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INTERSECTION GEOMETRIC DESIGN AND OPERATIONAL GUIDELINES FOR OLDER DRIVERS AND PEDESTRIANS, VOLUME 2 EXECUTIVE SUMMARY

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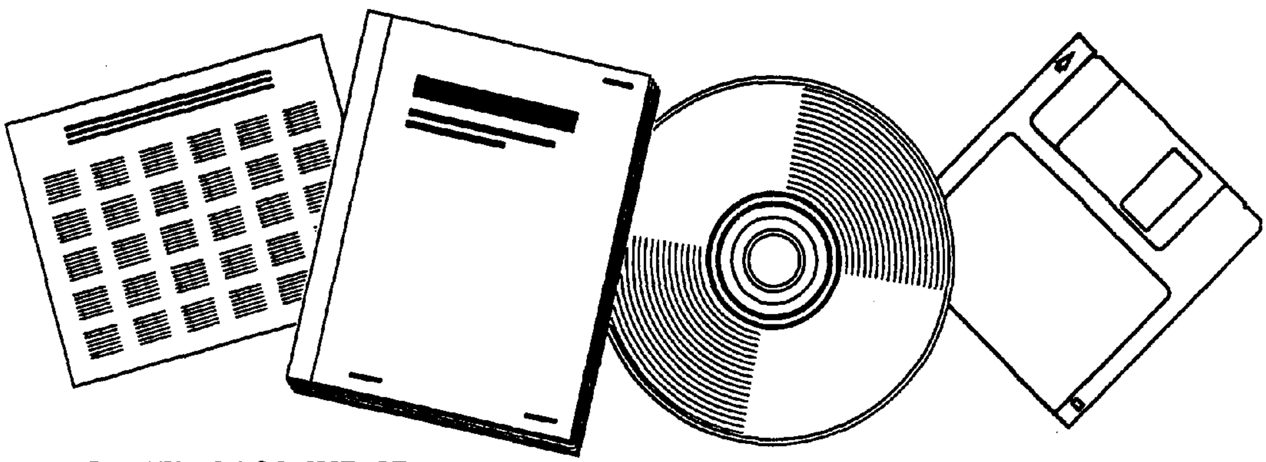

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Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians,

Volume II: Executive Summary

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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

NOTICE

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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 second in a series. The other volumes in the series are:

FHWA-RD-96-132 Volume I: Final Report
FHWA-RD-96-137 Volume III: Guidelines

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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
		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

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

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)

VOLUME I: FINAL REPORT
TABLE OF CONTENTS

VOLUME I: FINAL REPORT
TABLE OF CONTENTS (Continued)

VOLUME I: FINAL REPORT
LIST OF FIGURES

VOLUME I: FINAL REPORT
LIST OF FIGURES (Continued)

Figure | Page

VOLUME I: FINAL REPORT
LIST OF TABLES

VOLUME I: FINAL REPORT
LIST OF TABLES (Continued)

VOLUME I: FINAL REPORT
LIST OF TABLES (Continued)

VOLUME II: EXECUTIVE SUMMARY
TABLE OF CONTENTS

Page

VOLUME II: EXECUTIVE SUMMARY
LIST OF FIGURES

VOLUME III: GUIDELINES
TABLE OF CONTENTS

VOLUME III: GUIDELINES
LIST OF FIGURES

VOLUME III: GUIDELINES
LIST OF TABLES

EXECUTIVE SUMMARY

INTRODUCTION AND RESEARCH OBJECTIVES

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 and 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). These data 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). As part of a long-term program to accommodate this growing segment of the population, the specific objectives of this research were as follows:

- Identify the sensory/perceptual, cognitive, and physical (psychomotor) capabilities of older drivers and 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 road users, and develop and test alternative solutions to problems experienced by this group of 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, 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 appear feasible to alleviate the problems of older road users through changes to geometric design or operations, and suggest future research objectives and approaches most likely to fill gaps in the present knowledge and resolve outstanding problems in this area.

AGE, DIMINISHED CAPABILITIES, AND INTERSECTION NEGOTIATION PROBLEMS

Age-Related Functional Deficits

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 that probably 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 functions 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, which 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 (more than 24 cycles/deg) information, older road users' sensitivity to visual contrast at lower and middle-range spatial frequencies (i.e., for 6-, 12-, and 18-cycle/deg 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 overestimation 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. Also, these researchers have shown that older persons will have greater difficulty in situations where planned actions must be rapidly altered, and corrections during movement execution are slower and much less efficient. 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. Again, a need to avoid geometric designs which 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, 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.

