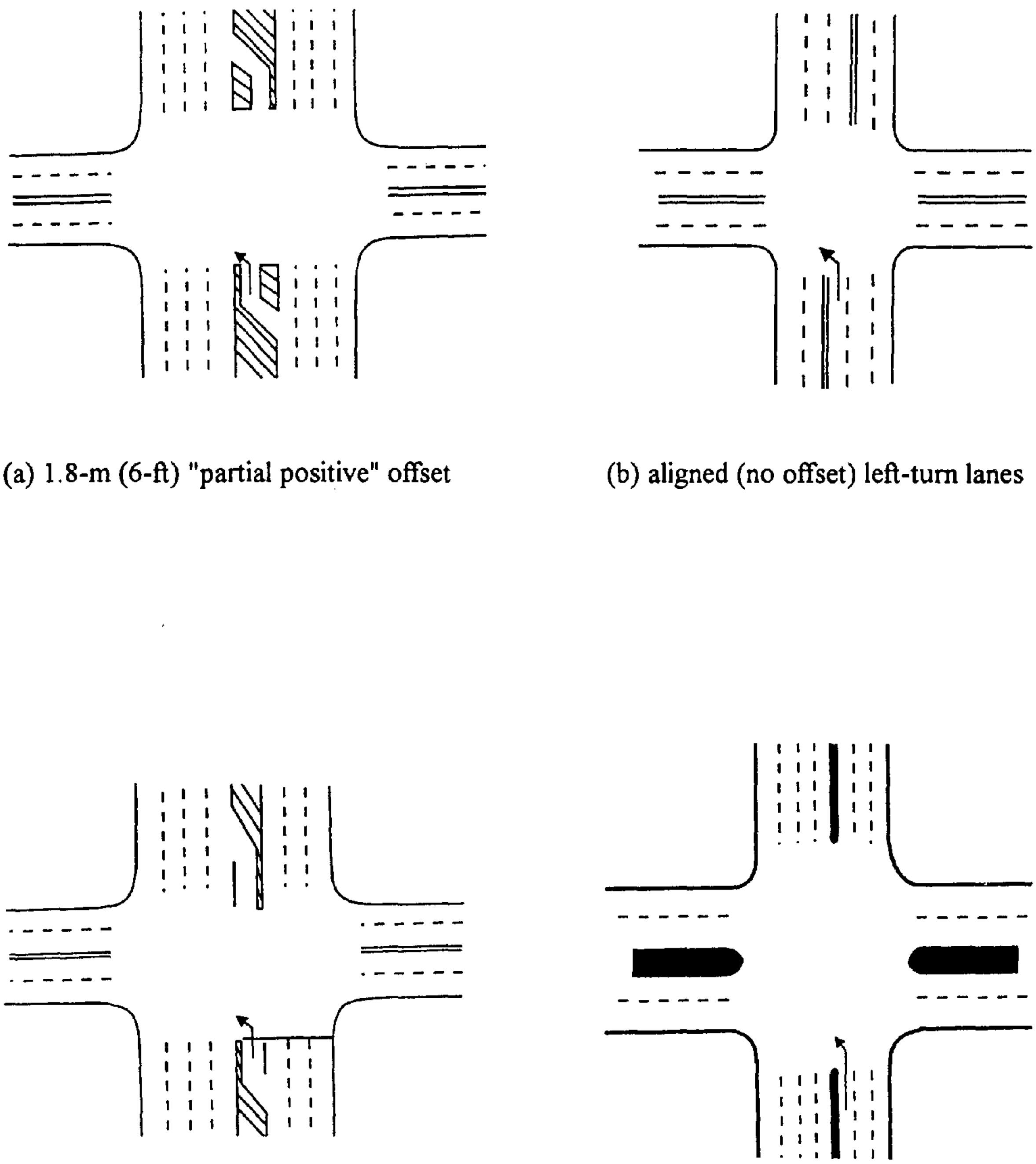
The methodology used a video-based driving simulator to present intersection test stimuli, displaying scenes which provided correct perspective and motion-in-depth cues. The test scenes were created from a 1/24-scale terrain board model of an intersection; this apparatus was filmed as vehicles propelled by a stepper motor approached the intersection. A Hi8mm recording format was used for filming, and laser discs provided the storage/playback medium. As subjects sat in the simulator cab, which was "positioned" at the stop bar in the left-turn bay, they watched a stream of vehicles approaching in one of the opposing through lanes and made go/no go turn decisions using a gaming device trigger apparatus. Squeezing the trigger meant that they **would go** ahead with a left turn, if they were actually driving and saw what was being presented in the video through their own windshield. Releasing the trigger meant that they **would not go** ahead with a left turn, based on what was presented in the video.

Statistically significant differences measured in the simulator, which also were judged to be of operational significance in guiding intersection design, included the findings listed below:

- Smaller critical gap size for the full positive geometry than for the partial positive, aligned, or partial negative geometries.
- Virtually equal "least safe gap" size (last safe moment to turn left in front of an oncoming vehicle) across geometry, except for a sharp decrease in mean least safe gap size for the partial negative offset condition.
- Increases in the mean least safe gap size with increasing driver age.
- Larger gaps required in the presence of an oncoming truck compared to the gap size for an oncoming passenger car.
- Significant three-way interaction between geometry, age, and oncoming vehicle type on mean least safe gap judgments, with the largest gap requirements for the 75+ age group with aligned geometry and a truck as the oncoming vehicle.
- Disproportionately higher percentages of unsafe gaps accepted by the 75+ age group under the partial negative geometry for both opposite left-turning vehicle types.
- Significant main effects of geometry and oncoming vehicle speed on subjective ratings of safety, where the geometries affording greater visibility of oncoming traffic were perceived to be safer than those providing poorer visibility, and higher vehicle speeds were associated with lower safety ratings.
- Significant interaction between geometry and driver age on perceived safety, where older drivers provided the lowest safety ratings for the partial negative geometry (even though all subjects responded with low ratings under this study condition).

Field Study

Four left-turn lane offset geometries also were studied in the field, where left-turn vehicles at all locations needed to cross the paths of two or three lanes of conflicting traffic (excluding parking lanes) at 90-degree, four-legged intersections. The four levels of offset of opposite left-turn lane geometry examined in the field, diagrammed in Figure 2, were as follows: (a) 1.8-m (6-ft) "partial positive" offset, (b) aligned (no offset) left-turn lanes, (c) 0.91-m (3-ft) "partial negative" offset, and (d) 4.3-m (14-ft) "full negative" offset. All intersections were located on major or minor arterials within a growing urban area where the posted speed limit was 56 km/h (35 mi/h). Additionally, all intersections were controlled by traffic-responsive semi-actuated signals, and all left-turn maneuvers were completed during the permissive left-turn phase at all study sites.



(a) 1.8-m (6-ft) "partial positive" offset

(b) aligned (no offset) left-turn lanes

(c) 0.91-m (3-ft) "partial negative" offset

(d) 4.3-m (14-ft) "full negative" offset

Figure 2. Alternative intersection geometries evaluated in the field study.

Seven measures of effectiveness were used in the field study to evaluate drivers of different age groups at different offset levels of left-turn lanes:

(1) *Critical Gap Size*: The gap size that had a 50/50 chance of being accepted or rejected, calculated from the accepted and rejected gaps using the LOGIT model. This measure was calculated only for subjects who made left-turn maneuvers when there was at least one vehicle in the opposite left-turn lane, and for subjects who positioned their vehicles within the intersection while waiting to turn.

(2) *Clearance Time*: The time it took the left-turning vehicle to complete the left-turn maneuver and clear the path of the conflicting traffic (i.e., the difference between the maneuver initiation and completion). This measure was calculated only for subjects who made left-turn maneuvers when there was at least one vehicle in the opposite left-turn lane, and for subjects who positioned their vehicles within the intersection while waiting to turn.

(3) *Left-Turn Conflict*: Conflict between a left-turning vehicle and an opposing vehicle, defined as the occurrence of either sudden and unavoidable lane change by a conflict vehicle because the test vehicle clearly accepted a dangerously small gap, or a complete or nearly complete stop by the conflict vehicle for the same reason.

(4) *Longitudinal and Lateral Positioning*: Positioning of left-turn vehicles within the intersection area.

(5) *Percentage of Drivers Positioning Themselves Within Intersection*: The percentage of drivers of different age groups who pulled into the intersection to improve their sight distance.

(6) *Site-Specific Intersection Use Survey*: A survey which included two site-specific questions regarding the level of comfort in making the turn and the ease or difficulty of performing the maneuver at each of the four intersections included in the study.

(7) *General Intersection Safety Survey*: A survey containing questions about the perceived safety of different types of left-turn displays.

A total of 100 subjects were tested across 3 age groups, with approximately equal numbers of males and females in each group. The three age groups were: (1) young/middle age, 25-45 years old; (2) young-old, 65-74 years old; and (3) old-old, 75+ years old.

Subjects drove their own vehicles through test circuits that were located on arterial streets in the Arlington, VA area during normal daytime driving conditions accompanied by a member of the research team. Subjects' vehicles were assumed to represent vehicles typically used by the age cohorts sampled in the study, and having subjects drive their own vehicles eliminated confounding effects of vehicle unfamiliarity on driving performance. Each subject drove around each circuit four times, making four left-turn maneuvers at each study location. Testing was conducted between 11:00 a.m. and 3:00 p.m., when opposing traffic volumes ranged between 900 and 1,200 vehicles per hour, which provided the maximum number of gaps within a 4- to12-s range. Driver performance measures were obtained both by the researcher in the subject's vehicle and through the use of video data collection equipment stationed at each intersection.

Findings in this study included:

- Significant main effects of age and geometry on critical gap size, with longer critical gaps demonstrated for the age 75+ drivers and the -4.3-m (-14-ft) left-turn lane offset.

- Significant main effect of geometry on lateral positioning and on longitudinal positioning, where the more negative the offset, the farther to the left and the closer drivers must move longitudinally to the center of the intersection to improve their visibility of through traffic.

- Significant main effects of age and gender on vehicle positioning within the intersection to improve sight distance, where older drivers and female drivers were less likely to position themselves within the intersection.

- Subjective responses to survey questions indicating that two-thirds of the drivers feel that a green arrow is safer than a green ball, 8 out of 10 drivers feel that making a left turn on a green ball is safe at some locations and unsafe in others (underscoring the importance of geometric elements), and 9 out of 10 drivers feel that making a left turn on a green ball is the most stressful of all intersection maneuvers.

The data included in these analyses were the left-turn maneuvers in which the subject positioned his/her vehicle within the intersection, and was opposed by at least one vehicle in the opposite left-turn lane. Gap acceptance data were analyzed using the LOGIT method, which fits a probabilistic model to the acceptance/rejection data. Table 1 shows the critical gap values, in seconds, for each age-gender group at the four study locations. Prominent trends indicate that older drivers have larger critical gap values at all locations, and all age-gender groups have larger values at the 4.3-m (14-ft) negative offset location. These data are also presented in Figure 3.

Statistical tests found that the young/middle-age and young-old groups were not significantly different from each other; however, both were significantly different from the old-old group. Tests conducted on the geometry factor (offset) showed that the -0.9-m, +1.8-m, and 0-m (-3-ft, +6-ft, and 0-ft) offsets were not significantly different from each other; however, all three were significantly different from the -4.3-m (-14-ft) offset location. Older drivers required the largest critical gap values at all locations, and all age-gender groups required larger critical gap values when the offset was -4.3 m (-14 ft).

Table 1. Left-turn critical gap, in seconds, followed by the number of gaps accepted (in parentheses), as a function of age and gender at each left-turn location.

Driver Age Group	Gender	Left-Turn Lane Geometry				Means (seconds)
		-14-ft Offset	-3-ft Offset	0-ft Offset	+6-ft Offset	
25-45	Female	6.10 (22)	5.92 (23)	5.78 (24)	5.80 (20)	5.90
	Male	6.23 (21)	5.79 (23)	5.72 (25)	5.90 (21)	5.91
65-74	Female	6.23 (21)	6.07 (23)	5.83 (20)	5.91 (21)	6.01
	Male	6.02 (23)	5.70 (28)	5.92 (22)	5.72 (26)	5.84
75+	Female	7.01 (19)	6.65 (15)	6.79 (15)	6.39 (17)	6.71
	Male	6.61 (17)	6.64 (15)	6.48 (15)	6.46 (16)	6.55
Means (seconds)		6.37	6.13	6.09	6.03	6.15

1 ft = 0.305 m

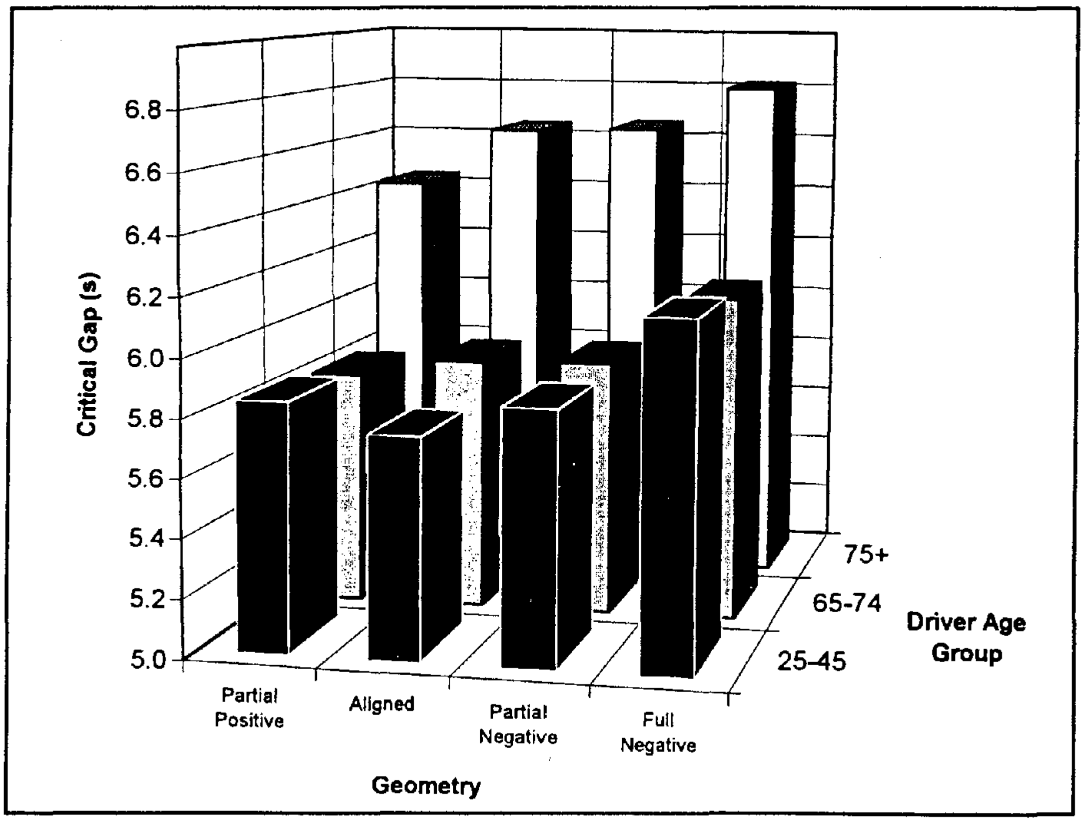


Figure 3. Field study mean left-turn critical gaps (in seconds) as a function of left-turn lane geometry and driver age group.