Identified Problems With Intersection Use

A series of project activities were conducted to better define the problems experienced by older road users at intersections, including: (1) a statewide (Michigan) intersection accident database analysis, using a case study approach; (2) a task analysis for intersection approach driving; (3) focus group discussions with "young-old" and "old-old" motorists; (4) a laboratory study of user preferences, using slides to present animated approaches to geometric features of interest; (5) an observational field study to contrast the behaviors of older drivers at intersections matched on operational criteria but differing in geometric design; and (6) consideration by an Older Road User Expert Panel of the most appropriate focus of the larger scale laboratory and field investigations to follow in this project.

A detailed description of procedures and results of these activities is contained in the Federal Highway Administration final report (publication no. FHWA-RD-96-132). Briefly, it may be noted that in the accident analysis, a case study approach of approximately 700 incidents indicated that geometric changes which reduced complexity or the probability of unexpected events will have the greatest benefit for older road users. The task analysis highlighted inadequate advance warning/advisory information for proper lane selection, and inconspicuous channelization and other physical barriers in median and shoulder areas as the most probable sources of older driver problems at intersections. The focus group discussions tied problems relating to vehicle steering control, vehicle speed control, conflict avoidance, navigational decisions, right-of-way decisions, and pedestrian crossing decisions to specific geometric and operational aspects of intersection use. The preliminary laboratory study evaluated the extent of problems experienced by older road users due to varying skew angles at intersections, varying radius of curvature of corner curb cuts, varying offset of opposite left-turn lanes, varying treatments for indicating prohibited driving areas in center- or turn-lane areas, and varying geometries for merging and lane-width transition operations in the vicinity of intersections. The preliminary field study collected observational data of errors committed during right-turning and left-turning movements at intersections by older drivers, at matched facilities with varying geometric characteristics. The expert panel, after reviewing these findings in the context of project objectives and available responses for later tasks, defined a broad set of guidelines for the primary empirical studies, as summarized below:

(1) Continuing research efforts in this project will be most productive if focused on developing and testing a limited set of hypothesized enhancements for a single problem situation, with enough conditions to systematically manipulate the intersection feature(s) of interest, while controlling for likely confounding variables. In contrast, any attempt to study a wide range of enhancements, with poorer experimental control over confounding variables, across a greater number of site types, will result in a weaker research product. By consensus, the primary focus of continuing project tasks should be **left-turn operations from one major roadway onto another at signalized intersections with permissive left-turn phasing**. Stop-controlled intersections, while not ruled out as a topic worthy of study, were not identified as a priority for this project.

(2) While ideally safety and mobility both will benefit from a given system enhancement, the first concern in this project must be on safety; accident prevention (at intersections) may, in itself, have the greatest impact on mobility by reducing congestion and the resulting loss in system efficiency and level of service. As a practical matter, in this project, the design and testing of improvements in intersection geometry and operations should focus on the needs of drivers, with one caveat: **enhancements should not be recommended that may be expected to have an adverse impact on pedestrians.**

(3) The following laboratory study in this project should examine: (a) positive (versus aligned versus negative) offset geometries for left-turn lanes; and/or (b) varying throat (lane) width on the receiving leg of intersections; and/or (c) varying lane width (2.7 to 3.7 m [9 to 12 ft]) on the intersection approach leg. Furthermore, this data collection effort should select measures of effectiveness (MOE's) which are most predictive of safety impacts (i.e., avoid measures such as "acceleration profile" unless a significant increase in likelihood of a collision is indicated) and should include realistic conflict scenarios in intersection test stimuli presented in the laboratory.

(4) The following field study in this project should examine: (a) varying offset geometries of left-turn lanes, specifically including positive offset; and/or (b) varying intersection width, including variation in median width and in throat (lane) width on the receiving leg. In addition, this data collection effort should consider "margin of safety," critical gaps, and traffic conflicts as MOE's; collect data during actual operations with test drivers, as opposed to a closed course, to maximize the validity and generalizability of study findings; and ensure that sites selected for data collection have appropriate volumes and operations for measurement of the designated MOE's (e.g., measurement of critical gap size is meaningless if all left-turning drivers are forced to turn during the clearance interval).

LABORATORY AND FIELD STUDIES OF ALTERNATIVE DESIGN ELEMENTS

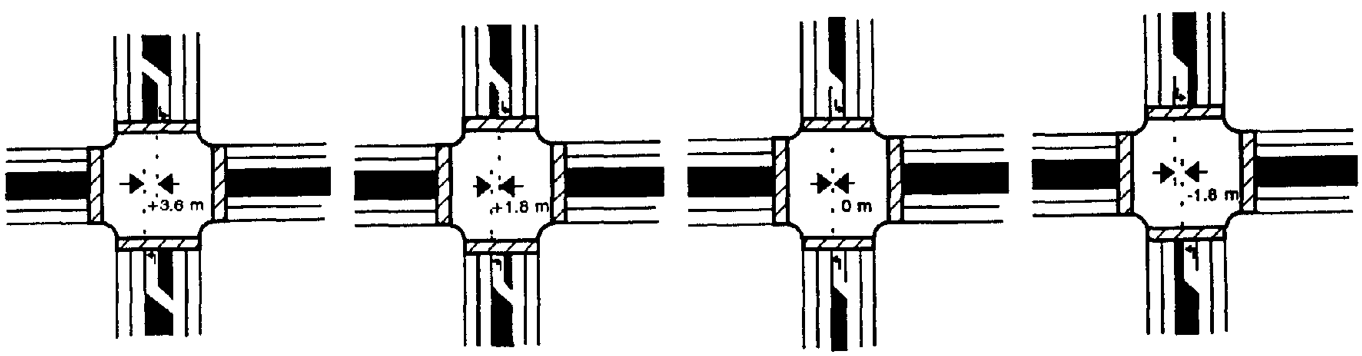
Consistent with the outcome of prior tasks that identified certain geometric elements as having the greatest impact on the safety and ease of use of intersections by older road users, the major laboratory studies in this project investigated: (1) the effect of alternative opposite left-turn lane geometries (OLTLG) on driver response, plus (2) pedestrian response to alternative median refuge island characteristics that are feasible to implement under a given turn-lane geometry. A complementary set of field studies examined: (1) driver and pedestrian response to intersections with varying left-turn lane geometries and associated median refuge island characteristics; (2) driver response to channelization, acceleration lanes, and the degree of skew at which the turn lane met the intersecting roadway; and (3) the effect of varying curb radii on the performance of right-turning drivers. In all cases, driver (or pedestrian) age was a key independent variable.

The largest share of project resources was devoted to the study of alternative left-turn lane geometry, and it was in this area only that results substantive enough to support recommendations and guidelines were obtained. The following summary therefore concentrates on this effort, with a brief overview of other findings deferred to the end of the section.

Alternative Left-Turn Lane Geometry and Pedestrian Crosswalk Configuration

Laboratory Study. This was a study of left-turn gap acceptance by drivers waiting in a left-turn storage bay to turn 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 turn lanes at suburban arterial intersections. The degree of offset for opposite left-turn lanes refers to the distance from the inner edge of one lane to the outer edge of the opposite lane. This geometric feature determines the available sight distance for left-turning traffic, which influences the extent to which vehicles in opposite turn lanes block each other's view of conflicting traffic (i.e., reduce sight distance). The level of blockage depends on how the opposite left-turn lanes are aligned with respect to each other. When the two 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:



(a) full positive offset (b) partial positive offset (c) aligned (d) partial negative offset

Figure 1. Alternative intersection geometries examined in the laboratory.

In addition, the following traffic operational factors were varied in the laboratory: (1) oncoming (through) traffic vehicle type (passenger car versus semi-tractor trailer); (2) oncoming traffic speed (56, 72, and 88 km/h [35, 45, 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 30.48-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 that 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 that 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 ages 25-45 ("young/middle-aged group"), 24 between ages 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 that 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, which were 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.

- Larger gaps required in the presence of an oncoming truck compared to the gap size for an oncoming passenger car.

- Mean least safe gap size increases with increasing driver age.

- 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 trucks 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 more safe 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).

A complementary study of pedestrian response to the alternative geometries described above was also performed. Specifically, three independent variables were included in a laboratory study of alternative crosswalk configurations: (1) opposite left-turn lane geometry, (2) driver age, and (3) design walking speed. The four levels of opposite left-turn lane geometry included partial negative offset, aligned, partial positive offset, and full positive offset. Associated with geometry were specific, covarying factors that included the presence or absence of a pedestrian refuge island, the width of the refuge island, the number of refuge islands, and the crossing-path distance. Two levels of design walking speed were also studied: 0.9 m/s (3 ft/s) and 1.2 m/s (4 ft/s). Driver ages were 25-45, 65-74, and 75+. The dependent measures included subjective ratings of safety and willingness to use the crosswalk under each geometry, and an objective measure of mobility, which was the amount of time after the beginning of the protected crossing phase that an individual remained willing to start crossing the intersection.