The data included in the analysis of clearance time were the left-turn maneuvers in which a subject positioned his/her vehicle within the intersection and was opposed by at least one vehicle in the opposite left-turn lane. Table 2 shows the clearance time values for each age-gender group at the four study locations. The first value in each cell is the sample size, and the second and third values are the mean clearance time and its standard deviation, respectively. The mean clearance times for older drivers were longer than for young and middle-aged drivers; however, the differences were less than 0.15 s in most cases. An Analysis of Variance (ANOVA) for the clearance time measure showed that there was no statistically significant effect of age, gender, or geometry on drivers' capabilities to accelerate and complete the left-turn maneuver.

Table 2. Sample size (n), and mean ($\bar{x}$) and standard deviation (s.d.) clearance time (in seconds) for positioned vehicles, as a function of age and gender at each left-turn location.

Driver Age Group	Gender		Left-Turn Lane Geometry: -14-ft Offset	-3-ft Offset	0-ft Offset	+6-ft Offset	All Sites
25-45	Female	n	22	23	24	20	89
		$\bar{x}$	3.23	3.08	3.18	3.10	3.15
		s.d.	0.41	0.52	0.50	0.49	0.48
	Male	n	21	23	25	21	90
		$\bar{x}$	3.19	3.22	3.16	3.20	3.19
		s.d.	0.37	0.37	0.43	0.38	0.39
65-74	Female	n	21	23	20	21	85
		$\bar{x}$	3.33	3.32	3.31	3.30	3.31
		s.d.	0.43	0.43	0.44	0.45	0.43
	Male	n	23	28	22	26	99
		$\bar{x}$	3.32	3.30	3.30	3.31	3.31
		s.d.	0.42	0.40	0.45	0.40	0.41
75+	Female	n	19	15	15	17	66
		$\bar{x}$	3.41	3.40	3.35	3.35	3.38
		s.d.	0.37	0.44	0.42	0.43	0.41
	Male	n	17	15	15	16	63
		$\bar{x}$	3.36	3.35	3.36	3.40	3.37
		s.d.	0.40	0.44	0.42	0.38	0.41
All Subjects		n	123	127	121	121	492
		$\bar{x}$	3.30	3.27	3.26	3.30	3.28
		s.d.	0.40	0.44	0.45	0.40	0.43

1 ft = 0.305 m

Clearance times for unpositioned vehicles are shown in Table 3. As expected, maneuver times of unpositioned vehicles are greater than those of positioned vehicles, as unpositioned vehicles must travel longer distances to complete the maneuver.

Table 3. Sample size (n), and mean ($\bar{x}$) and standard deviation (s.d.) clearance time (in seconds) for unpositioned vehicles, as a function of age and gender at each left-turn location.

Driver Age Group	Gender		Left-Turn Lane Geometry -14-ft Offset	-3-ft Offset	0-ft Offset	+6-ft Offset	All Sites
25-45	Female	n	2	3	4	2	11
		$\bar{x}$	6.25	5.60	5.98	5.40	5.82
		s.d.	0.21	0.56	0.24	0.14	0.43
	Male	n	1	1	1	0	3
		$\bar{x}$	6.00	6.10	5.30	—	5.80
		s.d.	—	—	—	—	0.44
65-74	Female	n	5	5	4	4	18
		$\bar{x}$	6.04	6.08	6.05	5.48	5.93
		s.d.	0.30	0.40	0.06	0.56	0.42
	Male	n	5	4	4	4	17
		$\bar{x}$	6.22	6.08	5.90	5.00	5.82
		s.d.	0.39	0.25	0.50	0.45	0.61
75+	Female	n	7	7	9	10	33
		$\bar{x}$	6.31	5.97	6.13	5.14	5.84
		s.d.	0.56	0.33	0.25	0.31	0.59
	Male	n	6	8	8	6	28
		$\bar{x}$	6.12	6.16	6.32	5.18	5.99
		s.d.	0.24	0.32	0.40	0.35	0.55
All Subjects		n	26	28	30	26	110
		$\bar{x}$	6.18	6.02	6.09	5.20	5.88
		s.d.	0.37	0.36	0.36	0.38	0.52

1 ft = 0.305 m

Table 4 presents the distances traveled by positioned and unpositioned vehicles at each location in the field study, and compares the 95th percentile clearance time for positioned and unpositioned vehicles with values used by AASHTO (1994) for acceleration time used in calculating Case III sight distance at intersections (AASHTO Figure IX-33) for the distances traveled in the field study.

Table 4. Comparison of field study clearance times with AASHTO *Green Book* values.

Measure	Vehicle Location	Left-Turn Lane Geometry			
		-14-ft Offset	-3-ft Offset	0-ft Offset	+ 6-ft Offset
Distance Traveled (ft)	Positioned	70 ft	67 ft	64 ft	70 ft
95th Percentile Clearance Time (s) From Field Study	Positioned	3.8 s	3.9 s	3.9 s	3.9 s
AASHTO Clearance Time (s) From Figure IX-33	Positioned	5.1 s	5.0 s	5.0 s	5.1 s
Distance Traveled (ft)	Unpositioned	106 ft	98 ft	84 ft	88 ft
95th Percentile Clearance Time (s) From Field Study	Unpositioned	6.7 s	6.4 s	6.6 s	5.7 s
AASHTO Clearance Time (s) From Figure IX-33	Unpositioned	6.5 s	6.2 s	5.9 s	6.0 s

1 ft = 0.305 m

Figure 4 depicts how the lateral positioning (shown as distance "x") and longitudinal positioning (shown as distance "y") of left-turning drivers were defined in the field study. In the analysis of the field study lateral positioning data, the mean lateral position values (across age-gender groups) with respect to the left boundary of the turning lane were 0.27 m (0.9 ft), 0.24 m (0.8 ft), 0.03 m (0.1 ft), and -1.46 m (-4.8 ft), respectively, for the partial positive, aligned, partial negative, and full negative offset geometries. Statistical tests found that the partial positive offset and aligned locations had the same effect on the lateral positioning behavior of drivers. At the same time, drivers moved approximately 1.5 m (5 ft) to the left when there was a large negative offset (-4.3 m [-14 ft]), clearly indicating that sight distance was limited. There was also a significant difference between the partial negative offset geometry (-0.9 m [-3 ft]) versus the partial positive offset and aligned geometries, suggesting a need for longer sight distances when opposite left-turn lanes are even partially negatively offset. Because of the fact that it was older drivers (and females) who were less likely to position themselves (i.e., pull into the intersection) in the field studies, *designers should focus on providing adequate sight distance for an unpositioned driver* if the overriding concern is to accommodate this user group.

Analysis of the longitudinal positioning data showed that geometry was the only significant variable. Drivers of all age-gender categories positioned themselves the same way at each of the study locations, and all positioned themselves closer to the center of the intersection (i.e., they pulled farther into the intersection) the more negative the offset, in order to see oncoming traffic in the opposing through lanes. By convention, longitudinal position in the intersection is referenced to the edge of the near lane on the cross street into which drivers turned. Therefore, a smaller longitudinal position value means a driver has pulled farther into the intersection. The aligned and -0.9-m (-3-ft) offsets had the same effect on the longitudinal positioning of drivers making the left-turn maneuver. The mean longitudinal positions were: 5.97 m (19.6 ft) for the full negative offset; 7.2 m (23.7 ft) for the partial negative offset; 7.16 m (23.5 ft) for the aligned geometry; and 8.08 m (26.5 ft) for the partial positive offset location.

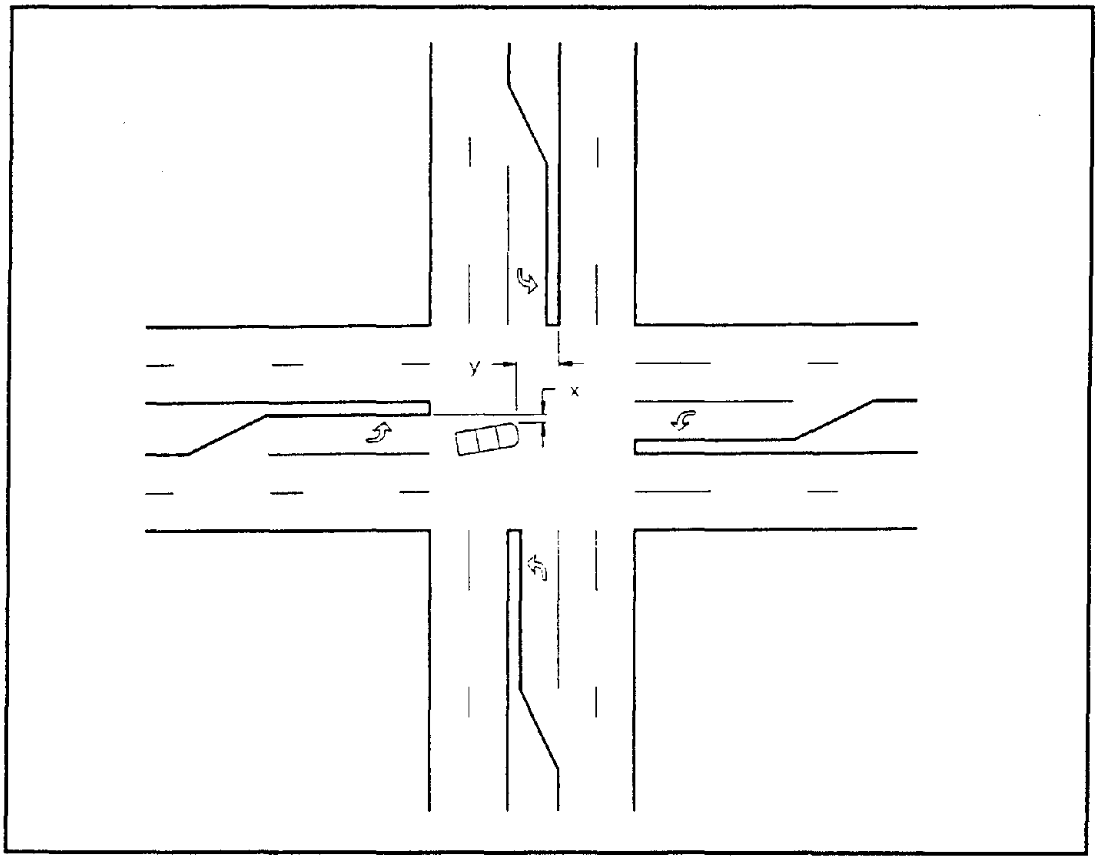


Figure 4. Longitudinal and lateral distances used to define vehicle position in the field study.

Related Studies

In a related study conducted by McCoy, Navarro, and Witt (1992), guidelines were developed for offsetting opposite left-turn lanes to eliminate the left-turn sight distance problem. All minimum offsets specified in the guidelines are positive. For 90° intersections on level tangent sections of four-lane divided roadways, with 3.6-m (12-ft) left-turn lanes in 4.9-m (16-ft) medians with 1.2-m (4-ft) medial separators, the following conclusions are stated by McCoy et al.: (1) a 0.6-m (2-ft) positive offset provides unrestricted sight distance when the opposite left-turn vehicle is a passenger car, and (2) a 1.06-m (3.5-ft) positive offset provides unrestricted sight distance when the opposite left-turn vehicle is a truck, for design speeds up to 113 km/h (70 mi/h).

In a recent study of median intersection design, Harwood, Pietrucha, Wooldridge, Brydia, and Fitzpatrick (1995) state that wider medians generally have positive effects on traffic operations and safety; however, at suburban signalized and unsignalized intersections, accidents and undesirable behavior increase as the median width increases. At suburban intersections, it is therefore suggested that the median should not generally be wider than necessary to accommodate the appropriate median left-turn treatment needed to serve current and anticipated future traffic volumes. Wider medians can result in sight restrictions for left-turning vehicles resulting from the presence of opposite left-turn vehicles if the left-turn lanes are placed in the traditional location, i.e., immediately adjacent to the same-direction through lane. The most common solution to this problem is to offset the left-turn lanes, using either parallel offset or tapered offset left-turn lanes. Figure 5 compares conventional left-turn lanes to these two alternative designs. As noted by the authors, parallel and tapered offset left-turn lanes are still not common, but are used increasingly to reduce the risk of accidents due to sight restrictions from opposite left-turn vehicles. Parallel offset left-turn lanes with 3.6-m (12-ft) widths can be constructed in raised medians with widths as narrow as 7.2 m (24 ft), and can be provided in narrower medians if restricted lane widths or curb offsets are used or a flush median is provided (Bonneson, McCoy, and Truby, 1993). Tapered offset left-turn lanes generally require raised medians of 7.2 m (24 ft) or more in width.

In a survey of 44 state highway agencies and 19 local highway agencies, Harwood et al. (1995) found that 62 percent of the state agencies and 42 percent of the local highway agencies have used offset left-turn lanes. It was noted in this research that there are presently no national design guidelines for offset left-turn lanes; parallel offset left-turn lanes are mentioned only briefly in the *Green Book* (AASHTO, 1994), and tapered offset left-turn lanes are not mentioned at all. The Illinois Department of Transportation (IDOT) was found to have the most extensive experience with the use of tapered offset left-turn lanes; IDOT provides tapered offset left-turn lanes under the following conditions: (1) where median widths are 12 m (40 ft) or more, (2) where the current crossroad average daily traffic (average of both approaches) is 1,500 veh/day or greater, and (3) where the current left-turn design hour volume (DHV) in each direction from the major road is greater than 60 veh/h. At signalized intersections, tapered offset left-turn lanes are used on a major road where only one left-turn lane in each direction of travel is needed for capacity.