The clearest trend emerging in these data was a relatively lower perceived safety level for the aligned geometry. No obvious influence of walking speed could be discerned. Differences related to the ages of subjects were mixed, and no interaction between age and geometry was readily apparent.

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 where the posted speed limit was 56 km/h (35 mi/h), and all left-turn maneuvers were completed during the permissive left-turn signal phase at all study sites.

Seven measures of effectiveness were used in the field:

(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.

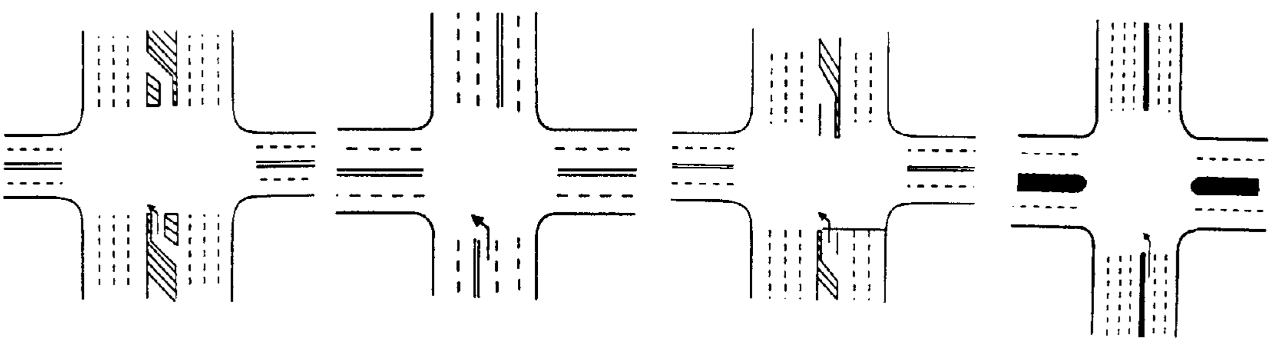
(3) *Left-Turn Conflict*: Conflict between a left-turning vehicle and an opposing vehicle, defined as the occurrence of either sudden and unavoidable lane change by a conflict vehicle because the test vehicle clearly accepted a dangerously small gap, or a complete or nearly complete stop by the conflict 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 that 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) 1.8-m (6-ft) "partial positive" offset (b) aligned (no offset) (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 of left-turn lane offset.

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-aged (25-45 years old); (2) young-old (65-74 years old); and (3) old-old (75+ years old). A repeated-measures research design was used in which 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. 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- to 12-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.

The data analyzed in this study were derived from 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. 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) opposite left-turn lane offset.
- Significant 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 effect of age and gender on vehicle positioning, where older drivers and female drivers were less likely to position themselves within the intersection to improve sight distance.
- Subjective responses to survey questions indicating that two-thirds of 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.

A complementary study of pedestrian response to varying crosswalk configurations was also conducted in the field. The independent variables in this study included four levels of pedestrian age groups (25-45, 46-64, 65-74, and 75+) and two levels of crosswalk design (pedestrian refuge island present versus no pedestrian refuge island). The refuge island had an area of more than 15.2 m^2 (50 ft^2), with a width varying from 0.9 to 4.5 m (3 to 15 ft), and was located in a crosswalk midway across a 29.5-m (97-ft) street. The control crosswalk (no refuge island) was 27.7 m (91 ft) long, and pedestrians were required to cross in one stage. Two types of dependent variables were measured. First, the percentage of pedestrians in each age group who did not comply with the flashing and steady DON'T WALK indications on the pedestrian control signal was calculated; this served as a measure of the degree to which a refuge island encourages pedestrians to cross without waiting for the WALK indication. The percentage was calculated based on the total number of pedestrians who had the opportunity to violate the signal (e.g., no vehicular traffic was close to the crosswalk to prevent a pedestrian from crossing). In addition, to measure how pedestrians of different age groups perceive the presence of median refuge islands as a safety measure, individuals were surveyed regarding the degree of difficulty they experienced crossing at each site type (with and without an island), and they were asked for their opinions regarding: (1) the removal of an island where one already existed, or (2) the installation of an island where presently none existed. Data were obtained for a total of 436 pedestrians.