Because the accident rate at suburban signalized intersections increases as the median width increases, Harwood et al. (1995) suggest that suburban signalized intersections can generally operate effectively with median widths less than 7.6 m (25 ft) and that medians wider than 7.6 m (25 ft) are not generally recommended at suburban signalized intersections unless required for the selected left-turn treatment. In their report, a table of feasible allocations of available width for various median widths and left-turn treatments is provided for intersections with raised or depressed medians. For example, a tapered offset left-turn lane with a 1.2-m (4-ft) left-turn lane offset, a 1.2-m (4-ft) medial separator width, a 0.6-m (2-ft) curb offset, a 3.6-m (12-ft) left-turn lane width, and a through-lane separator width of 2.4 m (8 ft) would require a median width of 7.9 m (26 ft). Harwood et al. (1995) classified parallel offset left-turn lanes with lane widths less than 3.6 m (12 ft) or offsets to the opposite left-turn lane of less than 1.2 m (4 ft) as marginal. Similarly, tapered offset left-turn lanes with lane widths less that 3.6 m (12 ft) or offsets to the opposite left-turn lane of less than 1.2 m (4 ft) were classified as marginal.

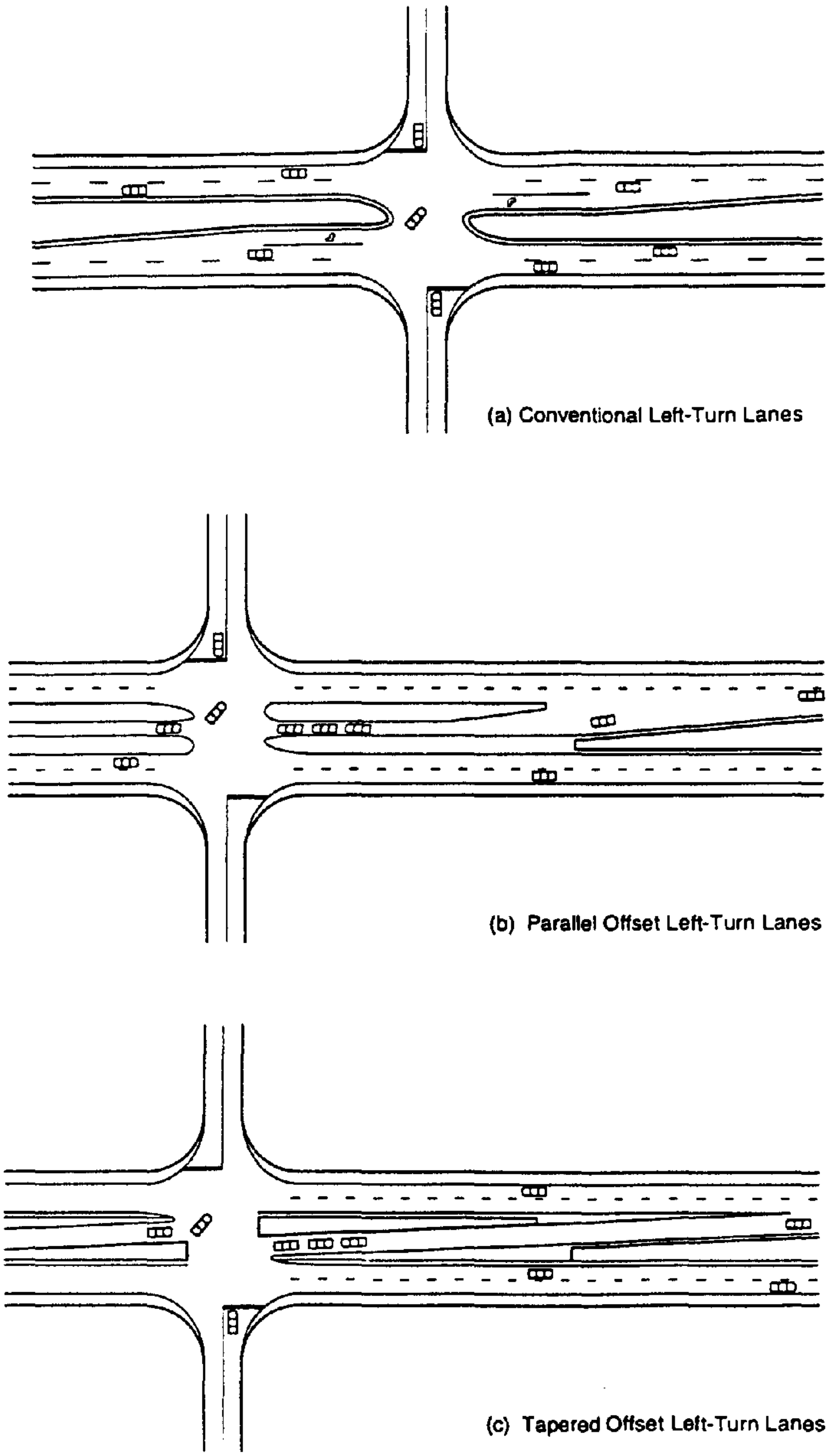


Figure 5. Alternative left-turn treatments for rural and suburban divided highways. [Taken from Bonneson, McCoy, and Truby (1993); in Harwood et al. (1995).]

DEVELOPMENT OF INTERSECTION SIGHT DISTANCE REQUIREMENTS FOR LEFT TURNS FROM A MAJOR HIGHWAY

INTERSECTION SIGHT DISTANCE CASE

Prior to the 1990 AASHTO *Green Book*, the issue of intersection sight distance (ISD) for a driver turning left off a major roadway onto a minor roadway or into an entrance was not specifically addressed. In the 1990 *Green Book*, the issue was addressed at the end of the Case III discussions in two paragraphs. In the 1994 *Green Book*, these same paragraphs have been placed under a new condition referred to as Case V. The equation used for determining ISD for Case V was simply taken from the Case IIIA (crossing maneuver at a stop-controlled intersection) and Case IIIB (left-turn maneuver from a stop-controlled minor road onto a major road) conditions, with the primary difference between the cases being the distance traveled during the maneuver. A central issue in defining the ISD for Case V involves a determination of whether the tasks which define ISD for Cases IIIA and IIIB are similar enough to the tasks associated with Case V to justify using the same equation, which follows:

$$\mathbf{SD=1.47\ V\ (J+t_a)} \qquad [1]$$

where: V = major roadway design speed (mi/h).
J = sum of perception-reaction time (PRT) and the time required to actuate the clutch or actuate an automatic shift (J is currently assumed to be 2.0 s).
t_a = time to cover a given distance during acceleration (i.e., maneuver time), which is read from AASHTO Figure IX-33.

For Case IIIA (crossing maneuver), the sight distance is calculated based on the need to clear traffic on the intersecting roadway on both the left and right sides of the crossing vehicle. For Case IIIB (left turn from a stop), sight distance is based on the requirement to, first, clear traffic approaching from the left, and then, enter the traffic stream of vehicles from the right. It may be demonstrated that the perceptual judgments required of drivers in both of these maneuver situations increase in difficulty when opposing through traffic must be considered.

PERCEPTION-REACTION TIME

The perceptual task of turning left from a major roadway at an unsignalized intersection or during a permissive signal phase at a signalized intersection requires a driver to make time-distance estimates of a longitudinally moving target as opposed to a laterally moving target. Lateral movement (also referred to as tangential movement), describes a vehicle that is crossing an observer's line of sight, moving against a changing visual background where it passes in front of one fixed reference point after another. Longitudinal movement, or movement in depth, results when the vehicle is either coming towards or going away from the observer. In this case, there is no change in visual direction, only subtle changes in the angular size of the visual image typically viewed against a constant background. Longitudinal movement is a greater problem for drivers because the same displacement of a vehicle has a smaller visual effect than when it moves laterally—that is, lateral movement results in a dramatically higher degree of relative motion (Hills, 1980).

In comparison to younger subjects, a significant decline for older subjects has been reported in angular motion sensitivity. In a study evaluating the simulated change in the separation of taillights indicating the overtaking of a vehicle, Lee (1976) found a threshold elevation greater than 100 percent for drivers ages 70-75 compared to drivers ages 20-29 for brief exposures at night. Older persons may, in fact, require twice the rate of movement to perceive that an object's motion in depth is approaching, given a brief duration (2.0 s) of exposure. In related experiments, Hills (1975) found that older drivers required significantly longer to perceive that a vehicle was moving closer at a constant speed: at 31 km/h (19 mi/h), decision times increased 0.5 s between ages 20 and 75. This body of evidence suggests that the 2.0-s perception-reaction time (PRT)—i.e., variable *J* in the ISD equation above—used for Cases III and V may not be sufficient for the task of judging gaps in opposing through traffic by older drivers. A revision of Case V to determine the minimum required sight distance that more accurately reflects the perceptual requirements of the left-turn task may therefore be appropriate. The following discussion addresses gap acceptance and PRT, and differences in performance as a function of driver age that underlie the ensuing recommendations.

Results of a recently completed project (NCHRP 15-14(1)) to redefine intersection sight distance specify that a gap acceptance model is more appropriate for determining the sight distance requirement for left turns from a major highway. The gap acceptance model developed and proposed to replace the current ISD AASHTO model is:

$$\mathbf{ISD = 1.47 * V * G} \qquad \textbf{[2]}$$

where: V = main road design speed (mi/h).
G = specified critical gap (s).

Field data were collected in the National Cooperative Highway Research Program (NCHRP) study to better quantify the gap acceptance behavior of passenger car and truck drivers, but only for left- and right-turning maneuvers from minor roadways controlled by a stop sign (Cases IIIB and C). In the Phase I interim report produced during the conduct of the NCHRP project, Harwood, Mason, Pietrucha, Brydia, Hostetter, and Gittings (1993) reported that the critical gap currently used by the California Department of Transportation is 7.5 s. When current AASHTO Case IIIB ISD criteria are translated to time gaps in the major road traffic stream, the gaps range from 7.5 s (67 m [220 ft]) at a 32-km/h (20-mi/h) design speed to 15.2 s (475 m [1,560 ft]) at a 113-km/h (70-mi/h) design speed. Harwood et al. (1993) stated that the rationale for gap acceptance as an ISD criterion is that drivers safely accept gaps much shorter than 15.2 s routinely, even on higher speed roadways.

In developing the gap acceptance model for Case V, Harwood et al. (*in press*) relied on data from studies conducted by Kyte et al. (1995) and Micsky (1993). Kyte et al. (1995) recommended a critical gap value of 4.2 s for left turns from the major road by passenger cars for inclusion in the unsignalized intersection analysis procedures presented in the *Highway Capacity Manual* (TRB, 1994). A constant value was recommended regardless of the number of lanes to be crossed, however, a heavy-vehicle adjustment of 1.0 s for two-lane highways and 2.0 s for multilane highways was recommended. Harwood et al. (*in press*) reported that Micsky's 1993 evaluation of gap acceptance behavior for left turns from the major roadway at two Pennsylvania intersections resulted in critical gaps with a 50 percent probability of acceptance (determined from logistic regression) of 4.6 s and 5.3 s, respectively. Using the rationale that design policies should be more conservative than operational criteria such as the *Highway Capacity Manual*, Harwood et al. (*in press)* recommended a critical gap for left turns from the major roadway of 5.5 s, and that the critical gap be increased to 6.5 s for left turns by single-unit trucks and 7.5 s for left turns by combination trucks. In addition, if the number of opposing lanes to be crossed exceeds one, an additional 0.5 s per additional lane for passenger cars and 0.7 s per additional lane for trucks is recommended.

It is important to note that the NCHRP study did not consider driver age as a variable. However, Lerner, Huey, McGee, and Sullivan (1995) collected judgments about the acceptability of gaps in traffic as a function of driver age, for left turn, right turn, and through movements at stop-controlled intersections. While noting that these authors found no significant differences between age groups in the *total* time required to perceive, react, and complete a maneuver in a related Case III PRT study, the Lerner et al. (1995) findings indicate that younger drivers accept shorter gaps than older drivers. The 50 percent gap acceptance point was about 7 s (i.e., if a gap is 7 s long, about half of the subjects would accept it). The 85th percentile point was approximately 11 s. The oldest group required about 1.1 s longer than the youngest group.

In the left-turn field study conducted in the present project, mean left-turn critical gap sizes (in seconds) across four locations where the main road design speed was 56 km/h (35 mi/h), for drivers who had positioned their vehicles within the intersection, were 5.90 s (young/middle-aged females), 5.91 s (young/middle-aged males), 6.01 s (young-old females), 5.84 s (young-old males), 6.71 s (old-old females), and 6.55 s (old-old males). A Tukey test for multiple comparisons showed that the young/middle-aged and young-old groups were not significantly different from each other; however, both were significantly different from the old-old group. Critical gap sizes displayed in the laboratory simulation study ranged from 6.4 s to 8.1 s for young/middle-aged drivers viewing oncoming vehicles traveling at 56 km/h (35 mi/h), while critical gaps for drivers age 75+ ranged from 5.8 s to 10.0 s.

These diverse findings argue that an appropriate value for G in the gap acceptance model (see equation [2]) will lie toward the upper end of the 7- to 11-s range to accommodate older drivers, while also preserving a margin of safety. This strategy acknowledges the diminished capability of older drivers to judge oncoming vehicle speed in a situation that places this group of road users at particular risk, i.e., when an opposing through vehicle approaches at excessive speed.

Regarding PRT for Cases III and V, AASHTO (1994) assumes a PRT of 2.0 s as the time necessary for the driver to look in both directions of the roadway, to perceive that there is sufficient time to perform the maneuver safely, and to shift gears, if necessary, prior to starting. This value is based on research performed by Johansson and Rumar (1971). The PRT is defined as the time from the driver's first look for possible oncoming traffic to the instant the car begins to move. Some of these operations are done simultaneously by many drivers, and some operations, such as shifting gears, may be done before searching for intersecting traffic. AASHTO states that a value of 2.0 s is assumed to represent the time taken by the slower driver.

A recent critique of these values questioned the basis for reducing the PRT from 2.5 s, as used in stopping sight distance (SSD) calculations, to 2.0 s in the Case III scenarios of the intersection sight distance calculations (Alexander, 1989). As noted by the author, "The elements of PRT are: detection, recognition, decision, and action initiation." For SSD, this is the time from object or hazard detection to initiation of the braking maneuver. Time to search for a hazard or object is not included in the SSD computation, and the corresponding PRT value is 2.5 s. Yet, in all Case III scenarios, the PRT has been reduced to 2.0 s *and now includes a search component which was not included in the SSD computations.* The author points out that a driver is looking straight ahead when deciding to perform a stopping maneuver and only has to consider what is in his/her forward view. At an intersection, however, the driver must look forward, to the right, and to the left. This obviously takes time, especially for those drivers with lower levels of head/neck mobility, e.g., older drivers. Alexander (1989) proposes the addition of a "search time" variable to the current equations for determining intersection sight distance, resulting in the use of the PRT value currently employed in the SSD computations (i.e., 2.5 s) for all intersection sight distance computations.

Neuman (1989) also argues that a PRT of 2.5 s for SSD may not be sufficient in all situations, and can vary from 1.5 s to 5.0 s depending on the physical state of the driver (alert versus fatigued), the complexity of the driving task, and the location and functional class of the highway. Hostetter, McGee, Crowley, Seguin, and Dauber (1986) concluded that a PRT of 2.0 s was adequate for Case IIIA; however, they recommended an increase in PRT of 2.0 s to 2.5 s for Cases IIIB and IIIC (left- and right-turning maneuvers, respectively).

Regarding the value of t_a, which is read from AASHTO Figure IX-33, the present field study found no significant differences in maneuver time as a function of age for the drivers turning left at the four intersections studied (which had distances ranging from 26 to 32 m [84 to 106 ft]). Maneuver times for positioned and unpositioned vehicles, however, were significantly different. Since significantly fewer older drivers positioned themselves in the field study, the design value for this factor (maneuver time) should be based on that obtained for unpositioned drivers. The 95th percentile maneuver time for opposed, unpositioned left-turn vehicles in the field study was 6.7 s to travel 32 m (106 ft) at the -4.3-m (-14-ft) offset location; 6.4 s to travel 30 m (98 ft) at the -0.91-m (-3-ft) offset location; 6.6 s to travel 26 m (84 ft) at the aligned location; and 5.7 s to travel 27 m (88 ft) at the +1.8-m (+6-ft) offset location. Looking at AASHTO Figure IX-33 for acceleration time, it can be seen that a value of 6.2 s (for a distance of 30 m [98 ft] traveled during acceleration) is the recommended time to be used for t_a in Equation [1] for passenger cars as the time needed to perform the necessary maneuvers for Cases IIIA and IIIB. The time-distance data cited by AASHTO were provided by the University of Michigan Transportation Research Institute (Fancher, 1984). Thus, the 95th percentile maneuver times obtained in the field study and the values plotted in AASHTO Figure IX-33 are in close agreement.

EXERCISE OF ALTERNATIVE MODELS AND SIGHT DISTANCE CALCULATIONS

Several issues were raised in the preceding section regarding the adequacy of the current and proposed ISD models for a driver turning left from a major roadway. At the same time, it has been shown through efforts in this research study that an increase in sight distance through positively offsetting left-turn lanes can be beneficial to left-turning drivers, particularly older drivers. In this section, current and proposed sight distance models are exercised, leading to a determination of offset values that can be used for design to achieve specific sight distances.

The data collected in this research study affords the opportunity to compare the intersection sight distance (ISD) models using both the values derived or assumed, as well as values produced from actual field data. Three of the four intersections where left-turn maneuver data were gathered are included in this analysis; the fourth field site, described by a 4.3-m (14-ft) negative offset, was explicitly excluded as a candidate for recommended practice (see Staplin, Harkey, Lococo, and Tarawneh, *in press*). The subject intersections include one with aligned left-turn lanes, one with negatively offset left-turn lanes (0.91 m [3 ft]) and one with positively offset left-turn lanes (1.8 m [6 ft]). It is important to note that all of the calculations and subsequent results are for tangent, level intersections. If the intersection is on a vertical or horizontal curve, the equations must be modified in accordance with the AASHTO design policy. The key vehicle positioning measures for guideline development, as obtained in the earlier field study in this project, are displayed in Table 5. The first three rows of values represent the positioning values needed to calculate the available sight distances, and the last two rows of values represent the maneuver time values needed to calculate the required sight distances.

Table 5. Vehicle positioning and maneuver time design values used to develop guidelines.

Value Description	Left-Turn Lane Offset		
	-3 ft	0 ft	+6 ft
5th Percentile Longitudinal Position of Opposed, Positioned Left-Turn Vehicles (feet)	9.3	14.0	16.3
95th Percentile Lateral Position of Opposed, Positioned Left-Turn Vehicles (feet)	1.5	1.8	1.7
95th Percentile Lateral Position of Opposed, Unpositioned Left-Turn Vehicles (feet)	3.8	3.8	3.8
95th Percentile Maneuver Time of Opposed, Positioned Left-Turn Vehicles (seconds)	3.9	3.9	3.9
95th Percentile Maneuver Time of Opposed, Unpositioned Left-Turn Vehicles (seconds)	6.4	6.6	5.7

1 ft = 0.305 m

For this comparison, two basic models were selected. The first model was the current model in the AASHTO *Green Book* for computing ISD, which relies on PRT and maneuver time and takes the form:

$$ISD = 1.47V(J + t_a)$$ **Model 1**

where: V = design speed on the major road (mi/h).
J = time to search for oncoming vehicles, perceive that there is sufficient time to make the left turn, and shift gears, if necessary, prior to starting (assumed to be 2.0 s).
t_a = time required to accelerate and traverse the distance to clear traffic in the approaching lane(s); obtained from Figure IX-33 in the AASHTO *Green Book.*

The second model was the gap model that has been developed as part of NCHRP Project 15-14(1) and relies on the critical gap in place of PRT and maneuver time. This model may replace the current ISD model in the *Green Book.* This model takes the form:

$$ISD = 1.47VG$$ **Model 2**

where: V = design speed on the major road (mi/h).
G = specified critical gap (s); equal to 5.5 s for crossing one opposing lane, plus an additional 0.5 s for each additional opposing lane.

Each of these models was used with the appropriate design values to compute the required sight distance at each of the selected intersections. The models were then used with adjusted design values or actual data collected in the field to also determine the required sight distance at each location.

The first adjustment made to the current AASHTO model (Model 1 above) was an increase in the PRT. As previously noted, several studies have examined and critiqued the use of 2.0 s for PRT in this model. Thus, an adjusted model with a PRT of 2.5 s, which is equivalent to the value used in SSD calculations, is also included in the analysis as follows:

$$ISD = 1.47V(J + t_a)$$ **Model 3**

where: V = design speed on the major road (mi/h).
J = time to search for oncoming vehicles, perceive that there is sufficient time to make the left turn, and shift gears, if necessary, prior to starting (assumed to be 2.5 s).
t_a = time required to accelerate and traverse the distance to clear traffic in the approaching lane(s); obtained from Figure IX-33 in the AASHTO *Green Book.*

One of the data elements collected as part of this research was the maneuver time of the left-turning driver. This time is equivalent to t_a in the AASHTO model. These times were measured from two locations, depending on how the drivers positioned themselves within the intersection prior to turning. The first location was from a position within the intersection, approaching the median or center line of the cross street. This type of driver was referred to as a "positioned" driver, and the maneuver time was measured from the instance the car began to move after a decision had been made to turn to the time when the car was clear of the opposing traffic lanes. The second location was from a position at or behind the stop bar or end of the left-turn bay. This type of driver was referred to as an "unpositioned" driver. The maneuver time was measured in the same manner for these left-turning drivers. (Refer to Figure 4, page 16, where longitudinal positioning is shown as distance "y" and lateral positioning is shown as distance "x"). Using the original AASHTO model (Model 1) and these field data maneuver times, sight distances were computed with these two additional models:

$$ISD = 1.47V(J + t_a)$$ **Model 4**

where: V = design speed on the major road (mi/h).
J = time to search for oncoming vehicles, perceive that there is sufficient time to make the left turn, and shift gears, if necessary, prior to starting (assumed to be 2.0 s).
t_a = maneuver time for an unpositioned driver; 95th percentile maneuver time from the distribution of all unpositioned drivers.

$$ISD = 1.47V(J + t_a)$$ **Model 5**

where: V = design speed on the major road (mi/h).
J = time to search for oncoming vehicles, perceive that there is sufficient time to make the left turn, and shift gears, if necessary, prior to starting (assumed to be 2.0 s).
t_a = maneuver time for a positioned driver; 95th percentile maneuver time from the distribution of all positioned drivers.

Critical gap data were also collected at each of the intersections as part of this study. These data were collected and analyzed by driver age group. The drivers in the age 75 or older group were shown to accept a significantly larger gap compared to the other age groups. Thus, two different critical gaps were used in adjusted gap models to compute the required sight distances. These models simply modify the value of G in Model 2 above and take the form:

$$ISD = 1.47VG$$ **Model 6**

where: V = design speed on the major road (mi/h).
G = critical gap (s) for all drivers as measured in the field.

$$ISD = 1.47VG$$ **Model 7**

where: V = design speed on the major road (mi/h).
G = critical gap (s) for drivers age 75 or older as measured in the field.

The computed required sight distances for each of the three intersections, using each of the seven models described above, are shown in Table 6. Perhaps the most significant result is the dramatic decrease in required sight distance that occurs with the gap model compared to the traditional AASHTO model. Across all three intersections and all design speeds, the required sight distance is approximately 23 percent less using the gap model. However, this was expected since the rationale behind the use of a gap model (see Harwood et al., *in press*) in place of the

Table 6. Required sight distance for the 0.91-m (3-ft) negative offset, aligned, and 1.8-m (6-ft) positive offset locations observed in the field study, using seven alternative models.

Offset Condition (-3 ft)

	d_a	t_a	NOL	G	Factor*V	Design Speed (mi/h) 20	25	30	35	40	45	50	55	60	65	70
Model 1 (AASHTO) = 1.47V(J+t_a); J = 2.0	98	6.3			12.20	244	305	366	427	488	549	610	671	732	793	854
Model 3 (AASHTO) = 1.47V(J+t_a); J = 2.5	98	6.3			12.94	259	323	388	453	517	582	647	711	776	841	906
Model 4 (AASHTO); t_a from field data for unpositioned drivers	98	6.4			12.35	247	309	370	432	494	556	617	679	741	803	864
Model 5 (AASHTO); t_a from field data for positioned drivers	67	3.9			8.67	173	217	260	304	347	390	434	477	520	564	607
Model 2 (Gap) = 1.47VG			3	6.5	9.56	191	239	287	334	382	430	478	526	573	621	669
Model 6 (Gap); critical gap for all drivers			3	6.1	8.97	179	224	269	314	359	404	448	493	538	583	628
Model 7 (Gap); critical gap for drivers age 75 or older			3	6.6	9.70	194	243	291	340	388	437	485	534	582	631	679

Aligned Condition

	d_a	t_a	NOL	G	Factor*V	Design Speed (mi/h) 20	25	30	35	40	45	50	55	60	65	70
Model 1 (AASHTO) = 1.47V(J+t_a); J = 2.0	84	5.8			11.47	229	287	344	401	459	516	573	631	688	745	803
Model 3 (AASHTO) = 1.47V(J+t_a); J = 2.5	84	5.8			12.20	244	305	366	427	488	549	610	671	732	793	854
Model 4 (AASHTO); t_a from field data for unpositioned drivers	84	6.6			12.64	253	316	379	442	506	569	632	695	759	822	885
Model 5 (AASHTO); t_a from field data for positioned drivers	64	3.9			8.67	173	217	260	304	347	390	434	477	520	564	607
Model 2 (Gap) = 1.47VG			2	6	8.82	176	221	265	309	353	397	441	485	529	573	617
Model 6 (Gap); critical gap for all drivers			2	6.1	8.97	179	224	269	314	359	404	448	493	538	583	628
Model 7 (Gap); critical gap for drivers age 75 or older			2	6.6	9.70	194	243	291	340	388	437	485	534	582	631	679

Offset Condition (+6 ft)

	d_a	t_a	NOL	G	Factor*V	Design Speed (mi/h) 20	25	30	35	40	45	50	55	60	65	70
Model 1 (AASHTO) = 1.47V(J+t_a); J = 2.0	88	5.8			11.47	229	287	344	401	459	516	573	631	688	745	803
Model 3 (AASHTO) = 1.47V(J+t_a); J = 2.5	88	5.8			12.20	244	305	366	427	488	549	610	671	732	793	854
Model 4 (AASHTO); t_a from field data for unpositioned drivers	88	5.7			11.32	226	283	340	396	453	509	566	623	679	736	792
Model 5 (AASHTO); t_a from field data for positioned drivers	70	3.9			8.67	173	217	260	304	347	390	434	477	520	564	607
Model 2 (Gap) = 1.47VG			3	6.5	9.56	191	239	287	334	382	430	478	526	573	621	669
Model 6 (Gap); critical gap for all drivers			3	6	8.82	176	221	265	309	353	397	441	485	529	573	617
Model 7 (Gap); critical gap for drivers age 75 or older			3	6.4	9.41	188	235	282	329	376	423	470	517	564	612	659

NOL = number of lanes

d_a = distance traveled during acceleration (ft)

t_a = time to accelerate distance d_a (maneuver time in seconds)

1 ft = 0.305 m

1 mi/h = 1.61 km/h

current AASHTO model is the fact that drivers accept shorter gaps than those implied by the current model. In other words, the additional sight distance provided by the current model does not help the driver in terms of selecting an appropriate gap.

Examining only the current and adjusted AASHTO models, it was found that the positioned left-turning drivers required the least amount of sight distance. In fact, the amount of sight distance required by such drivers at all three intersections was not only less than required by the current AASHTO model, but was also less than required by the gap model. For unpositioned drivers, however, the current model distances exceeded the required distances from the field data for the positively offset intersection only. The negatively offset intersection produced results which were very close, but the current model still produced slightly smaller distances than those produced from the field data. Finally, the aligned intersection resulted in the largest differences, with the current model producing distances which were approximately 9 percent lower than what would be required based on the field data.

Comparing the gap models, it can be seen that the proposed model (Model 2) provided sight distances which exceeded the required distances based on the critical gaps of all drivers at two of the three intersections. The intersection with aligned left-turn bays produced required distances from the field data that were 2 percent greater than those produced by the proposed model. From these results, it would appear that the gap model is satisfactory for providing the necessary sight distance for left-turning drivers. However, a comparison of the required distances produced by the proposed model with distances produced from the older driver field data revealed some potential problems. The required distances from the field data for older drivers at the negatively offset intersection and the aligned intersection exceeded those distances produced by the proposed gap model. The aligned location produced required distances which were 10 percent greater than those produced by the proposed model, while the negatively offset location produced distances which were 2 percent greater. Greater distances from the proposed model, as compared to the older driver field data were produced only for the positively offset location.