Results showed a striking and significant difference in the rates of pedestrian control signal violations as a function of age: 40.7 percent for pedestrians under the age of 65, versus 1.8 percent for pedestrians age 65 and older. Females of all ages were less likely to violate than males. Also, violation rates were higher at locations *with* a refuge island than *without* an island, 48.4 percent versus 31.1 percent for pedestrians under age 65 and 2.9 percent versus 0 percent for pedestrians age 65 and older. In the analyses of the subjective data, pedestrians perceived locations with refuge islands as being more difficult to cross; but, all age/gender groups supported installation of islands where none exist, and felt even more strongly that removal of existing islands was not desirable.

Alternative Right-Turn Lane Geometry

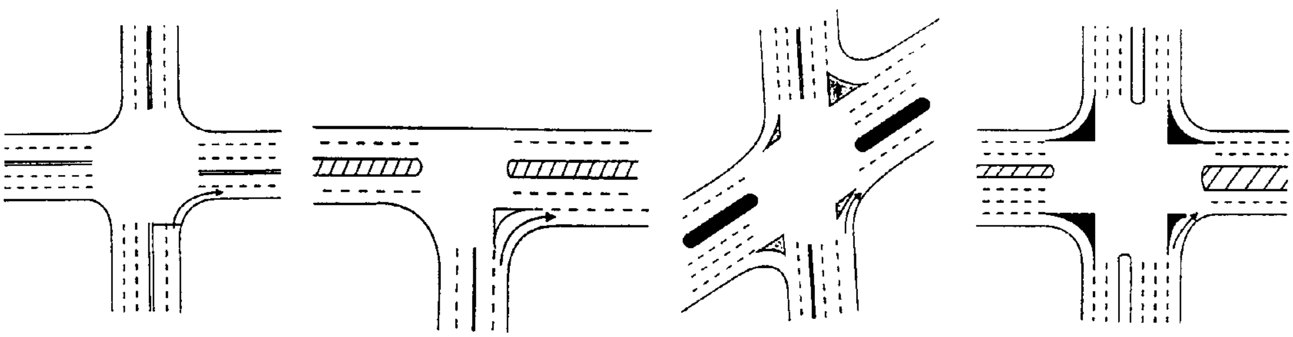
In the study of channelization and skew for right-turn lanes, four right-turn lane geometries were examined, as diagrammed in Figure 3:

(a) Non-channelized 90-degree intersection where drivers had the chance to make a right-turn-on-red around a 12.2-m (40-ft) radius. This site served as a control geometry to examine how channelized intersections compared to non-channelized intersections.

(b) Channelized right-turn lane at a 90-degree intersection with an exclusive-use (acceleration) lane on the receiving street. Under this geometric configuration, drivers did not need to stop at the intersection and they were removed from the conflicting traffic upon entering the cross street. They had the opportunity to accelerate in their own lane on the cross street, and then change lanes downstream when they perceived that it was safe to do so.

(c) Channelized right-turn lane at a 65-degree skewed intersection without an exclusive-use lane on the receiving street.

(d) Channelized right-turn lane at a 90-degree intersection without an exclusive-use lane on the receiving street. Under this geometry, drivers needed to check the conflicting traffic and complete their turn into a through-traffic lane on the cross street.



(a) Non-channelized right-turn lane at 90-degree intersection

(b) Channelized right-turn lane with exclusive-use lane at 90-degree intersection

(c) Channelized right-turn lane without exclusive-use lane at skewed intersection

(d) Channelized right-turn lane without exclusive-use lane at 90-degree intersection

Figure 3. Alternative intersection geometries evaluated in the field study of right-turn lane channelization.

The measures of effectiveness for the study of right-turn channelization and skew included: (1) percentage of drivers who attempted a right-turn-on-red (RTOR) maneuver (i.e., continuously moved head/neck toward conflicting traffic or used side mirror for same purpose); (2) percentage of drivers who used head/neck movement only (did not use mirror) in their attempt to make an RTOR; (3) percentage of drivers who used side mirrors (either exclusively or as a supplement to direct looks); (4) percentage of drivers who completed an RTOR; (5) percentage of drivers who made an RTOR without a complete stop; (6) acceleration profile after making right turn (time to accelerate 30.5 m [100 ft]); (7) free-flow speed while making the right turn; (8) site-specific survey questions measuring level of comfort with the right-turn maneuver and degree of ease or difficulty at each site; and (9) general survey questions about personal responses to various traffic control devices.