Because the number of intersections in the analysis was limited, the results described in this report could be strengthened through further investigations. Taking the current AASHTO model as the one most appropriate for calculating ISD as it relates to drivers turning left from a major roadway, there is evidence that the PRT value should be increased to 2.5 s to provide adequate sight distance at most locations. Even so, this increase may not produce adequate sight distances at all locations, but it provides the closest fit between the model and what was found in the field data collection efforts in this research. *If* the gap model is going to be used, particularly where there are significant volumes of older left-turning drivers, there appears to be a need to apply an adjustment factor to increase the sight distance to better accommodate this group of road users. Moreover, to the extent that the current AASHTO ISD model produces longer sight distances than the gap model, it may be most prudent—taking into account the projected increases in the numbers and exposure of drivers with diminished capabilities—to regard the difference as simply a "margin of safety" that will also improve the efficiency of intersection operations.

Regardless of which model is deemed most appropriate for computing ISD for drivers turning left off a major roadway, one way to increase the sight distance is through positively offset left-turn lanes. As shown in the results of this study, such designs result in significantly better performance on the part of all drivers, but especially older drivers. Prior work by McCoy et al.

(1992) examined the issue of offset left-turn lanes and developed an approach that could be used to compute the amount of offset that is required to minimize or eliminate the sight restriction caused by opposing left-turn vehicles. This approach was applied to the three intersections in this study to determine the amount of offset that would be required when using the current AASHTO model vs. the modified AASHTO model (i.e., J = 2.5 s) vs. the proposed gap model.

The first step was to compute the available sight distance at each of the intersections. This distance is shown in Figure 6 and can be expressed as follows:

$$SD_a = Y_a + Y_b \qquad [3]$$

where: SD_a = available sight distance (ft).

Y_a = distance from the front of the left-turning vehicle to the front of the opposing left-turning vehicle (ft). For two unpositioned vehicles, this distance is equal to the width of the median opening. For two positioned vehicles, this distance is equal to twice the 5th percentile longitudinal position of opposed left-turning vehicles as measured in the field. For one positioned and one unpositioned vehicle, the distance is equal to half the median opening width minus half the cross-street median width plus the 5th percentile longitudinal position.

Y_b = distance from the front of the opposing left-turning vehicle to the front of the oncoming through vehicle in the lane closest to the median or center line (ft).

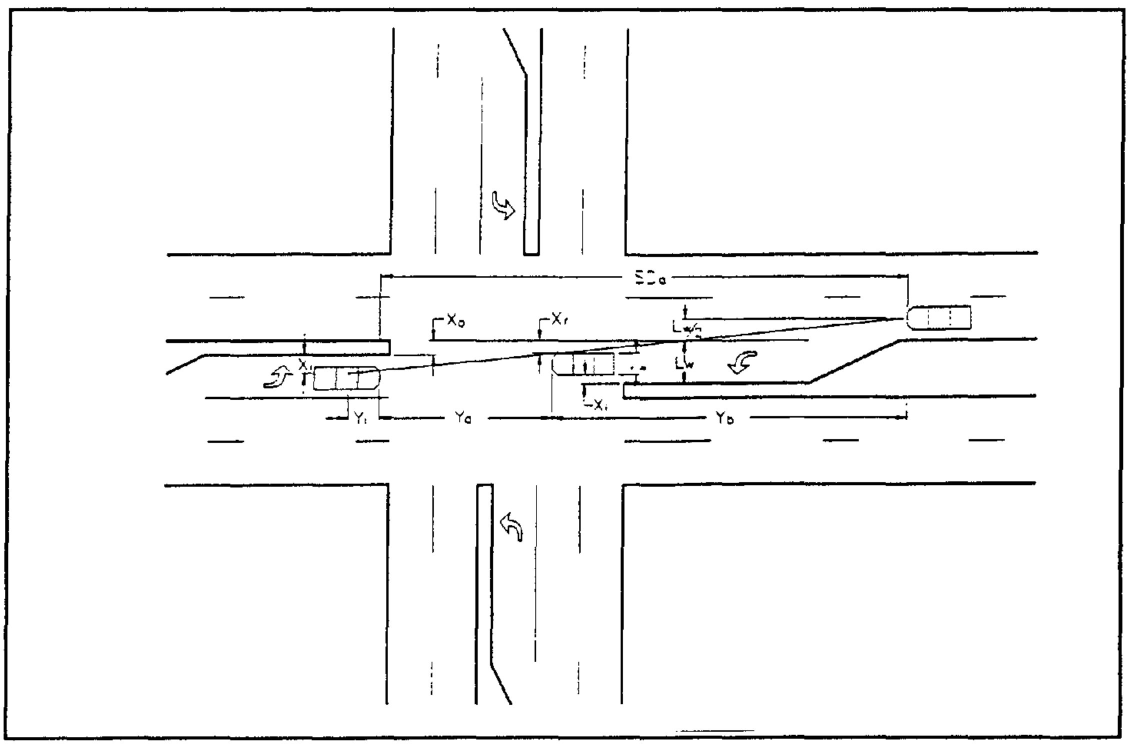


Figure 6. Available sight distance.
[Taken from McCoy, Navarro, and Witt (1992).]

Of course, Y_a and Y_b can change based on the position of the left-turning vehicle and the opposing left-turning vehicle. Y_a was determined from field measurements of the intersections and data collected on left-turn vehicle positioning as described above. The equation for calculating Y_b is shown below and is derived from geometric relationships between similar triangles as shown in Figure 6:

$$Y_b = \frac{(Y_a + Y_i)(X_r + 0.5\ L_w)}{X_i - X_r - X_o} \qquad [4]$$

where: Y_i = longitudinal distance from the front of the left-turning vehicle to the driver's eye (ft); assumed to be 3 m (10 ft) (AASHTO *Green Book*).

L_w = lane width of the left turn and through lanes (ft); measured in the field to be 3.7 m (12 ft).

X_i = lateral distance of the left-turning driver's eye to the edge of the left-turn lane (ft); sum of the 95th percentile lateral position of opposed left-turning vehicles as measured in the field and the distance from the left edge of the car to the driver's eye (assumed to be 0.5 m [1.5 ft]).

X_o = offset between opposing left-turn lanes (ft); measured in the field.

X_r = lateral distance from the right-front corner of the opposing left-turn vehicle to the right edge of the opposing left-turn lane (ft); calculated from the equation:

$$X_r = L_w - V_w - X_l \qquad [5]$$

where: V_w = vehicle width (ft); assumed to be 2.1 m (7 ft) for cars and 2.6 m (8.5 ft) for trucks (AASHTO *Green Book*).

X_l = lateral distance from the median separator to the left edge of the opposing left-turn vehicle; equal to the 95th percentile position of an opposed left-turning vehicle as measured in the field.

Shown in Table 7 are the values for each of the variables in the equation and the resulting sight distance equations for each of the intersections. Of particular interest is that available sight distance at the negative 0.91-m (3-ft) offset location is less than what was required from Table 6, using the current AASHTO model and field data maneuver times obtained for positioned drivers (Model 5) at the posted speed limit of 56 km/h (35 mi/h). The other six models produced even longer required sight distances than were available at this location. The available sight distance at the aligned condition fell short of what was required, except for cases when both cars were positioned or an unpositioned car was opposed by a positioned car. The sight distance for left-turning vehicles at the positive offset location was not restricted by opposite left-turning vehicles.

Table 7. Available sight distance at the 0.91-m (3-ft) negative offset, aligned, and 1.8-m (6-ft) positive offset locations observed in the field study.

Offset Condition (-3 ft)	Y_l	L_w	V_w	Y_a	X_l	X_l	X_r	X_l-X_r	Y_a+Y_l	X_r+L_w/2	Y_b (num)	X_o	Sight Distance Available*	Calculated Sight Distance (ft)*
Positioned/Positioned Car	10	12	7.0	15.6	3.0	1.5	3.5	-0.5	25.6	9.5	243.2	-3.0	15.6 + {243.2/(-0.5-X_o)}	113
Positioned/Unpositioned Car	10	12	7.0	52.3	3.0	3.8	1.2	1.8	62.3	7.2	448.6	-3.0	52.3 + {448.6/(1.8-X_o)}	146
Unpositioned/Positioned Car	10	12	7.0	52.3	5.3	1.5	3.5	1.8	62.3	9.5	591.9	-3.0	52.3 + {591.9/(1.8-X_o)}	176
Unpositioned/Unpositioned Car	10	12	7.0	86.0	5.3	3.8	1.2	4.1	96.0	7.2	691.2	-3.0	86.0 + {691.2/(4.1-X_o)}	183
Positioned/Positioned Truck	10	12	8.5	15.6	3.0	1.5	2.0	1.0	25.6	8.0	204.8	-3.0	15.6 + {204.8/(1.0-X_o)}	67
Positioned/Unpositioned Truck	10	12	8.5	52.3	3.0	3.8	-0.3	3.3	62.3	5.7	355.1	-3.0	52.3 + {355.1/(3.3-X_o)}	109
Unpositioned/Positioned Truck	10	12	8.5	52.3	5.3	1.5	2.0	3.3	62.3	8.0	498.4	-3.0	52.3 + {498.4/(3.3-X_o)}	131
Unpositioned/Unpositioned Truck	10	12	8.5	86.0	5.3	3.8	-0.3	5.6	96.0	5.7	547.2	-3.0	86.0 + {547.2/(5.6-X_o)}	150

Aligned Condition	Y_l	L_w	V_w	Y_a	X_l	X_l	X_r	X_l-X_r	Y_a+Y_l	X_r+L_w/2	Y_b (num)	X_o	Sight Distance Available*	Calculated Sight Distance (ft)*
Positioned/Positioned Car	10	12	7.0	28.0	3.3	1.8	3.2	0.1	38.0	9.2	349.6	0.0	28.0 + {349.6/(0.1-X_o)}	3524
Positioned/Unpositioned Car	10	12	7.0	55.0	3.3	3.8	1.2	2.1	65.0	7.2	468.0	0.0	55.0 + {468.0/(2.1-X_o)}	278
Unpositioned/Positioned Car	10	12	7.0	55.0	5.3	1.8	3.2	2.1	.65.0	9.2	598.0	0.0	55.0 + {598.0/(2.1-X_o)}	340
Unpositioned/Unpositioned Car	10	12	7.0	82.0	5.3	3.8	1.2	4.1	92.0	7.2	662.4	0.0	82.0 + {662.4/(4.1-X_o)}	244
Positioned/Positioned Truck	10	12	8.5	28.0	3.3	1.8	1.7	1.6	38.0	7.7	292.6	0.0	28.0 + {292.6/(1.6-X_o)}	211
Positioned/Unpositioned Truck	10	12	8.5	55.0	3.3	3.8	-0.3	3.6	65.0	5.7	370.5	0.0	55.0 + {370.5/(3.6-X_o)}	158
Unpositioned/Positioned Truck	10	12	8.5	55.0	5.3	1.8	1.7	3.6	65.0	7.7	500.5	0.0	55.0 + {500.5/(3.6-X_o)}	194
Unpositioned/Unpositioned Truck	10	12	8.5	82.0	5.3	3.8	-0.3	5.6	92.0	5.7	524.4	0.0	82.0 + {524.4/(5.6-X_o)}	176

Offset Condition (+6 ft)	Y_l	L_w	V_w	Y_a	X_l	X_l	X_r	X_l-X_r	Y_a+Y_l	X_r+L_w/2	Y_b (num)	X_o	Sight Distance Available*	Calculated Sight Distance (ft)
Positioned/Positioned Car	10	12	7.0	30.6	3.2	1.7	3.3	-0.1	40.6	9.3	377.6	6.0	30.6 + {377.6/(-0.1-X_o)}	**
Positioned/Unpositioned Car	10	12	7.0	58.3	3.2	3.8	1.2	2.0	68.3	7.2	491.8	6.0	58.3 + {491.8/(2.0-X_o)}	**
Unpositioned/Positioned Car	10	12	7.0	58.3	5.3	1.7	3.3	2.0	68.3	9.3	635.2	6.0	58.3 + {635.2/(2.0-X_o)}	**
Unpositioned/Unpositioned Car	10	12	7.0	84.0	5.3	3.8	1.2	4.1	94.0	7.2	676.8	6.0	84.0 + {676.8/(4.1-X_o)}	**
Positioned/Positioned Truck	10	12	8.5	30.6	3.2	1.7	1.8	1.4	40.6	7.8	316.7	6.0	30.6 + {316.7/(1.4-X_o)}	**
Positioned/Unpositioned Truck	10	12	8.5	58.3	3.2	3.8	-0.3	3.5	68.3	5.7	389.3	6.0	58.3 + {389.3/(3.5-X_o)}	**
Unpositioned/Positioned Truck	10	12	8.5	58.3	5.3	1.7	1.8	3.5	68.3	7.8	532.7	6.0	58.3 + {532.7/(3.5-X_o)}	**
Unpositioned/Unpositioned Truck	10	12	8.5	84.0	5.3	3.8	-0.3	5.6	94.0	5.7	535.8	6.0	84.0 + {535.8/(5.6-X_o)}	**

1 ft = 0.305 m

* Based solely on sight distance restriction by an opposing left-turn vehicle. Does not account for effects of roadway curvature or other physical restrictions.

** When X_o is less than X_l-X_r, the sight distance is not restricted by opposing left-turn vehicles.

By setting the equations for available sight distance in Table 7 equal to the required sight distance equations, the amount of offset needed to achieve the required sight distance can be determined.

The first model for which this was done was the current AASHTO model with maneuver times (t_a) from the field data (Models 4 and 5). The resulting offsets are shown in Table 8.

Overall, the vehicle positionings requiring the largest amount of offset, in order, were:

(1) Unpositioned left-turn car/Unpositioned opposing left-turn truck.
(2) Unpositioned left-turn car/Unpositioned opposing left-turn car.
(3) Unpositioned left-turn car/Positioned opposing left-turn truck.
(4) Positioned left-turn car/Unpositioned opposing left-turn truck.
(5) Unpositioned left-turn car/Positioned opposing left-turn car.

These results indicate which vehicle positions will generally govern the design. The offsets for conditions 3 and 4 above are very similar. Thus, the remainder of the tables include calculations for *unpositioned left-turn cars only* in combination with the four opposing vehicle types/positions.

Typically, a cross-section design will include elements such as lane widths and median widths that are specified to the nearest 0.1 m (0.5 ft). Thus, the offsets that are derived should be rounded up to the nearest 0.1 m (0.5 ft) for use in design. Shown in Figure 7 are the minimum design values for offsetting left-turn lanes that should be used to achieve the required sight distances computed from the AASHTO model using field-measured maneuver times. These values range from 0.15 m (0.5 ft) for a 32-km/h (20-mi/h) design speed to 1.1 m (3.5 ft) for design speeds of 97 km/h (60 mi/h) and greater when the opposing vehicle is a car. When the opposing vehicle is a truck, the design values range from 0.8 m (2.5 ft) for a 32-km/h (20-mi/h) design speed to 1.5 m (5.0 ft) for design speeds of 80 km/h (50 mi/h) and greater.

The next model for which offsets were computed was the modified AASHTO model (Model 3) with a PRT of 2.5 s. In this model, the value t_a was obtained from the AASHTO *Green Book* (Figure IX-33). These values are shown in Table 9 and are very similar to the offsets produced from the above models with the smaller PRT value and the field maneuver times. The offset values produced were so similar that the design values from Figure 7 also apply when using this model. This fact is another indication of how the modified AASHTO model with the longer PRT is a good predictive model of actual field operations.

The final model for which offset values were produced was the gap model (Model 2), which may replace the current AASHTO model. The resulting offsets produced from this model are shown in Table 10. Since the required sight distances produced from this model are always less than those produced by the AASHTO models, it was no surprise that the offsets produced were also less than those produced by the AASHTO models. The offsets were rounded up to the nearest 0.1 m (0.5 ft) to produce the design values that are plotted in Figure 8. The minimum offsets required to achieve the required sight distances produced from this model ranged from 0 m (0 ft) for design speeds of 32 and 40 km/h (20 and 25 mi/h) to 0.91 m (3.0 ft) for design speeds of 89 km/h (55 mi/h) and greater when the opposing left-turning vehicle is a car. When the opposing

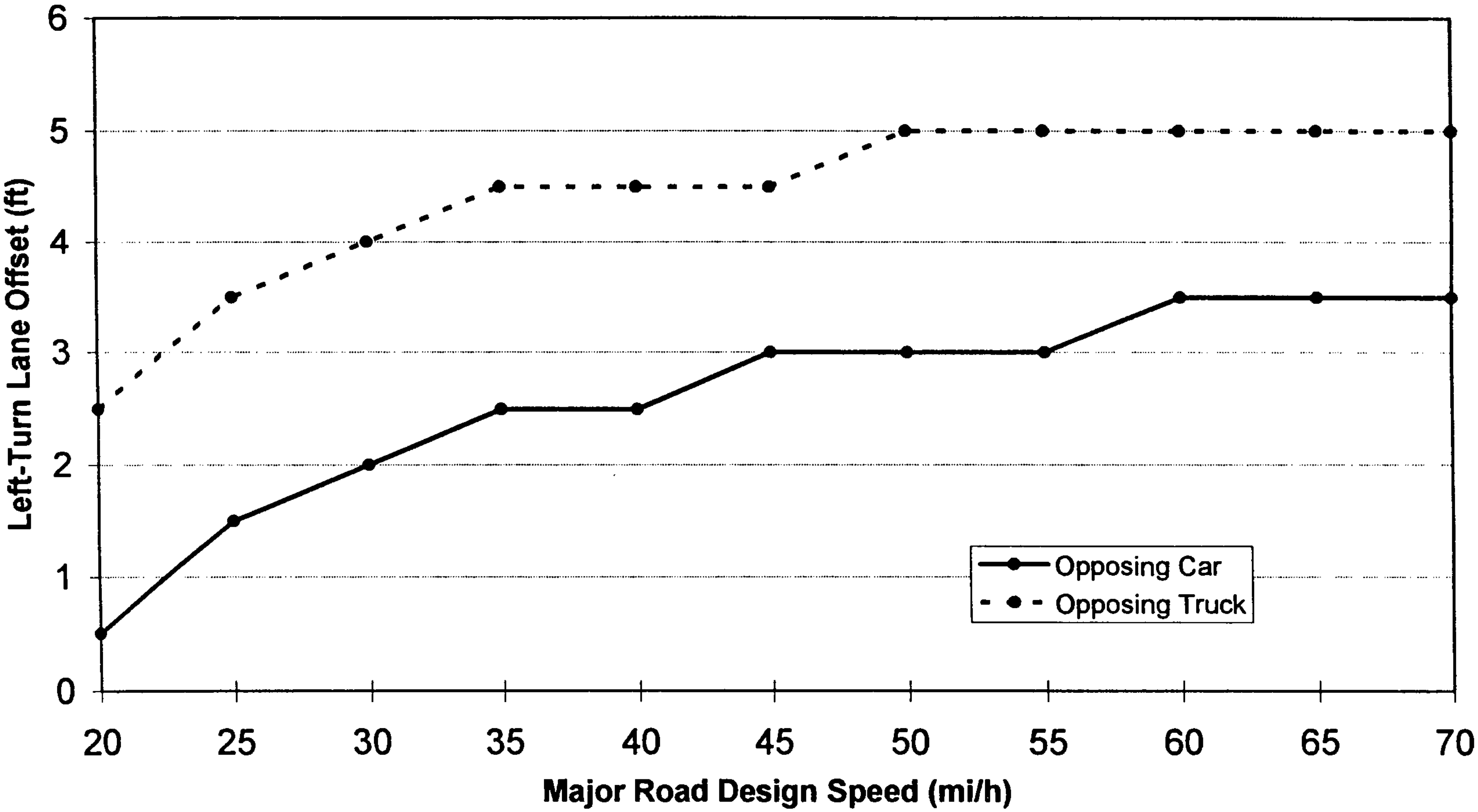
Table 8. Offsets necessary for achieving required sight distances using the AASHTO model with field data maneuver times (t_a) and J=2.0 s.

Offset Condition (-3 ft)	ASD	RSD	X_e =	20	25	30	35	40	45	50	55	60	65	70
				Offset (ft) by Design Speed (mi/h)										
Positioned/Positioned Car	15.6 + {243.2/(-0.5-X_e)}	8.67V	(-0.5) - {243.2/(8.67V-15.6)}	-2.0	-1.7	-1.5	-1.3	-1.2	-1.1	-1.1	-1.0	-1.0	-0.9	-0.9
Positioned/Unpositioned Car	52.3 + {448.6/(1.8-X_e)}	8.67V	1.8 - {448.6/(8.67V-52.3)}	-1.9	-0.9	-0.4	0.0	0.3	0.5	0.6	0.7	0.8	0.9	1.0
Unpositioned/Positioned Car	52.3 + {591.9/(1.8-X_e)}	12.35V	1.8 - {591.9/(12.35V-52.3)}	-1.2	-0.5	-0.1	0.2	0.5	0.6	0.8	0.9	0.9	1.0	1.1
Unpositioned/Unpositioned Car	86.0 + {691.2/(4.1-X_e)}	12.35V	4.1 - {691.2/(12.35V-86.0)}	-0.2	1.0	1.7	2.1	2.4	2.6	2.8	2.9	3.0	3.1	3.2
Positioned/Positioned Truck	15.6 + {204.8/(1.0-X_e)}	8.67V	1.0 - {204.8/(8.67V-15.6)}	-0.3	0.0	0.2	0.3	0.4	0.5	0.5	0.6	0.6	0.6	0.7
Positioned/Unpositioned Truck	52.3 + {355.1/(3.3-X_e)}	8.67V	3.3 - {355.1/(8.67V-52.3)}	0.4	1.1	1.6	1.9	2.1	2.2	2.4	2.5	2.5	2.6	2.7
Unpositioned/Positioned Truck	52.3 + {498.4/(3.3-X_e)}	12.35V	3.3 - {498.4/(12.35V-52.3)}	0.7	1.4	1.7	2.0	2.2	2.3	2.4	2.5	2.6	2.6	2.7
Unpositioned/Unpositioned Truck	86.0 + {547.2/(5.6-X_e)}	12.35V	5.6 - {547.2/(12.35V-86.0)}	2.2	3.1	3.7	4.0	4.3	4.4	4.6	4.7	4.8	4.8	4.9

Aligned Condition	ASD	RSD	X_e =	20	25	30	35	40	45	50	55	60	65	70
				Offset (ft) by Design Speed (mi/h)										
Positioned/Positioned Car	28.0 + {349.6/(0.1-X_e)}	8.67V	0.1 - {349.6/(8.67V-28.0)}	-2.3	-1.8	-1.4	-1.2	-1.0	-0.9	-0.8	-0.7	-0.6	-0.6	-0.5
Positioned/Unpositioned Car	55.0 + {468.0/(2.1-X_e)}	8.67V	2.1 - {468.0/(8.67V-55.0)}	-1.9	-0.8	-0.2	0.2	0.5	0.7	0.9	1.0	1.1	1.2	1.3
Unpositioned/Positioned Car	55.0 + {598.0/(2.1-X_e)}	12.64V	2.1 - {598.0/(12.64V-55.0)}	-0.9	-0.2	0.3	0.6	0.8	0.9	1.1	1.2	1.2	1.3	1.4
Unpositioned/Unpositioned Car	82.0 + {662.4/(4.1-X_e)}	12.64V	4.1 - {662.4/(12.64V-82.0)}	0.2	1.3	1.9	2.3	2.5	2.7	2.9	3.0	3.1	3.2	3.3
Positioned/Positioned Truck	28.0 + {292.6/(1.6-X_e)}	8.67V	1.6 - {292.6/(8.67V-28.0)}	-0.4	0.0	0.3	0.5	0.7	0.8	0.9	0.9	1.0	1.1	1.1
Positioned/Unpositioned Truck	55.0 + {370.5/(3.6-X_e)}	8.67V	3.6 - {370.5/(8.67V-55.0)}	0.5	1.3	1.8	2.1	2.3	2.5	2.6	2.7	2.8	2.9	2.9
Unpositioned/Positioned Truck	55.0 + {500.5/(3.6-X_e)}	12.64V	3.6 - {500.5/(12.64V-55.0)}	1.1	1.7	2.1	2.3	2.5	2.6	2.7	2.8	2.9	2.9	3.0
Unpositioned/Unpositioned Truck	82.0 + {524.4/(5.6-X_e)}	12.64V	5.6 - {524.4/(12.64V-82.0)}	2.5	3.4	3.8	4.1	4.4	4.5	4.6	4.7	4.8	4.9	4.9

Offset Condition (+6 ft)	ASD	RSD	X_e =	20	25	30	35	40	45	50	55	60	65	70
				Offset (ft) by Design Speed (mi/h)										
Positioned/Positioned Car	30.6 + {377.6/(-0.1-X_e)}	8.67V	(-0.1) - {377.6/(8.67V-30.6)}	-2.7	-2.1	-1.7	-1.5	-1.3	-1.2	-1.0	-0.9	-0.9	-0.8	-0.8
Positioned/Unpositioned Car	58.3 + {491.8/(2.0-X_e)}	8.67V	2.0 - {491.8/(8.67V-58.3)}	-2.3	-1.1	-0.4	0.0	0.3	0.5	0.7	0.8	0.9	1.0	1.1
Unpositioned/Positioned Car	58.3 + {635.2/(2.0-X_e)}	11.32V	2.0 - {635.2/(11.32V-58.3)}	-1.8	-0.8	-0.3	0.1	0.4	0.6	0.7	0.9	1.0	1.1	1.1
Unpositioned/Unpositioned Car	84.0 + {676.8/(4.1-X_e)}	11.32V	4.1 - {676.8/(11.32V-84.0)}	-0.7	0.7	1.5	1.9	2.3	2.6	2.7	2.8	3.0	3.1	3.1
Positioned/Positioned Truck	30.6 + {316.7/(1.4-X_e)}	8.67V	1.4 - {316.7/(8.67V-30.6)}	-0.8	-0.3	0.0	0.2	0.4	0.5	0.6	0.7	0.8	0.8	0.9
Positioned/Unpositioned Truck	58.3 + {389.3/(3.5-X_e)}	8.67V	3.5 - {389.3/(8.67V-58.3)}	0.1	1.0	1.6	1.9	2.2	2.3	2.5	2.6	2.7	2.7	2.8
Unpositioned/Positioned Truck	58.3 + {532.7/(3.5-X_e)}	11.32V	3.5 - {532.7/(11.32V-58.3)}	0.3	1.1	1.6	1.9	2.1	2.3	2.5	2.6	2.6	2.7	2.8
Unpositioned/Unpositioned Truck	84.0 + {535.8/(5.6-X_e)}	11.32V	5.6 - {535.8/(11.32V-84.0)}	1.8	2.9	3.5	3.9	4.1	4.3	4.5	4.6	4.7	4.8	4.8

1 ft = 0.305 m
1 mi/h = 1.61 km/h



1 ft = 0.305 m
1 mi/h = 1.61 km/h

Figure 7. Design values for left-turn lane offsets to achieve the required sight distances computed from the AASHTO model with field data maneuver times (t_a) and J=2.0 s.

Table 9. Offsets necessary for achieving required sight distances using the modified AASHTO model (J=2.5 s).