A total of 100 subjects divided across 3 age groups drove their own vehicles around test routes using the local street network in Arlington, VA. The three age groups were: "young/middle-aged" (ages 25-45), which contained 32 drivers; "young-old" (ages 65-74), containing 36 drivers; and "old-old" (age 75+), containing 32 drivers.

In this study, the right-turn maneuver at all locations was made against two lanes carrying through (conflicting) traffic. The two through lanes were the only ones that had a direct effect on the right-turn maneuver. All intersections were located on major or minor arterials where the posted speed limit was 56 km/h (35 mi/h). Test subjects drove their own vehicles. All intersections were controlled by traffic signals, with yield signs controlling the three channelized right-turn lanes.

The results indicated that right-turn channelization affects the speed at which drivers make right turns and the likelihood that they will stop before making an RTOR. Drivers, especially younger drivers, turned right at speeds 4.8 to 8.0 km/h (3 to 5 mi/h) higher on intersection approaches with channelized right-turn lanes than they did on approaches with unchannelized right-turn lanes. Also, young/middle-aged and young-old drivers were much less likely to stop before making an RTOR on approaches with channelized right-turn lanes. The increased mobility exhibited by the younger drivers at the channelized right-turn lane locations was not, however, exhibited by the old-old drivers, who stopped in 19 of the 20 turns executed at the channelized locations.

Unfavorable intersection skew affected the RTOR behavior of drivers. Drivers were less likely to attempt to make an RTOR at a skewed intersection where the viewing angle to conflicting traffic from the left on the cross street was greater than 90 degrees. Also, drivers turning right at these locations were more likely to rely on their side mirrors than they were when making an RTOR at non-skewed intersections.

Driver perceptions of the level of comfort and degree of difficulty were influenced by age as well as right-turn lane geometry. Young/middle-aged and old-old drivers were most comfortable making (90-degree) right turns on approaches with *un*channelized right-turn lanes, whereas young-old drivers were most comfortable making right turns on approaches with channelized right-turn lanes with acceleration lanes on the cross street. *All* drivers perceived making a right turn on an approach with a channelized right-turn lane *without an acceleration lane on the cross street* as being more difficult than at other locations, even more difficult than at skewed intersections.

Varying Right-Turn Curb Radius

In a field study of the effect of alternative curb radius on driver behavior, observations were conducted at three intersections characterized as follows: (a) large curb radius of 12.2 m (40 ft); (b) medium curb radius of 7.6 m (25 ft); and (c) small curb radius of 4.6 m (15 ft). The measures of effectiveness for the study of right-turn curb radius included:

(1) *Entrance distance*: the radial distance between the right front wheel of the vehicle and the edge of the pavement, measured at the point where the circular curve of the corner starts.

(2) *Center distance*: the radial distance between the right front wheel of the vehicle and the edge of the pavement, measured at the center of the circular curve.

(3) *Exit distance*: the radial distance between the right front wheel of the vehicle and the edge of the pavement, measured at the end of the circular curve, on the cross-street side.

(4) *Free-flow speed*: the speed measured at the center of the circular curve.

The same test sample was used that participated in the study of channelization and skew; these subjects drove their own vehicles. The study was conducted on major and minor arterials where the speed limit was 56 km/h (35 mi/h). Data were collected only for turns executed on a steady green signal phase.

The results indicated that center distances were independent of driver age and gender, but dependent on the curb radius. Specifically, the path of the driver more closely followed the edge of the pavement when the radius of the curb was larger, because the difference between the exit distance and entrance distance was reduced as the curb radius increased. The differences between the overall exit and entrance distances were about 0.6 m (2 ft) for the 4.6-m (15-ft) radius, 0.3 m (1 ft) for the 7.6-m (25-ft) radius, and 0.2 m (0.7 ft) for the 12.2-m (40-ft) radius.

Furthermore, larger curb radii increased the turning speeds of all drivers, with young/middle-aged and young-old drivers traveling faster than old-old drivers when making right turns. There was no significant difference in the turning paths of older and younger drivers, however, suggesting that older drivers were not as willing to experience the higher lateral accelerations that are accepted by younger drivers.