Offset Condition (-3 ft)	ASD	RSD	X_o =	Offset (ft) by Design Speed (mi/h) 20	25	30	35	40	45	50	55	60	65	70
Unpositioned/Positioned Car	52.3 + {591.9/(1.8-X_o)}	12.94V	1.8 - {591.9/(12.94V-52.3)}	-1.1	-0.4	0.0	0.3	0.5	0.7	0.8	0.9	1.0	1.0	1.1
Unpositioned/Unpositioned Car	86.0 + {691.2/(4.1-X_o)}	12.94V	4.1 - {691.2/(12.94V-86.0)}	0.1	1.2	1.8	2.2	2.5	2.7	2.9	3.0	3.1	3.2	3.3
Unpositioned/Positioned Truck	52.3 + {498.4/(3.3-X_o)}	12.94V	3.3 - {498.4/(12.94V-52.3)}	0.9	1.5	1.8	2.1	2.2	2.4	2.5	2.5	2.6	2.7	2.7
Unpositioned/Unpositioned Truck	86.0 + {547.2/(5.6-X_o)}	12.94V	5.6 - {547.2/(12.94V-86.0)}	2.4	3.3	3.8	4.1	4.3	4.5	4.6	4.7	4.8	4.9	4.9

Aligned Condition	ASD	RSD	X_o =	Offset (ft) by Design Speed (mi/h) 20	25	30	35	40	45	50	55	60	65	70
Unpositioned/Positioned Car	55.0 + {598.0/(2.1-X_o)}	12.20V	2.1 - {598.0/(12.20V-55.0)}	-1.1	-0.3	0.2	0.5	0.7	0.9	1.0	1.1	1.2	1.3	1.4
Unpositioned/Unpositioned Car	82.0 + {662.4/(4.1-X_o)}	12.20V	4.1 - {662.4/(12.20V-82.0)}	0.0	1.1	1.8	2.2	2.5	2.7	2.8	3.0	3.1	3.2	3.2
Unpositioned/Positioned Truck	55.0 + {500.5/(3.6-X_o)}	12.20V	3.6 - {500.5/(12.20V-55.0)}	1.0	1.6	2.0	2.3	2.4	2.6	2.7	2.8	2.9	2.9	3.0
Unpositioned/Unpositioned Truck	82.0 + {524.4/(5.6-X_o)}	12.20V	5.6 - {524.4/(12.20V-82.0)}	2.4	3.2	3.8	4.1	4.3	4.5	4.6	4.7	4.8	4.9	4.9

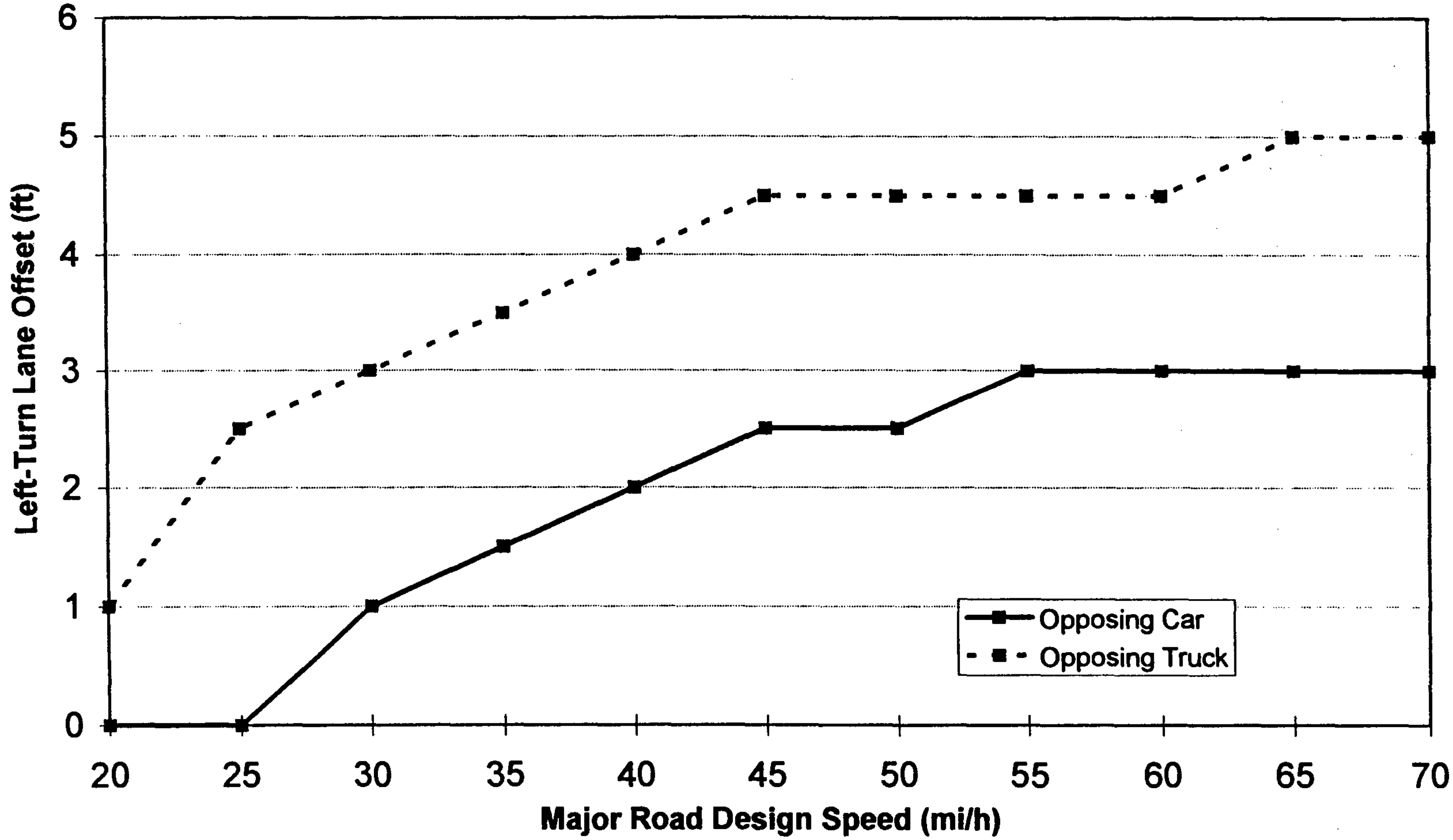
Offset Condition (+6 ft)	ASD	RSD	X_o =	Offset (ft) by Design Speed (mi/h) 20	25	30	35	40	45	50	55	60	65	70
Unpositioned/Positioned Car	58.3 + {635.2/(2.0-X_o)}	12.20V	2.0 - {635.2/(12.20V-58.3)}	-1.4	-0.6	-0.1	0.3	0.5	0.7	0.8	1.0	1.1	1.1	1.2
Unpositioned/Unpositioned Car	84.0 + {676.8/(4.1-X_o)}	12.20V	4.1 - {676.8/(12.20V-84.0)}	-0.1	1.0	1.7	2.1	2.4	2.6	2.8	2.9	3.1	3.1	3.2
Unpositioned/Positioned Truck	58.3 + {532.7/(3.5-X_o)}	12.20V	3.5 - {532.7/(12.20V-58.3)}	0.6	1.3	1.8	2.1	2.3	2.4	2.5	2.6	2.7	2.8	2.8
Unpositioned/Unpositioned Truck	84.0 + {535.8/(5.6-X_o)}	12.20V	5.6 - {535.8/(12.20V-84.0)}	2.3	3.2	3.7	4.0	4.3	4.4	4.6	4.7	4.8	4.8	4.9

1 ft = 0.305 m
1 mi/h = 1.61 km/h

Table 10. Offsets necessary for achieving required sight distances using the proposed gap model.

Offset Condition (-3 ft)	ASD	RSD	X_o =	20	25	30	35	40	45	50	55	60	65	70
				Offset (ft) by Design Speed (mi/h)										
Unpositioned/Positioned Car	52.3 + {591.9/(1.8-X_o)}	9.56V	1.8 - {591.9/(9.56V-52.3)}	-2.5	-1.4	-0.7	-0.3	0.0	0.2	0.4	0.5	0.7	0.8	0.8
Unpositioned/Unpositioned Car	86.0 + {691.2/(4.1-X_o)}	9.56V	4.1 - {691.2/(9.56V-86.0)}	-2.5	-0.4	0.7	1.3	1.8	2.1	2.3	2.5	2.7	2.8	2.9
Unpositioned/Positioned Truck	52.3 + {498.4/(3.3-X_o)}	9.56V	3.3 - {498.4/(9.56V-52.3)}	-0.3	0.6	1.2	1.5	1.8	2.0	2.1	2.2	2.3	2.4	2.5
Unpositioned/Unpositioned Truck	86.0 + {547.2/(5.6-X_o)}	9.56V	5.6 - {547.2/(9.56V-86.0)}	0.4	2.0	2.9	3.4	3.8	4.0	4.2	4.4	4.5	4.6	4.7
				Offset (ft) by Design Speed (mi/h)										
Aligned Condition	**ASD**	**RSD**	**X_o =**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**
Unpositioned/Positioned Car	55.0 + {598.0/(2.1-X_o)}	8.82V	2.1 - {598.0/(8.82V-55.0)}	-2.8	-1.5	-0.8	-0.3	0.1	0.4	0.6	0.7	0.8	0.9	1.0
Unpositioned/Unpositioned Car	82.0 + {662.4/(4.1-X_o)}	8.82V	4.1 - {662.4/(8.82V-82.0)}	-2.9	-0.7	0.5	1.2	1.7	2.0	2.3	2.5	2.6	2.8	2.9
Unpositioned/Positioned Truck	55.0 + {500.5/(3.6-X_o)}	8.82V	3.6 - {500.5/(8.82V-55.0)}	-0.5	0.6	1.2	1.6	1.9	2.1	2.3	2.4	2.5	2.6	2.7
Unpositioned/Unpositioned Truck	82.0 + {524.4/(5.6-X_o)}	8.82V	5.6 - {524.4/(8.82V-82.0)}	0.0	1.8	2.7	3.3	3.7	3.9	4.1	4.3	4.4	4.5	4.6
				Offset (ft) by Design Speed (mi/h)										
Offset Condition (+6 ft)	**ASD**	**RSD**	**X_o =**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**
Unpositioned/Positioned Car	58.3 + {635.2/(2.0-X_o)}	9.56V	2.0 - {635.2/(9.56V-58.3)}	-2.8	-1.5	-0.8	-0.3	0.0	0.3	0.5	0.6	0.8	0.9	1.0
Unpositioned/Unpositioned Car	84.0 + {676.8/(4.1-X_o)}	9.56V	4.1 - {676.8/(9.56V-84.0)}	-2.2	-0.3	0.8	1.4	1.8	2.1	2.4	2.6	2.7	2.8	2.9
Unpositioned/Positioned Truck	58.3 + {532.7/(3.5-X_o)}	9.56V	3.5 - {532.7/(9.56V-58.3)}	-0.5	0.6	1.2	1.6	1.9	2.1	2.2	2.4	2.5	2.6	2.6
Unpositioned/Unpositioned Truck	84.0 + {535.8/(5.6-X_o)}	9.56V	5.6 - {535.8/(9.56V-84.0)}	0.6	2.1	3.0	3.5	3.8	4.1	4.2	4.4	4.5	4.6	4.7

1 ft = 0.305 m
1 mi/h = 1.61 km/h

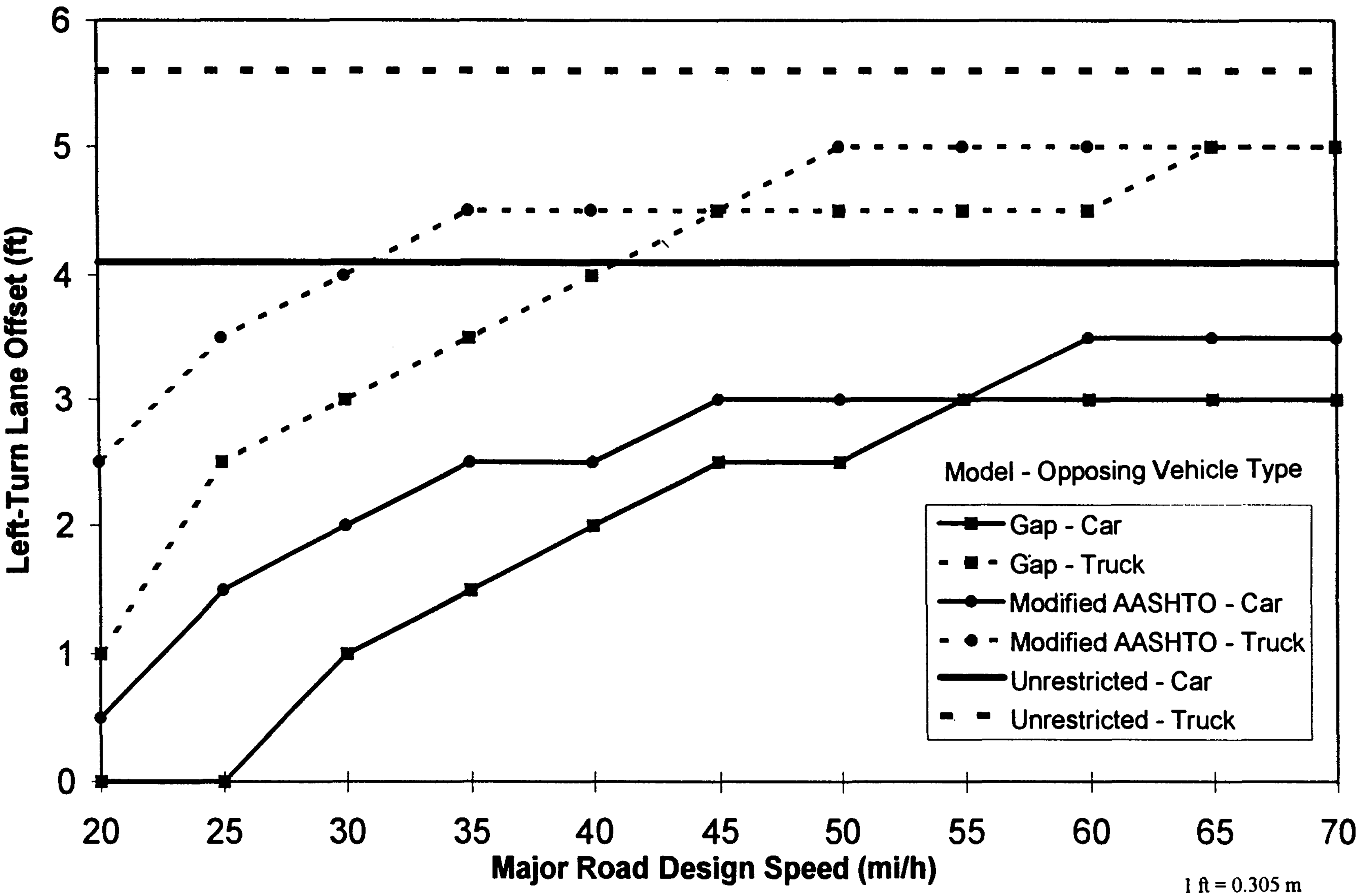


1 ft = 0.305 m
1 mi/h = 1.61 km/h

Figure 8. Design values for left-turn lane offsets to achieve the required sight distances computed from the proposed gap model.

vehicle is a truck, the design offset values range from 0.3 m (1.0 ft) for a design speed of 32 km/h (20 mi/h) to 1.5 m (5.0 ft) for design speeds of 105 km/h (65 mi/h) and greater.

By plotting the design values from the AASHTO models and the gap model together as shown in Figure 9, the effect of the smaller required sight distances produced by the gap model on the amount of offset needed can be shown. For example, when designing a 40-km/h (25-mi/h) roadway, the left-turn lane offsets would not be necessary to achieve the required sight distance for cars from the gap model, but would need to be 0.5 m (1.5 ft) to achieve the required sight distance from the AASHTO model. At a design speed of 80 km/h (50 mi/h) at a location with significant turning truck traffic, the offset needed according to the gap model would be 1.4 m (4.5 ft), while the AASHTO model would require an offset of 1.5 m (5.0 ft). As shown in the figure, however, if the roadway is built to provide unrestricted sight distance, then the offset values from either of the two models become irrelevant. Based on intersections in this study, the offset necessary to achieve unrestricted sight distance for opposing left-turning cars is 1.2 m (4.1 ft) and for opposing left-turning trucks it is 1.7 m (5.6 ft).