PROJECT RECOMMENDATIONS

Following completion of the contract activities summarized above, a second expert panel meeting critiqued the findings and provided guidance for the development of recommendations. By consensus, supporting evidence for the development of recommendations exists only with respect to left-turn lane geometry and operations; present findings suggesting operational differences in right-turn operations as a function of channelization and curb radius by drivers of various ages require further study. Accordingly, an extensive sight distance analysis was performed, contrasting the current AASHTO Case V intersection sight distance (ISD) model, a modified AASHTO model using a perception-reaction time (PRT) of 2.5 s, and a gap-acceptance model as proposed in the recently completed NCHRP Project 15-14(1), leading to the set of recommendations for improved intersection design and operations that follows.

Recommendations for design presented below are directed not to any specific, physical measure of left-turn lane offset that is to be applied without regard to other factors, but instead they seek to ensure adequate visibility of through traffic by the turning driver, taking age-related performance limitations into account. Therefore:

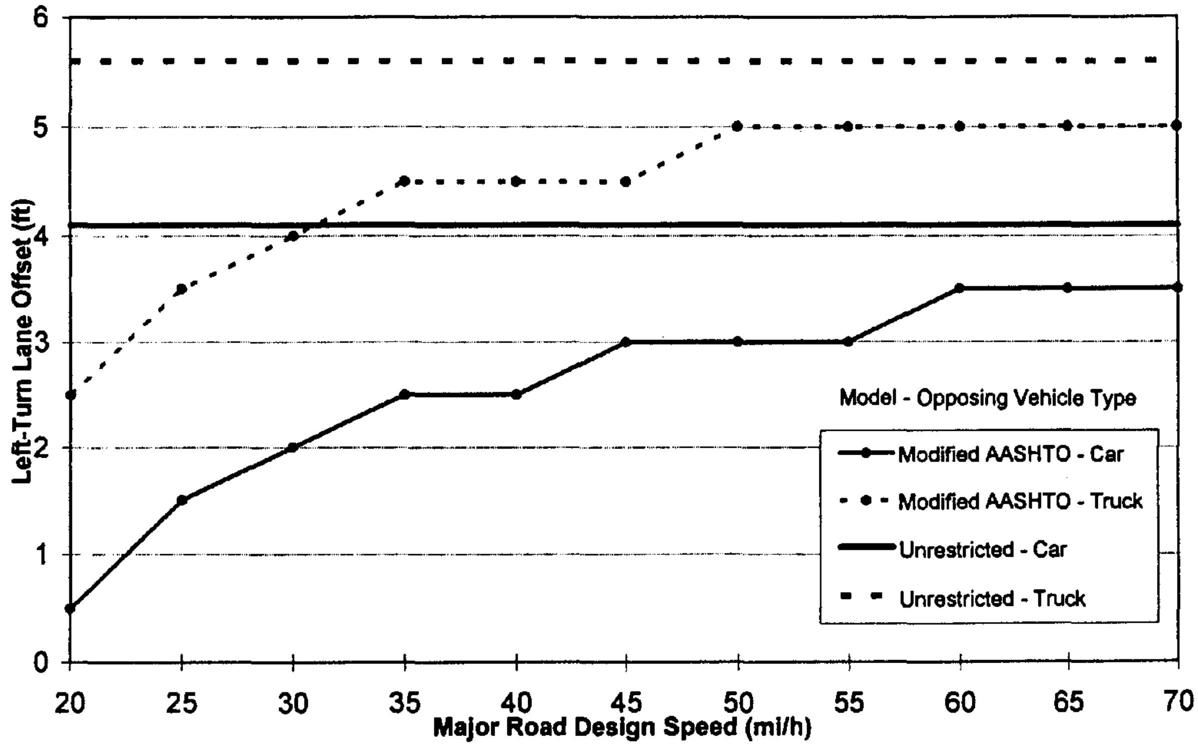
- **Unrestricted sight distances and corresponding left-turn lane offsets are recommended, whenever possible, in the design of opposite left-turn lanes at intersections.**
- **The offsets required to provide unrestricted sight distances for opposing left-turning trucks should be used at intersections where, based on engineering judgment, the volume of heavy vehicles is sufficient to result in probable encounters between such vehicles during normal operations.**

At the same time, it is recognized that a number of factors may prohibit the provision of unrestricted sight distance in a given location. Under these circumstances, 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 collected in this study, and will provide an additional margin of safety over distances obtained with the traditional ISD model or the proposed gap model. The recommended left-turn lane offsets derived using this model are shown in Figure 4.

- **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*.**



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

Figure 4. 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; drivers over 60 years of age are excessively involved in such wrong-way movements on a per-mile-driven 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. 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 (see Figure 5):

- **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.**
- **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.**
- **Delineation of median noses using reflectorized paint and other treatments to increase their visibility and improve driver understanding of the intersection design and function is recommended.**

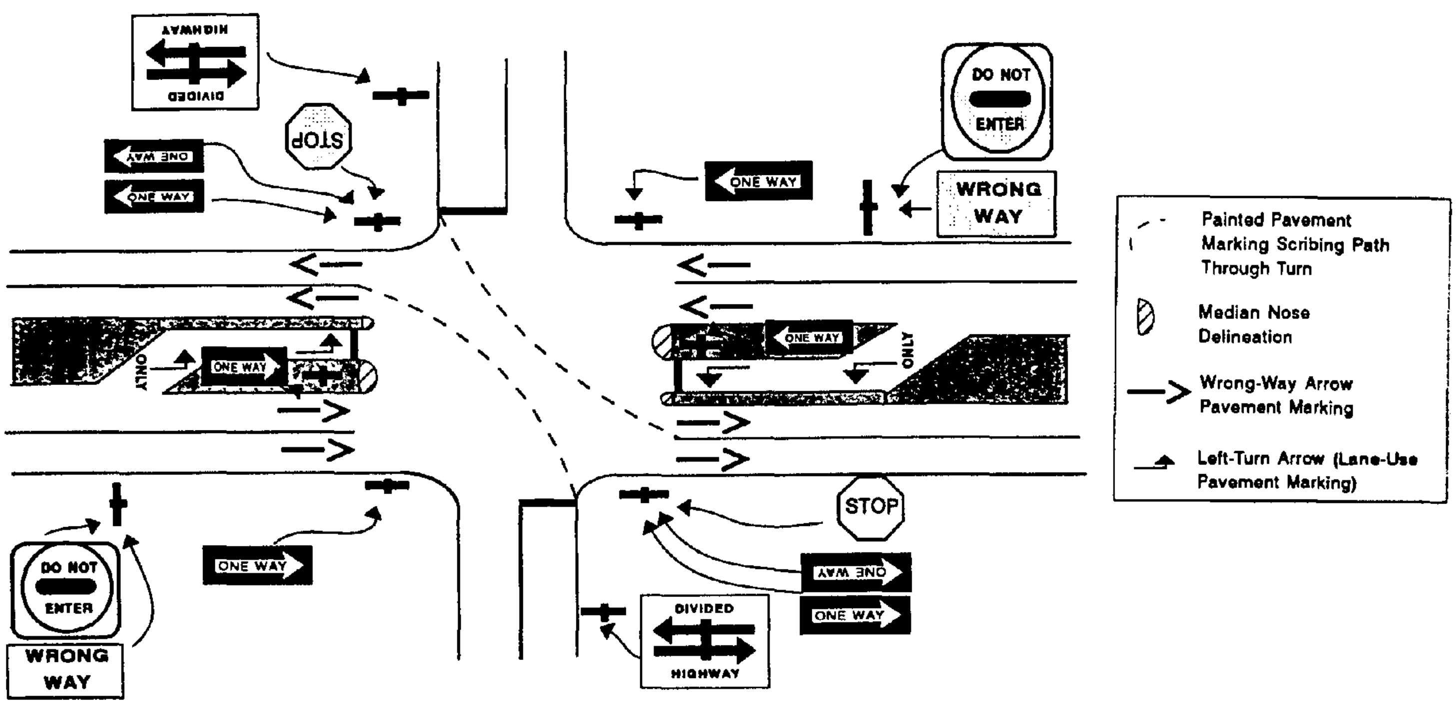


Figure 5. Recommended signing and delineation treatments for intersections with channelized left-turn lanes to reduce the potential for wrong-way movements for drivers turning left from the minor roadway.

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

- **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.

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

- **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.**

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

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

The concluding activity in this project was to develop recommendations for future research. The following priorities, described in more detail in the Final Report, were identified:

(1) Measure the relative contributions of situational factors and individual differences to pedestrian behaviors for different intersection geometries and traffic control practices.

(2) Measure the effect on drivers' gap decisions and resulting behaviors of differences in intersection geometry, operations, and demographic and situational factors *in combination.*

(3) Quantify the workload associated with the approach to and negotiation of intersections with varying geometric and operational characteristics.

(4) Establish human factors requirements for and test the effectiveness of "active" traffic and pedestrian control devices at intersections that are sensitive to real-time conditions.

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