1 ft = 0.305 m
1 mi/h = 1.61 km/h

Figure 9. Left-turn lane offset design values to achieve required sight distances for the modified AASHTO model (J=2.5 s) and the proposed gap model, and for unrestricted sight distances.

RECOMMENDATIONS FOR DESIGN

The preceding rationale and discussion in this document support primary design recommendations (1) and (2) as stated below.

(1) Unrestricted sight distances and corresponding left-turn lane offsets are recommended, whenever possible, in the design of opposite left-turn lanes at intersections.

(2) At intersections where there are large percentages of left-turning trucks, the offsets required to provide unrestricted sight distances for opposing left-turning trucks should be used.

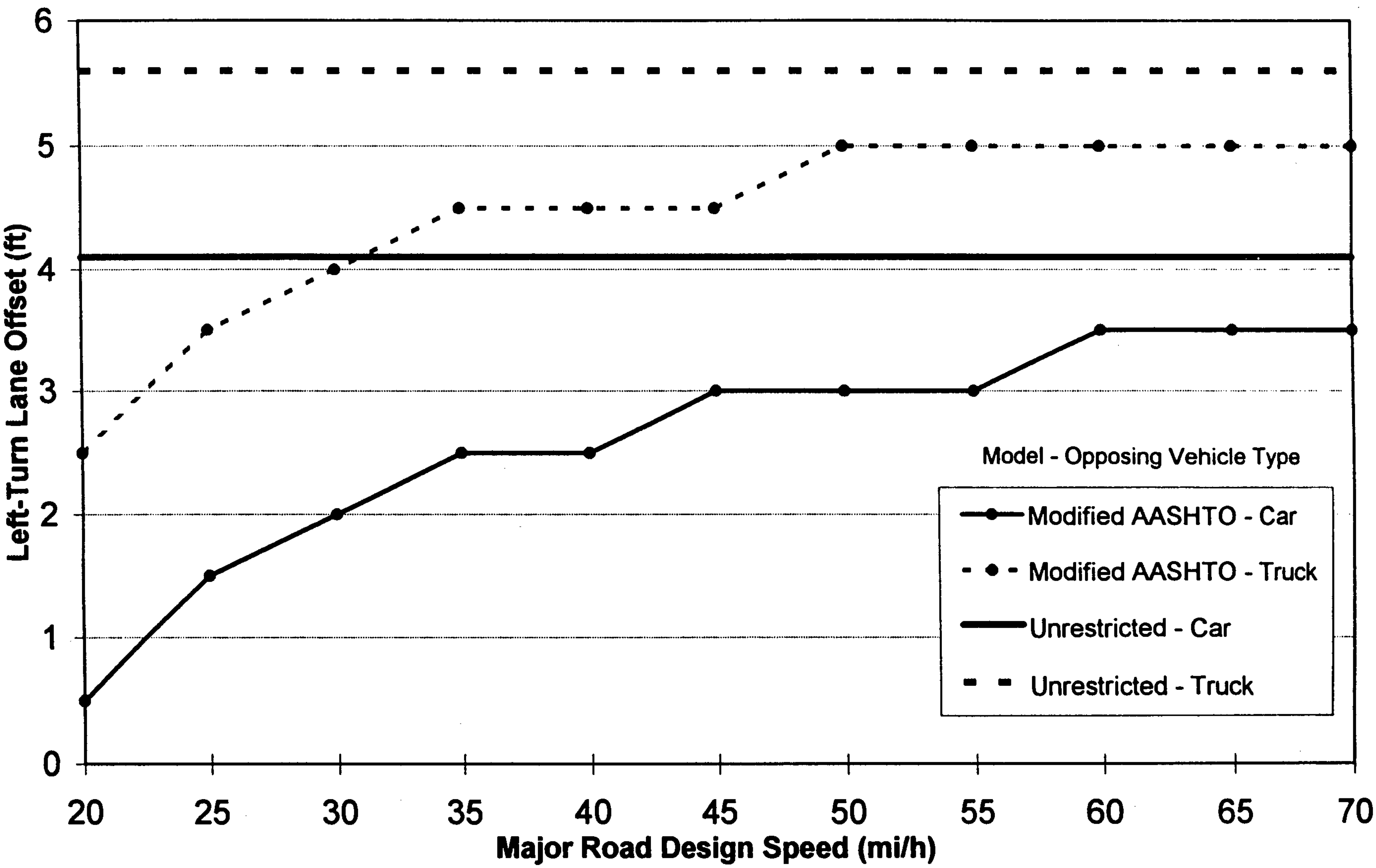
It is recognized that a number of factors may prohibit the provision of unrestricted sight distance in a given location. Under these circumstances, as stated in recommendation (3) below, the ISD values computed using the modified AASHTO model should be used for design purposes. These distances generally will exceed the distances required based on field maneuver data and will provide an additional margin of safety over distances obtained with the traditional ISD model or the proposed gap model. The left-turn lane offsets derived using this model are presented in Figure 10.

(3) Where the provision of unrestricted sight distance is not feasible, ISD values for left-turning traffic that must yield to opposing traffic on the major roadway (ISD, Case V) should be computed using the modified AASHTO model, as follows:

$$ISD = 1.47V(J + t_a)$$

where:
V = design speed on the major road (mi/h).
J = time to search for oncoming vehicles, perceive that there is sufficient time to make the left turn, and shift gears, if necessary, prior to starting (assumed to be 2.5 s).
t_a = time required to accelerate and traverse the distance to clear traffic in the approaching lane(s); obtained from Figure IX-33 in the AASHTO *Green Book*.

If the gap model is accepted as the appropriate model for computing ISD for left-turning vehicles off of a major roadway, a need for further research exists to evaluate the potential difficulties this may pose for older drivers. Analyses presented in the previous section showed the critical gaps for older drivers (age 75 or older) to be greater than the proposed critical gaps in the model. The reduced sight distances obtained with the proposed gap model may present significant problems for older drivers who have been shown to require larger gaps.



1 ft = 0.305 m
1 mi/h = 1.61 km/h

Figure 10. Recommended left-turn lane offset design values.

Further recommendations apply to channelized offset left-turn lanes. A particular concern with older drivers is the potential for wrong-way movements at complex intersections. Crowley and Seguin (1986) reported that drivers over 60 years of age are excessively involved in wrong-way movements on a per mile basis. The potential for wrong-way movements at intersections with channelized (positive) offset left-turn lanes within a raised median is most likely for the driver turning left from the minor road onto the major road, who must correctly identify the proper median opening into which he/she should turn. The following countermeasures are recommended at intersections with a divided median on the receiving leg to reduce the potential for wrong-way maneuvers by drivers turning left from the stop-controlled minor roadway. The recommended placement of these traffic control devices (TCD's) is shown in Figure 11.

(4) At intersections where the left-turn lane treatment results in channelized offset left-turn lanes (e.g., a parallel or tapered left-turn lane between two medians), the following countermeasures are recommended to reduce the potential for wrong-way maneuvers by drivers turning left from the stop-controlled minor roadway:

- **Proper signing (advanced DIVIDED HIGHWAY CROSSING signs, and proper positioning of WRONG WAY, DO NOT ENTER, and ONE WAY signing at the intersection) must be implemented.**

- **Channelized left-turn lanes should contain white pavement lane-use arrows (left-turn only).**

- **Pavement markings which scribe a path through the turn are recommended to reduce the likelihood for the wrong-way movement.**

- **Use of a wide (61-cm [24-in]) white stop bar is recommended at the end of the channelized left-turn lane as a countermeasure to aid in preventing a potential wrong-way movement. This countermeasure was found to be effective in preventing wrong-way entries onto freeway exit ramps in Georgia (Parsonson and Marks, 1979).**

- **Placement of 7.2-m (23.5-ft) wrong-way arrows in the through lanes is recommended, as specified in the *Manual on Uniform Traffic Control Devices* (MUTCD) requirements for wrong-way traffic control for locations determined to have a special need, section 2E-40. Wrong-way arrows have been shown to reduce the frequency of wrong-way movements at freeway interchanges (Parsonson and Marks, 1979).**

- **Indistinct medians are considered to be design elements that tend to reduce a driver's ability to see and understand the overall physical and operational features of an intersection, increasing the frequency of wrong-way movements (Scifres and Loutzenheiser, 1975). Delineation of the median noses will increase their visibility and should improve driver understanding of the intersection design and function.**

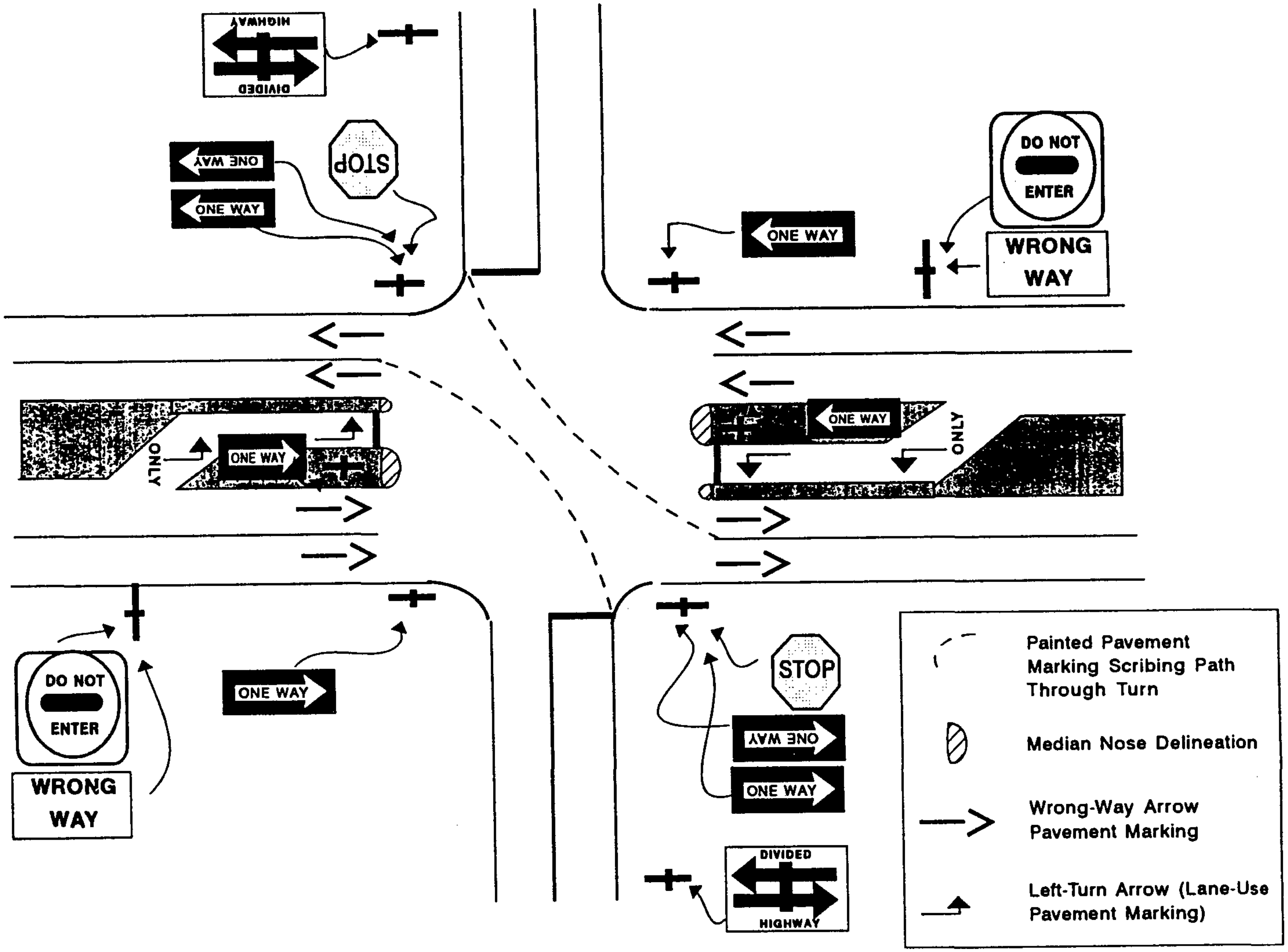


Figure 11. Recommended signing and delineation treatments for intersections with channelized left-turn lanes to reduce the potential for wrong-way movements for drivers turning left from the minor roadway.[1]

[1] It is recommended that the broken line scribing the path through the turn be placed on the right side of the path instead of on the left side of the path, where lines are traditionally placed, because of the advantages it offers in conveying the following guidance cues: (1) it guides drivers further away from turning into the channelized left-turn lane, and (2) it maintains separation between the paths of opposing left-turning drivers.

RECOMMENDATIONS FOR OPERATIONAL AND TRAFFIC CONTROL COUNTERMEASURES

It must be recognized that situations will exist where geometric design changes are not feasible at intersections as a result of restricted right-of-way and where special sight distance requirements are defined as a result of the horizontal and/or vertical curvature of the opposing roadway approach. The following list of recommendations for operational changes and the use of traffic control devices apply where problems with sight-restricted geometries are intractable.

Where problems with sight-restricted geometries are intractable, the following list of recommendations for operational changes and traffic control devices are recommended:

(1) Eliminate permissive left turns at intersections and implement only protected/prohibited left-turn operations where:

(a) the sight distance achievable/feasible at a location, with or without geometric redesign, falls significantly below the required (minimum) sight distance as calculated using a modified AASHTO ISD model with a 2.5-s PRT; or

(b) a pattern of permissive left-turn accidents occurs.

(2) Restrict permissive left turns to low-volume conditions (such as during non-rush hour).

(3) Narrow the left-turn lanes (either physically or by applying painted lane lines) to force the lateral position of drivers as close to the right edge of the opposite left-turn lane as possible. Forcing drivers to the left, even by 0.5 m (1.5 ft), will result in a net gain of 0.91 m (3 ft) (both opposing left-turning drivers), which will improve sight distance.

(4) Add a lag-protected phase (i.e., briefly display a yellow arrow after the permissive phase) to clear out queued drivers.

(5) Consider the use of intelligent signal phasing (such as gap-sensitive signal phasing).

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